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THIS MONTH:

Carbonate chimneys on the outer continental shelf

and

Oregon earthquake symposium report

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COVER FIGURE

Composite sketch of fluid-venting site 1428 on marginal thrust ridge on outer continental shelf off the coast of Oregon. Colonies of tube worms occupy the ledge above the canyon wall, and several clusters of giant white clams are aligned along presumed zones of fluid expulsion. The origin of the cone-shaped carbonate chimney structure with attached corals, which is shown at the top of this sketch, is discussed in paper beginning on the next page. Location of site 1428 is shown on Figure 4. Venting sites cover an area of about 20 m². (Figure from Suess and others, 1985, their Figure 1.)

In memoriam: Hollis M. Dole, 1914-1987

Hollis Mathews Dole, former State Geologist of Oregon and former Assistant Secretary for Energy and Minerals in the U.S. Department of the Interior, died of a heart attack on Monday, July 20, 1987.

Hollis M. Dole

Born in Paonia, Colorado, on September 4, 1914, Hollis moved to Oregon in 1917 and spent his childhood in various parts of the state, including Portland, Independence, and Grants Pass. He earned his B.S. and M.S. degrees in geology from Oregon State University and did additional work on economic geology at the University of California and the University of Utah.

After periods of employment with Bohemia Mines, Cottage Grove; American Trust Company, Palo Alto, California; the U.S. Bureau of Mines at Scappoose; and the U.S. Geological Survey at Tucson, Arizona; and after serving as a Navy lieutenant during World War II, Hollis came to the Oregon Department of Geology and Mineral Industries in 1948 when F.W. Libbey was Director. Upon Mr. Libbey's retirement in 1954, Hollis became head of the Department, serving as Director and State Geologist until March 1969.

During his tenure with the Department, Hollis initiated, among other things, the long-range investigation of the geothermal potential of Oregon. One of his proudest moments was in the summer of 1965, when the Department was the host for the first International Lunar Geological Field Conference, which was held in Bend. The conference was a huge success and put Oregon "on the map" among the geological fraternity for the first time.

In 1968, Hollis resigned his position with the State and was appointed Assistant Secretary for Energy and Minerals in the U.S. Department of the Interior. Following his government service, he

(Continued on page 98, ***Dole)***

Oil and gas news

Leadco, Inc., permits issued

Permits for two new Leadco, Inc., locations (June 1987 *Oregon Geology*) were issued on July 1. The locations, 3 mi northwest of Pittsburg in Columbia County, are scheduled to be drilled this season, according to the operator. Taylor Drilling will be the contractor.

Mist gas storage project update

The storage project at Mist is operated by Oregon Natural Gas Development and has been injecting gas since February 1987. The total gas injected into the Bruer and Flora Pools through May was 2.7 Bcf. The goal by September is a total of 5.5 Bcf, being added at a monthly rate of about 0.7 Bcf per month. Reservoir pressures at the end of the 1987 injection season will be 75 percent of original pressures. At present, all Mist production from other pools is being bought and stored in the Bruer and Flora Pools. □

Carbonate chimneys on the outer continental shelf: Evidence for fluid venting on the Oregon margin

by Nanci A.M. Schroeder[1], *LaVerne D. Kulm*[2], *and Gary E. Muehlberg*[3]

ABSTRACT

Three large, unique chimney structures were dragged from the seafloor by commercial fishermen about 32 km west of Cape Falcon on the outermost continental shelf off northern Oregon. They include one cylindrical and two conical chimneys from 1 to 2 m high that weigh from about 880 to 1,985 kg (400 to 900 lbs). The conical chimneys have a large internal cavity with openings at the top and along the side; the cylindrical chimney has a round, internal plumbing tube in the main chamber. All chimneys are composed chiefly of authigenic dolomite, with minor amounts of clastic particles. Stable carbon-13 and oxygen-18 isotope values of the carbonate range from -16.9 to -21.9 per mil and +7.62 to +7.87 per mil PDB, respectively. The shelf chimneys are similar in appearance and composition to carbonate chimneys discovered at active fluid vents with the *Alvin* submersible on the lower continental slope off central Oregon (Kulm and others, 1986). The sources of carbon for the vent carbonates are the methane and dissolved carbonate-bearing fluids being expelled from the pore waters in the underlying Pleistocene and Pliocene portions of the accretionary prism, whereas the source for the shelf chimneys is believed to be the pore waters of the older Oligocene to Miocene portions of the prism. The heavier carbon and oxygen isotope values of the shelf chimneys, compared to those on the slope (-32.5 and +6.2 per mil, respectively), suggest different sources and histories for the fluids from the two portions of the prism. We propose that the shelf chimneys form above the seafloor because of their shape, open plumbing network, and dominant authigenic carbonate composition. They serve as conduits to the overlying water column through which fluids flow from deep subsurface sources.

INTRODUCTION

During the summer of 1985, while dragging for bottom fish in an area known to Oregon coast fishermen as the "pinnacles", the vessel *Kodiak* entangled its net in seafloor rocks. With tremendous effort, the crew managed to salvage the damaged net and haul in the catch of the day: three very large rocks weighing nearly two tons. These chimneylike rocks were located in a water depth of about 247 m on the outer edge of the continental shelf, approximately 32 km west of Cape Falcon (Figures 1 and 2).

The unique physical characteristics of these rocks prompted the boat owners to notify the Geology Department at Clatsop Community College in Astoria, Oregon. The rocks were initially examined by Nanci Schroeder and Gary Muehlberg, who recognized them as chimney structures. It was obvious to them, however, that the chimneys were *not* the polymetallic sulfide chimneys typically found at hydrothermal vents on the Juan de Fuca Ridge some 500 km offshore (Normark and others, 1986). Because such chimney structures had not yet been reported from continental margins, it was not immediately clear how they came to be located in relatively shallow water so close to shore or how they were related to the geology of the surrounding seafloor. Therefore, a study was begun in the fall of 1985 to determine the nature and origin of the continental shelf chimneys. Interestingly, this study coincided with a similar discovery of chimney structures made on the lower continental slope off central Oregon with the aid of the submersible *Alvin* in August 1984 (Kulm and others, 1986). In this paper, we describe the characteristics of the shelf chimneys and compare them with those found in deeper water to determine their possible origin.

