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Eocene deep-sea communities in localized limestones formed by subduction-related methane seeps, southwestern Washington

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ABSTRACT

Densely populated communities of soft-bottom–dwelling taxa similar to those found today along subduction zones off the coasts of Japan and Oregon have been discovered in very localized deep-water limestones of late middle to late Eocene age along the southwestern margin of Washington. Subduction was prevalent in this area during this time, and compressive forces squeezed subsurface methane-rich waters onto the ocean floor, where opportunistic bivalves (especially *Modiolus*, *Calyptogena*, and *Thyasira*), vestimentiferan? tube worms, serpulid tube worms, siliceous sponges, very small limpets, trochid and turbinid archaeogastropods, and other macrobenthos colonized. These assemblages are the earliest recorded biologic communities formed in response to methane seeps in subduction zones.

INTRODUCTION

The western margin of Washington has been the site of active subduction since early Eocene time (Armentrout, 1987). Rocks of late middle to late Eocene age in southwestern Washington represent deposits in a fore-arc basin and are mostly deep-marine tuffaceous siltstone or muddy siltstone virtually barren of macrofossils (Rau, 1986; Wells, 1989). The presence of three localized limestone deposits enclosed within these siltstones and containing high numbers of articulated specimens of soft-bottom–dwelling bivalves is, therefore, very unusual. Previous workers (Glover, 1936; Hodge, 1938; Danner, 1966) briefly described the geology and chemical makeup of the limestones, but they did not do any detailed paleontological investigations.

We have discovered that each limestone has its own distinct community of organisms. Modiolid bivalves are always present with either vesicomyid bivalves or thyasirid bivalves. Worm tubes, siliceous sponges, very small limpets, and trochid and turbinid archaeogastropods may also be present. Hickman (1984) recognized six Cenozoic deep-water mollusk communities of the marginal northeastern Pacific, but these three limestone communities are different in terms of taxonomic composition, much greater abundance of specimens, and association with limestone.

Here we describe the taxonomic composition of the limestones and discuss their environment of deposition in conjunction with recent discoveries of modern biologic communities along subduction zones in the Pacific Ocean.

The limestones are referred to as the Humptulips, Bear River, and Menlo deposits (Fig. 1). The abbreviation LACMIP (used for catalogue and locality numbers) stands for the Natural History Museum of Los Angeles County, Invertebrate Paleontology section.

LITHOLOGY, FOSSIL CONTENT, AND AGE OF THE LIMESTONES

Shared Characteristics

All three limestone deposits are now covered with slope wash and dense vegetation. Each limestone is enclosed within deep-water siltstone, and contacts with these surrounding strata are covered.

The limestone consists of lime mud surrounding unabraded macrofossils. A checklist of macrofossils and their abundance in each deposit is given in Table 1. New species are being described and named by us in a separate paper. All of the bivalves in each deposit are articulated and randomly oriented in all planes. The limestones emit a strong petroliferous odor when broken, and their chemical compositions (Danner, 1966) are very similar.

Humptulips Deposit

The Humptulips deposit is enclosed within siltstone of the Humptulips Formation, which has been assigned to the foraminiferal Narizian Stage of late middle to late Eocene age (Rau, 1986). The deposit is cut by an abandoned meander on the East Fork of the Humptulips River in the northwest part of sec. 4, T. 20 N., R. 9 W., Quinault Lake 15-minute quadrangle, Grays Harbor County. The locality is equivalent to locality LACMIP 12385. Danner (1966) reported the deposit to be 15 m thick, 30 m long, and 15 m wide.

Bulk collecting of about 20 kg revealed a growth series of the bivalve *Thyasira* (Fig. 2a) with individuals up to 6 cm in height. Specimens are usually in clusters of about five or six. There are two types of very small, high-profiled limpets. A patelliform type (Figs. 2b, 2c) has an imperforate apex, and a fissurellid? type (Figs. 2d, 2e) seems to have a perforated apex. Specimens of the turbinid archaeogastropod *Homalopoma*? sp. A (Fig. 2f) show a growth series. Specimens of a naticid gastropod (Fig. 2g) are minute. The scaphopod specimen, *Dentalium* sp. (Fig. 2h), is broken but unabraded.

Serpulid worm tubes are present in the limestone as either solitary specimens (Fig. 2i) or as colonies of white-shelled calcareous circular tubes (Fig. 2j) up to 1.5 mm in diameter.

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