GEOLOGIC SETTING

Underthrusting of the Juan de Fuca Plate and consequent deformation and uplift of the North American Plate during the past 60 million years (m.y.) has developed a structurally and stratigraphically complex continental margin (Kulm and Fowler, 1974; Snavely and others, 1980). As clastic sediments are scraped off of the subducting oceanic plate, they are accreted onto the continental margin, producing an accretionary prism. This prism is comprised of a series of fold/thrust ridges, with intervening basins, striking subparallel to parallel to the Oregon-Washington margin (Figure 3) (Kulm and others, 1973a; Kulm and Fowler, 1974; Barnard, 1978; Snavely and others, 1980). Both seaward-verging (i.e., landward-dipping fault planes) and landward-verging (i.e., seaward-dipping fault planes) sedimentary sequences produce large anticlinal ridges. The most recently deformed ridges (< 2 m.y. old) lie farthest seaward at the toe of the continental slope (Figure 4) (Kulm and others, 1973b; Kulm and Fowler, 1974). Progressing landward, the ridges become successively older and more complexly deformed.

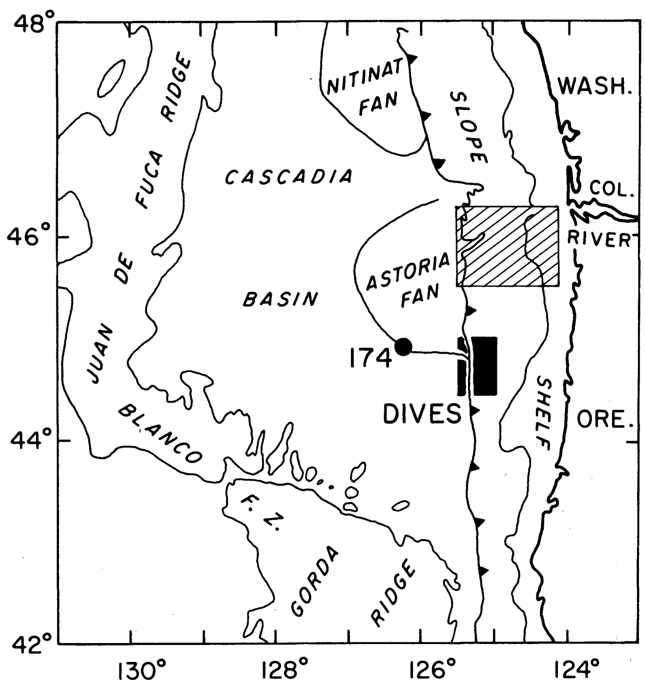

Figure 1. Location map of the Oregon continental margin (shelf and slope), Juan de Fuca Plate (Cascadia Basin), and spreading Juan de Fuca and Gorda Ridges. Subduction zone (saw teeth on upper plate) is located on the continental slope. Location of Deep Sea Drilling Site 174 on the Astoria Fan is shown by solid dot. The Alvin *dive area (labeled "dives") is shown by the black box. Study area is shown as lined box (see also Figure 2).*

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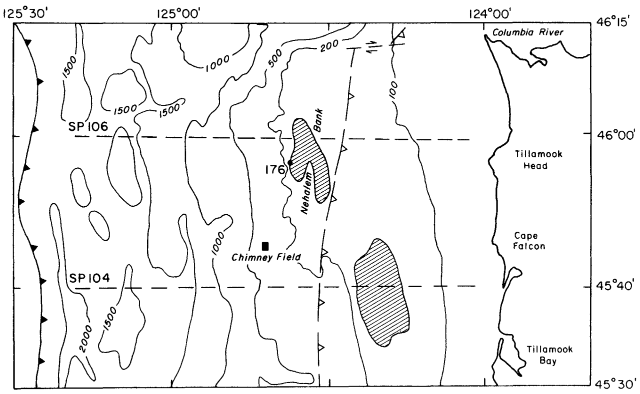

Figure 2. Map of the study area (modified from Peterson and others, 1986; see Figure 1 for location) on the continental shelf and slope off northern Oregon showing the location of the carbonate chimneys (solid square labeled "Chimney Field") on the outer shelf. Note the thrust boundaries between Juan de Fuca Plate and Oregon margin (solid barbs on upper plate) and between the accretionary prism (west) and the Eocene volcanic rocks with overlying younger basinal deposits (east) along the outer shelf (dashed line with open barbs). Lined pattern represents seafloor exposures of Miocene to Pliocene mudstone and siltstone with minor sandstone. Deep Sea Drilling Project (DSDP) drill site 176 is shown as solid dot. Locations of seismic reflection lines Sp-104 and -106 crossing the margin are indicated by dashed lines. Contours in meters. (See also Figure 3 for location of structures.)

Some of the most strikingly folded and faulted areas of the continental margin occur beneath submarine banks forming the outer edge of the continental shelf (Kulm and Fowler, 1974; Snavely and others, 1980). The chimneys described in this paper are located on the "pinnacles," an area that is better known as Nehalem Bank, on the outermost edge of the shelf (Figure 3). An Oligocene to Miocene accretionary prism underlies this portion of the bank and underthrusts the Eocene volcanic rocks to the east (Snavely and others, 1980; Peterson and others, 1986). Miocene to Pleistocene sedimentary deposits overlie the prism and contain unconformities that are late Miocene to late Pliocene in age (Kulm and Fowler, 1974).

RELEVANT OREGON SUBMERSIBLE STUDIES

Fluid venting sites were recently observed from the submersible *Alvin* on the lower continental slope off central Oregon (Kulm and others, 1986). They occur on the crest of a Pleistocene thrust ridge about 110 km to the south of the shelf chimney field at a water depth of 2,036 m (Figure 4). Each vent site is characterized by chemosynthetic-type animals, authigenic carbonate chimneys and slabs, and anomalous concentrations of methane (Figure 5) (Suess and others, 1985; Kulm and others, 1986; Ritger and others, 1987). Methane concentrations, which range from 180 to 420 nl/liter at 1 m above the seafloor at one vent site, are three to six times higher than those found in the ambient waters on the adjacent abyssal plain (Kulm and others, 1986). The methane is derived from the pore waters that migrate through the sediments of the accretionary prism that underlies the vents. The ultimate source of the methane-enriched fluids is the clastic sediment of the Astoria Fan (Figure 1), which has been accreted to the continental slope during the late Pleistocene.

Carbonate slabs (frequently concretions) are found a few centimeters beneath the sediment surface at each vent site, and the edges of the slabs are occasionally exposed on the seafloor (Ritger and others, 1987). Isolated, conical carbonate chimneys rise from 1 to 2 m above these sediment-covered vent sites (see cover figure). One isolated carbonate chimney occurs above a sharp-crested ridge on the second thrust ridge landward of the marginal ridge (Figure 4). All chimneys exhibit numerous cavities, grooves, and flutes, which have smoothly rounded edges giving the chimneys a "sculptured" appearance (Ritger and others, 1987). Each chimney is covered with numerous corals and sponges.

The two slope chimneys that were sampled consist chiefly of magnesian calcite, dolomite, and aragonite, with minor amounts of detrital clays, silt, and sand (Ritger and others, 1987). One sample contained abundant rounded and cemented mudstone pebbles and areas of pure carbonate cement, indicating an authigenic origin; another sample that consisted of finely cemented mudstone pebbles was also considered a typical authigenic carbonate.

The authigenic carbonates are being produced at each vent site from the methane-enriched pore waters that were being expelled from the underlying accretionary prism (Ritger and others, 1987). Stable isotope data indicated that the carbon in the carbonates came from a reservoir that was extremely depleted in carbon-13. Values of $\delta^{13}C$ of all carbonate samples collected on the margin range from -34.9 to -66.7 per mil PDB, which indicates a methane-derived carbon source (Ritger and others, 1987). The two slope chimneys that were analyzed have $\delta^{13}C$ values of -32.5 and -32.6 per mil and $\delta^{18}O$ values of +5.4 to +6.2 per mil. These more positive values indicate that the carbonates are marine, but they are also related to factors other than just the temperature of formation (Ritger and others, 1987), such as the history of the composition of the fluids (Suess and Whiticar, 1986).

CONTINENTAL SHELF CHIMNEYS

Physical description

The chimneys on the outer shelf range in height from 1 to 2 m (Table 1; Figures 5 and 6). The conical chimneys (Figure 5, chimneys 1 and 3) appear to be very similar in shape and size to those found on the lower slope; however, the cylindrical chimney (Figure 6, chimney 2) has, as yet, no counterpart in deep water. In general, each chimney has a hollow center, or vertical cavity, along with at least one large cavity in the side wall. Numerous smaller tubes penetrate the walls as well. Wall thickness varies greatly, from 3 to 30 cm; the walls are frequently cracked or broken. Surfaces are pitted and grooved, apparently from dissolution by seawater or by the habitation of benthic marine life. Chimneys 1 and 2 are similar in surface texture, coloration, and abundant biota. Chimney 2 is unique in that its cylindrical shape contains more small tubes and cavities than the conical ones. Situated within the hollow of the chimney is a secondary tube that runs parallel to the main cavity. This tube extends the length of the chimney, except where it is disrupted about one-third of the way up from the bottom. An opening in the outer wall reveals the inner tube, which appears to have collapsed against a blockage that fills the hollow. Chimney 3

Table 1. *Physical characteristics of the carbonate chimneys recovered from the outer continental shelf of northern Oregon. Dimensions given in metric system (meters and centimeters) and weight in English system (pounds).*

Characteristic	Chimney #1	Chimney #2	Chimney #3
Shape	conical	cylindrical	conical
Weight estimate	900 lb	400 lb	500 lb
Height	1.0 m	1.7 m	90 cm
Top diameter	40 cm	30 cm	30-50 cm
Base diameter	75 cm	30 cm	40-60 cm
Wall thickness	10-30 cm	3-15 cm	30-16 cm
Vertical vent hole diameter			
top	10 cm	13 cm	10 cm
base	30 cm	13 cm	18 cm
Color*	mostly lt gr N-7	same	same
	Br Gy 5YR 5/1**	same	same
Biological artifacts	abundant	abundant	common

* Geological Society of America color chart
** In vent holes

has a softer carbonate substance that can be easily scratched with a pocket knife. Dissolution features and surface discolorations are not as prominent as chimneys 1 and 2.

Still attached to the chimneys are the skeletons of encrusting corals and sponges. Calcareous and parchment-type worm tubes are abundant. Other noticeable biota include brachiopod shells and a few bryozoan colonies. Unidentified fossils and the tracks from burrowing organisms cover the chimneys.

Mineralogy and isotopic composition

Major-element chemistry (Table 2) and X-ray diffraction analyses show that the continental shelf chimneys consist chiefly of dolomite (69-89 percent carbonate), SiO_2 (14-22 percent), and Al_2O_3 (4-6 percent). All three chimneys are quite similar in chemical composition. Scattered quartz and feldspar grains as well as the tests of foraminifera occur within the carbonate matrix. Throughout the sampling process, there was no evidence of any embedded or cemented pebbles as found in the lower slope chimneys.

Table 2. *Major-element chemistry of three carbonate chimneys shown in Figures 5 and 6. Values are in weight percent.*

Component	Chimney #1	Chimney #2 (a)**	Chimney #2 (b)	Chimney #2 (c)	Chimney #3
$CaCO_3$ *	42.75	41.0	40.2	40.0	38.5
$MgCO_3$	34.16	31.0	27.5	30.0	26.7
$FeCO_3$	2.32	2.41	2.8	3.0	3.44
Σ Carbonate	79.2	74.4	70.5	73.8	68.7
SiO_2	14.2	15.9	17.9	18.4	22.8
Al_2O_3	3.93	4.22	4.77	5.0	6.49
Total Components	97.3	94.5	93.2	97.2	98.0

* calculated from acid soluble Ca, Mg, and Fe content

**samples 2(a) near bottom of outer chimney wall, 2(b) near top of outer chimney wall, and 2(c) upper portion of inner tube

The stable isotopic composition of the three shelf chimneys is quite similar (Table 3). The negative $\delta^{13}C$ values (-16.9 to -21.9 per mil) indicate that the carbon in these carbonates is moderately depleted in carbon-13. On the other hand, the large positive $\delta^{18}O$ values (+7.62 to +7.87 per mil) are heavier than those found in other authigenic carbonates on the Oregon margin (Ritger and others, 1987).

Table 3. *Stable carbon and oxygen isotopic values (per mil relative to PDB) of the carbonate chimneys described in Table 2.*

Chimney sample	$\delta^{13}C$	$\delta^{18}O$
#1	-21.9	+7.87
#2	-16.9	+7.28
#3	-20.5	+7.62

DISCUSSION

Comparison of structural-tectonic settings at venting sites

The lower continental slope carbonate chimneys are situated directly over the Pleistocene (vent sites 1426 and 1428) and Pliocene (chimney site 1423) portions of the accretionary prism. The prism is comprised of partly consolidated sands and muds derived from the adjacent Astoria Fan, whose deposits contain biogenic methane (McIver, 1973). In contrast, the chimney field on the outer shelf appears to be situated atop exposed, dipping sedimentary layers or diapiric structures that may be connected to the Miocene-Oligocene

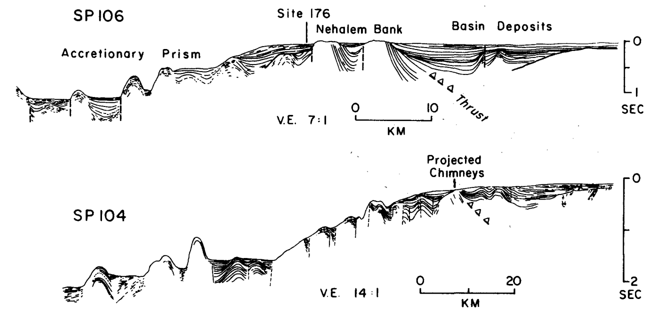

Figure 3. Line-drawing interpretations of Oregon State University single channel seismic reflection lines Sp-104 and -106 showing shelf basin deposits and accretionary prism. Dashed lines with open barbs show thrust boundary between the two features. See Figure 2 for location. Drill site 176 and the Nehalem Bank are indicated on Sp-106. Note projected location of carbonate chimneys over accretionary prism on Sp-104.

accretionary prism below (Figure 3). Pliocene fissile shale drilled on the outer edge of the shelf (Figure 2, DSDP site 176) shows that deep structures have been uplifted at least 500 m from a depositional site lower on the continental slope (Kulm and others, 1973b). Shallow-water megafossils and an angular unconformity between the upper Pleistocene clayey silts and the Pliocene shale indicate that the outer shelf has been truncated by a lower sea level and that it has most recently subsided more than 100 m with the subsequent deposition of Pleistocene shelf sediments. While the structural-tectonic setting of the outer shelf is more complicated than that of the lower slope, similar carbonate chimneys are forming in each area, indicating that the expelled fluids are derived from sediments of both the youngest and oldest portions of the accretionary prism off Oregon. In all areas, the chimneys apparently serve as conduits through which pore fluids from the prism are expelled onto the seafloor.

Chimney characteristics and internal plumbing

The carbonate chimneys found on the continental shelf and lower slope are similar in physical appearance and size, with the exception of the cylindrical chimney, which is unique among the venting structures discovered on the margin. The shelf chimneys exhibit an internal plumbing system consisting of small tubes and large cavities, whereas only small exterior holes could be observed from *Alvin* in the slope chimneys. This plumbing network permits the methane-enriched fluids, which are derived from permeable sand zones or fault zones within the underlying strata, to flow through the chimneys and precipitate the authigenic carbonate that forms the chimney. The flow probably emanates from holes in the top and side walls of the chimney, and precipitation occurs over the nearby external portions of the structure. The distribution of tubes within the cylindrical chimney suggests that precipitation patterns may periodically reroute the plumbing system, producing several tubes with external openings. It is clear from the cylindrical chimney that this precipitation can create extremely uniform tubes that themselves may become constricted as precipitation progresses (Figure 6, bottom left). The hollow cavity in the conical chimneys is larger at the base and smaller at the top, which suggests that the nature of the fluid flow and/or the precipitation pattern may control the dimensions of the hollow and the eventual shape of the chimney. While we, as yet, have no information on how the chimney is constructed by the precipitating fluids, it would appear that, as the flow slacks, the hole at the top may become smaller, and one would expect the internal cavity to become smaller as the fluids precipitate carbonate minerals. We speculate that there may be a relation between the nature of the internal plumbing system and the rate of flow of fluid through the structure. Given the same volume of available fluid, the conical chimneys

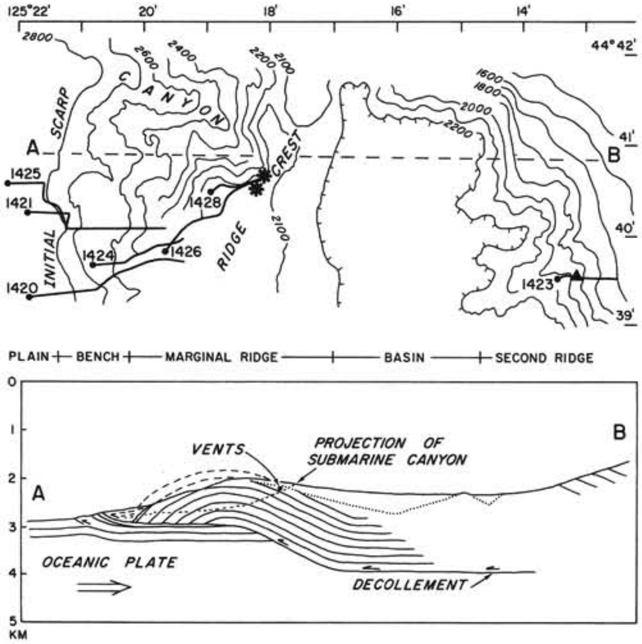

Figure 4. (Top diagram) Alvin *submersible transects and SeaBeam bathymetry map across the lower continental slope (see Figure 1, dive area). Contours in meters; numbered dives commence at the solid dots. Asterisks indicate fluid-venting sites and carbonate chimneys (i.e., northern site 1428 and southern site 1426 on marginal ridge); triangle indicates carbonate chimneys at site 1423 on the second ridge. (Bottom diagram) Interpretive structural depth section of the deformation front along profile A-B (dashed line across contour map at top). (From Kulm and others, 1986, their Figure 2)*

may indicate a slow rate of flow whereas the cylindrical one, with its small internal tubes, suggests a faster rate of flow through the chimney.

Nature and sources of fluids

The sources of the precipitating fluids at the venting sites are the pore waters that were trapped within the clastic sediments of the accretionary prism. According to Ritger and others (1987), the methane in these fluids must be oxidized before the carbon is incorporated into the authigenic carbonate minerals that comprise the chimneys. Because of the presence of authigenic pyrite, which forms under anoxic sulfate reducing conditions within both the shelf and slope carbonates, the methane must be oxidized near the base of the sulfate reducing zone (usually a few meters or tens of meters subsurface) within the sediments beneath the chimneys. This oxidation probably occurs by a microbially mediated reaction related to sulfate reduction as given in equation 1:

$CH_4+SO_4^{-2} \rightarrow HS^- + HCO_3^- + H_2O$ (equation 1).

If sulfate is available within the deeper strata of the accretionary prism, it may also facilitate the methane oxidation during the upward migration of the fluids to the vent sites. The two possible sources of methane, biogenic and thermogenic, may be mixing at various levels in the prism during the migration process, producing the heavier $\delta^{13}C$ values (-16.9 to -21.9 per mil) determined for the shelf carbonates relative to the slope carbonates (i.e., biogenic methane has $\delta^{13}C$ values between -75 to -90 per mil [Claypool and others, 1973] and thermogenic -30 to -50 per mil [Vinogradov and Galimov, 1970]).

The mineralogy of all the chimneys is similar and consists essentially of dolomite and magnesian calcite. Minor terrigenous grains of quartz and feldspar are scattered through the carbonate matrix. This detrital material may be derived from the surrounding unconsolidated clastic sediments (Kulm and others, 1975) and plastered onto the chimneys by high-velocity unidirectional currents (up to

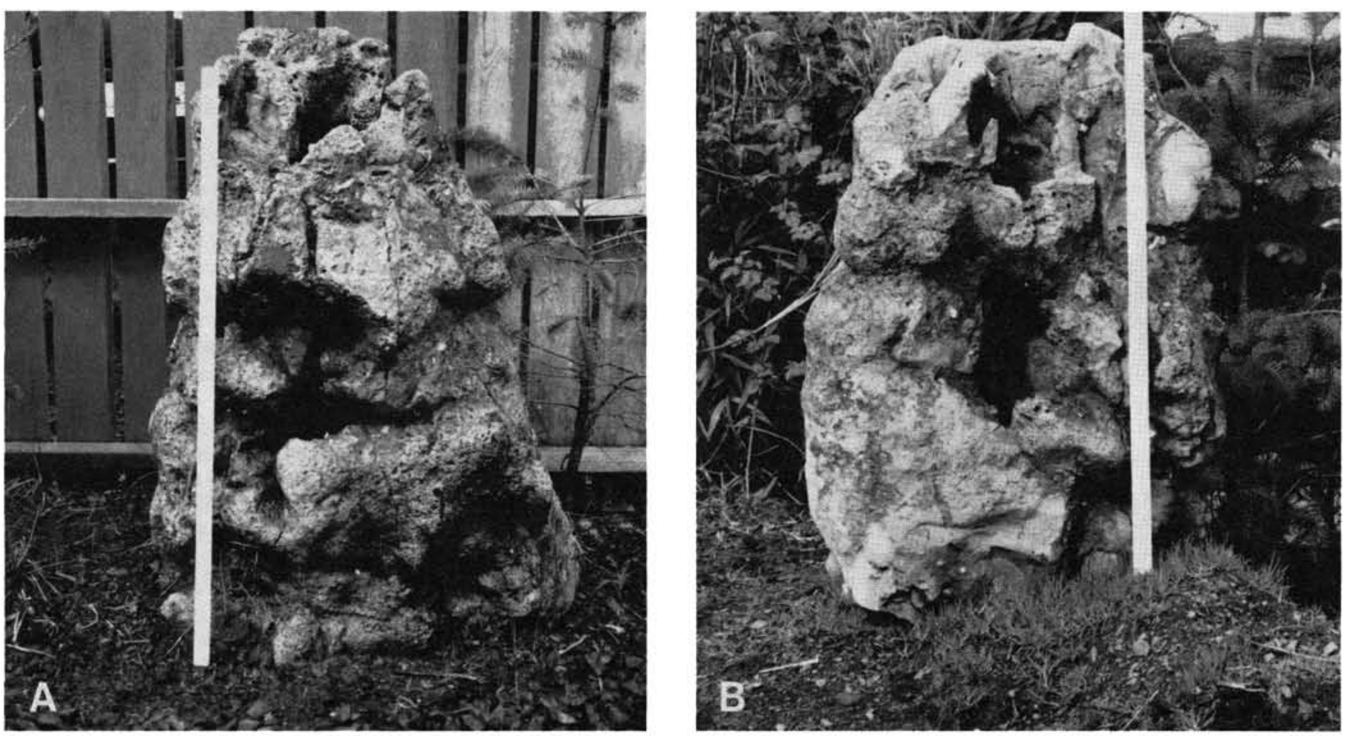

Figure 5. Conical carbonate chimneys (A=chimney 1; B=chimney 3) dragged from the outer continental shelf off northern Oregon. See Figure 2 for location designated "Chimney Field." Note conelike shape and large internal cavities viewed through openings in the side walls and top. See Table 1 and text for detailed description of chimneys. Scale is 1-m ruler.

40 cm/sec) sweeping the shelf (Smith and Hopkins, 1972) as the carbonate is precipitated in situ on the exterior of the chimney. Furthermore, the settling of sediment particles from the overlying water column off the Columbia River during the growth of the chimneys would impart a terrigenous component to their carbonate matrix.

One lower slope chimney contains mudstone pebbles that were not observed in the shelf chimneys, but Ritger and others (1987) believe that these pebbles are included in the cemented layers that form the basal part of chimney and that the upper portion may contain nearly pure carbonate.

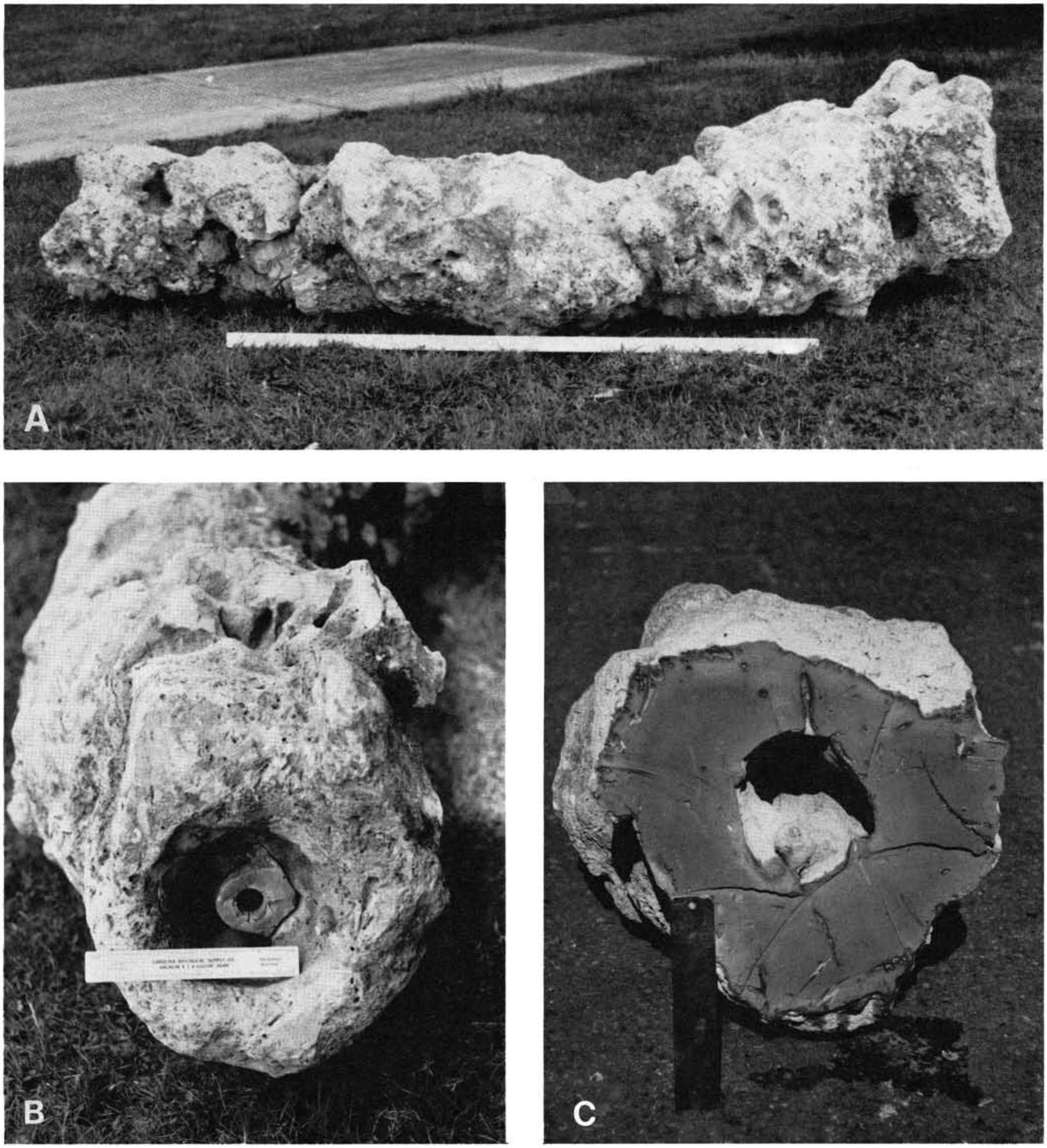

Figure 6. (A) Cylindrical carbonate chimney 2 (lying on its side), which was dragged from same location as conical chimneys (see Figure 2). It is not known which end is the top and which end is the bottom of the chimney, but for sampling purposes the top and bottom were arbitrarily chosen. (B) End view of cylindrical chimney; note internal cavity with its well-rounded, open plumbing tube that runs parallel to the main chamber. Scale is 6-inch ruler. (C) Cross-sectional cut of the smaller of the two ends of cylindrical chimney; burrowing animals produce grooves in dense carbonate lithology. See Table 1 and text for detailed description of chimney. Scale is 6-inch ruler.

Origin of shelf chimneys

Two logical hypotheses that have been proposed for the origin of the lower slope chimneys can also be applied to the shelf chimneys: (1) upward growth of the chimney above the seafloor, and (2) chimney formation below the seafloor within the sediment column with later exhumation by uplift and erosion (Ritger and others, 1987). The shelf chimneys consist largely of authigenic dolomite (69 to 89 percent) with patches of pure dolomite, suggesting a relatively minor terrigenous involvement in their origin. The terrigenous components could be added by sediment resuspension processes as noted previously or through the diagenetic replacement of terrigenous sediments by carbonate, producing chimneylike structures surrounded completely by terrigenous sediments. In the latter case, the terrigenous grains and foraminifera would be residual components of the replacement diagenetic process; the Pliocene to Pleistocene sedimentary deposits that are presently exposed on the shelf near the chimney field could be the host strata (Kulm and Fowler, 1974). If the shelf chimneys are formed by diagenetic replacement processes below the seafloor, it is difficult to reconcile the large cavities and small open tubes that characterize these structures. The tubes suggest that there is a uniform flow through the structures; this could not occur if the structure were encased within a sedimentary mass. In addition, the openings in the side walls of the chimneys appear to be primary features that developed as a result of uneven precipitation over the chimney. Alternatively, the openings could represent dissolution features, which were produced after the chimney was exhumed. But the continental shelf lies above the calcite compensation depth, so dissolution should not be that important in the alteration of the chimneys.

Considering all of the above factors, we believe that the shelf chimneys were formed above the seafloor and that they represent relatively recent venting of methane and dissolved carbonate-bearing fluids from the underlying Oligocene to Miocene accretionary prism. Carbon-14 dating of the carbonate carbon in a lower slope concretion at vent site 1428 reveals an age >40,000 years, but the calculated age based upon the sedimentation rates for the terrigenous sediments overlying it gives a much younger age of 2,500 years. The addition of old methane carbon from the deeply buried sources within the prism precludes the accurate dating of the carbonate chimneys. However, the shelf chimneys most likely formed sometime after the last erosional truncation event on the outer shelf, which was produced by one of the Pleistocene low sea level stands on the shelf.

CONCLUSIONS

1. One cylindrical and two conical carbonate chimneys were recovered from a water depth of 247 m on the outermost continental shelf off northern Oregon. They have an internal plumbing network consisting of cavities and/or small tubes with openings at the top and sides. They are quite similar in physical appearance to carbonate chimneys observed from a submersible at active fluid-venting sites on the lower continental slope and have given us first-hand evidence that fluids can be flushed through their plumbing system.

2. The chimneys consist largely of dolomite (69 to 89 percent), with minor amounts of terrigenous particles and foraminifera. Their $\delta^{13}C$ isotopic composition is noticeably heavier (-16.9 to -21.9 per mil) than other carbonate chimneys (-32.5 per mil) and concretions (-38.3 per mil) found at the venting sites on the lower slope. This indicates that the fluid sources of methane are different for shelf carbonates from those reported at the slope vent sites.

3. We propose that the shelf chimneys were constructed on and above the seafloor through dolomite precipitation from methane and dissolved carbonate-rich fluids that emanate from the chimneys. This hypothesis is supported by the open plumbing network, conical-cylindrical shapes, high mineral carbonate content, and stable carbon isotopic composition of the chimneys. The source zones of the fluids appear to be the Oligocene to Miocene accretionary prism strata beneath the chimneys. Updip migration along permeable horizons within the deeply buried accreted strata is the most likely source zone of fluids.

4. Fluid venting apparently occurs across the entire accretionary prism off central and northern Oregon from the late Pleistocene- to Oligocene-age strata. The carbonate chimneys provide a valuable geochemical record of this fluid expulsion.

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*(Continued on page 98, **Chimneys**)*

Summary of symposium on Oregon's earthquake potential held February 28, 1987, at Western Oregon State College in Monmouth

by Robert S. Yeats, Department of Geology, Oregon State University, Corvallis, Oregon 97331

The problem with studying earthquakes in Oregon is that there are so few of them. A map recently released by the Oregon Department of Geology and Mineral Industries (DOGAMI), prepared by Randall Jacobson of Oregon State University (OSU), shows a few earthquakes, including an event of magnitude 5.5 near Portland, but the amount of seismicity in Oregon is low as compared to adjacent states. The instrumental seismicity of western Washington is moderately high, but in adjacent parts of northwestern Oregon, the seismicity is much lower. Finally, no obvious major active faults have been mapped onshore west of the Cascades.

But most participants in a February 28 symposium at the annual meeting of the Oregon Academy of Science at Monmouth indicated that the lack of earthquakes in Oregon is misleading. Preliminary evidence reported at the symposium suggests that western Oregon may have been visited by large earthquakes in the recent past.

Thomas Heaton of the U.S. Geological Survey (USGS) office at Pasadena pointed out the similarity of the Cascadia subduction zone off Oregon and Washington to the subduction zone off southern Chile. Like Oregon, the southern Chile plate boundary is marked by a sediment-filled trench with little topographic expression, low hills near the coast, a central valley like the Willamette, and volcanoes farther east. Until 1960, the plate boundary had another similarity—low seismicity, but the Chilean plate boundary ruptured in 1960, resulting in an earthquake with a magnitude of 9.5, the largest of the twentieth century. The subducting oceanic crust off Chile and Oregon is so young that it is still warm from being recently generated at an oceanic spreading center. Being warm makes the crust buoyant and hard to subduct, and thus it is expected to be strongly coupled to the overriding continental plate. When the bond between the two plates breaks, great earthquakes occur, at least in Chile, and possibly in Oregon as well. Heaton found similar correlations between young subducted crust and earthquakes off Colombia, Mexico, and southwest Japan. In contrast, old and cold oceanic crust is being subducted in the Marianas trench in the western Pacific. Because it is cold, the crust is heavy and sinks readily, and it is not well coupled to the overriding plate. Earthquakes occur there, but they are much smaller than those where subducting crust is very young, and much of the interplate slip is not accompanied by earthquakes. Since the Monmouth meeting, Heaton's findings have been published in *Science* (Heaton and Hartzell, 1987).

Until recently, aseismic slip was also thought to characterize the Cascadia subduction zone, and John Adams, now of the Geological Survey of Canada, found apparent support for this when he reported in 1982 that historic eastward tilt based on releveling of Coast Range highway survey monuments occurred at about the same rate as eastward tilt of Pleistocene terraces in the Coos Bay area. Adams pointed out that the Pleistocene terraces reach a zero isobase (no uplift or subsidence) not far east of the coastline, whereas the geodetic tilt reaches a zero isobase in Puget Sound and the Willamette Valley. For this reason, the comparison cannot be used as evidence for or against aseismic slip.

Robert Crosson of the University of Washington described a cross section of seismicity in the Puget Sound region that showed a gap between shallow earthquakes in the North American Plate and deep earthquakes in the underlying Juan de Fuca Plate. Crosson came to the remarkable conclusion that the plate boundary itself lies in the seismic gap and is not marked by earthquakes. Does this mean that the plate boundary is coupled, releasing only in great earthquakes? Why, then, is there so much seismicity within both plates and nearly none at the plate boundary?

There have been no great earthquakes in the recorded history of Oregon, but it should be noted that the record covers only about 175 years. Parke Snavely of the USGS at Menlo Park reported that the Indians of the Cape Flattery region of the Olympic Peninsula spoke of a great wave that occurred far back in their history and that most likely represented a tsunami from a large earthquake. Snavely also suggested that the two major mudflows that buried Indian longhouses at the Ozette site on Cape Alava may have been generated by earthquakes. Radiocarbon dating of cultural organic material, reported from this site by R.D. Daugherty and his graduate students at Washington State University, indicates that the oldest mudflow is about 800 years old and the youngest about 350 years old.

Brian Atwater of the Seattle office of the USGS has found evidence of prehistoric earthquakes expressed as coseismic subsidence or uplift.

Scientists have observed elsewhere in the world that prior to a great earthquake, the overriding plate near the trench is dragged down elastically toward the trench, but farther away from the trench, the overriding plate bulges upward elastically. During the earthquake, the plate boundary snaps, collapsing the bulge, and causing instantaneous uplift close to the trench. During the great Alaska earthquake of 1964, for example, much of the Kenai Peninsula and Kodiak Island dropped suddenly, drowning coastal villages, whereas offshore islands closer to the trench were uplifted suddenly, exposing the sea floor. Drowned marshes on the Kenai Peninsula are now overlain abruptly by barren sands and muds of the supratidal zone.

In early 1986, Atwater began in the state of Washington to compare historic evidence of differential uplift or subsidence with Holocene, prehistoric evidence. At Neah Bay, on the Olympic coast of Washington, he found a buried marsh surface very similar to those on the Kenai Peninsula. Later, at Willapa Bay, he found six cycles, with a characteristic succession consisting of an organic layer overlain abruptly by barren sand and mud, which grades upward into organic sediments containing rhizomes of marsh grass.

Atwater compared this cyclic succession with marsh sequences of stable coastlines and became convinced that a nonseismic origin such as megastorms or closing of a baymouth bar did not explain the abrupt upward change from organic marsh deposits to barren supratidal muds. His conclusion, later published in *Science* (Atwater, 1987), was that this abrupt change was due to sudden submergence during a great earthquake.

Curt Peterson of OSU and Mark Darienzo of the University of Oregon recorded the same abrupt change upward from marsh deposits to barren sandy muds in cores from Netarts Bay southwest of Tillamook in Oregon. At least five cycles of marsh development and burial were observed in the Netarts Bay marsh cores, and two subsidence events have occurred there in the past 1,500 years. It is not yet known whether the subsidence events recorded in the Netarts Bay marsh reflect instantaneous (coseismic) submergence or longer term episodes of submergence superimposed on a static or uplifting coast.

Unfortunately, the plate boundary megathrust is at the base of the continental slope and hard to measure directly. Snavely, however, showed seismic records with evidence of episodic Holocene thrusting and folding in the upper plate in many places on the continental slope and shelf. Furthermore, the plate boundary appears to come ashore south of Crescent City, California, where it has been studied by Gary Carver and his associates at Humboldt State University. Carver reported evidence of active Holocene thrusting and folding that accounts for much of the convergence rate between the Gorda and North American Plates. Trench excavations reveal displacements up to 4.5 meters (m) in individual faulting events, evidence that movement was jerky and coseismic rather than gradual and aseismic.

Evidence for faulting within the overriding plate was reported both onshore and offshore by Snavely, and he cautioned that warped marine terraces and a 1,700-year-old drowned forest at Neskowin may be due to local tectonics rather than deformation affecting the entire upper plate. Robert Yeats of OSU, building on earlier work of Marvin Beeson and his students at Portland State University, pointed out that linear ridges within the Willamette lowland, including the Portland Hills, Eola Hills, and Salem Hills, may mark active faults. Wendy Grant and Craig Weaver of the USGS Seattle office documented a linear zone of seismicity that extends under Mount St. Helens in which focal-mechanism solutions suggested right-lateral strike-slip faulting. Curiously, this shallow seismic fault has not been found at the surface.

The USGS has responded to the evidence for large earthquakes in the Puget Sound and Portland metropolitan areas. Albert Rogers of the USGS Denver office announced a new five-year program that would involve scientists from USGS, DOGAMI, and other institutions. For example, Alan Nelson of the USGS Denver office will be investigating the marshes between Coos Bay and Astoria for possible evidence for prehistoric earthquakes, and Steve Personius, also of the USGS Denver office, will study the long-term history of several Coast Range rivers to determine deformation styles and rates. The program will also evaluate seismic shaking potential for major urban areas of western Oregon and Washington.

In informal sessions preceding the symposium, participants observed that the low instrumental seismicity of western Oregon may be due in part to the small number of seismograph stations compared to adjacent states. A seismic network proposed for the Willamette Valley by Eugene Humphreys and Mark Richards of the University of Oregon probably would locate many earthquakes that now go unrecorded. In addition, such a network, when combined with existing stations in southern Washington, would allow the study of the crust and the plate boundary by the new technique of seismic tomography in which the crust and mantle are imaged by the distortion of seismic waves that pass through them.

Geodetic study of crustal deformation may provide one of the most critical clues to predicting a megathrust earthquake, according to Herb Dragert of the Pacific Geosciences Centre, Sidney, B.C. Recently completed geodetic measurements across Juan de Fuca Strait indicate that (1) horizontal shear strain is currently accumulating at a rate of about 0.2 ppm each year in coastal areas of northwest Washington and southwest British Columbia, and (2) Global Positioning Satellite (GPS) surveys can now be utilized to determine shear strain by resurveying older (pre-1950) triangulation control points. John Adams used highway releveling data from the Coast Range of Oregon and Washington for evidence of tectonic tilt, but he pointed out that many of these roads have not been releveled since the 1940's. A trilateration network measuring horizontal distortion does not exist in western Oregon.

The conveners, Robert S. Yeats of OSU and Donald A. Hull of DOGAMI, expressed hope that the conference would lead to an increase in neotectonic studies in western Oregon. The sites of active deformation reported by Parke Snavely onshore and offshore need to be examined in detail, looking for rates of deformation and individual deformation events. Perhaps in a few years, scientists can answer the question that was the title of the symposium: Could there be a devastating earthquake in Oregon?

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***(Dole,** continued from page 90)*

was placed in charge of the Colony Development oil shale program in Colorado. During the last ten years of his life, Hollis maintained a busy schedule as private consultant to several national and international organizations in the fields of energy and minerals.

Hollis is survived by his wife, Ruth, and two sons, Michael Hollis and Stephen Eric. We, his friends, will miss him.

—Andy Corcoran, former State Geologist

***(Chimneys,** continued from page 96)*

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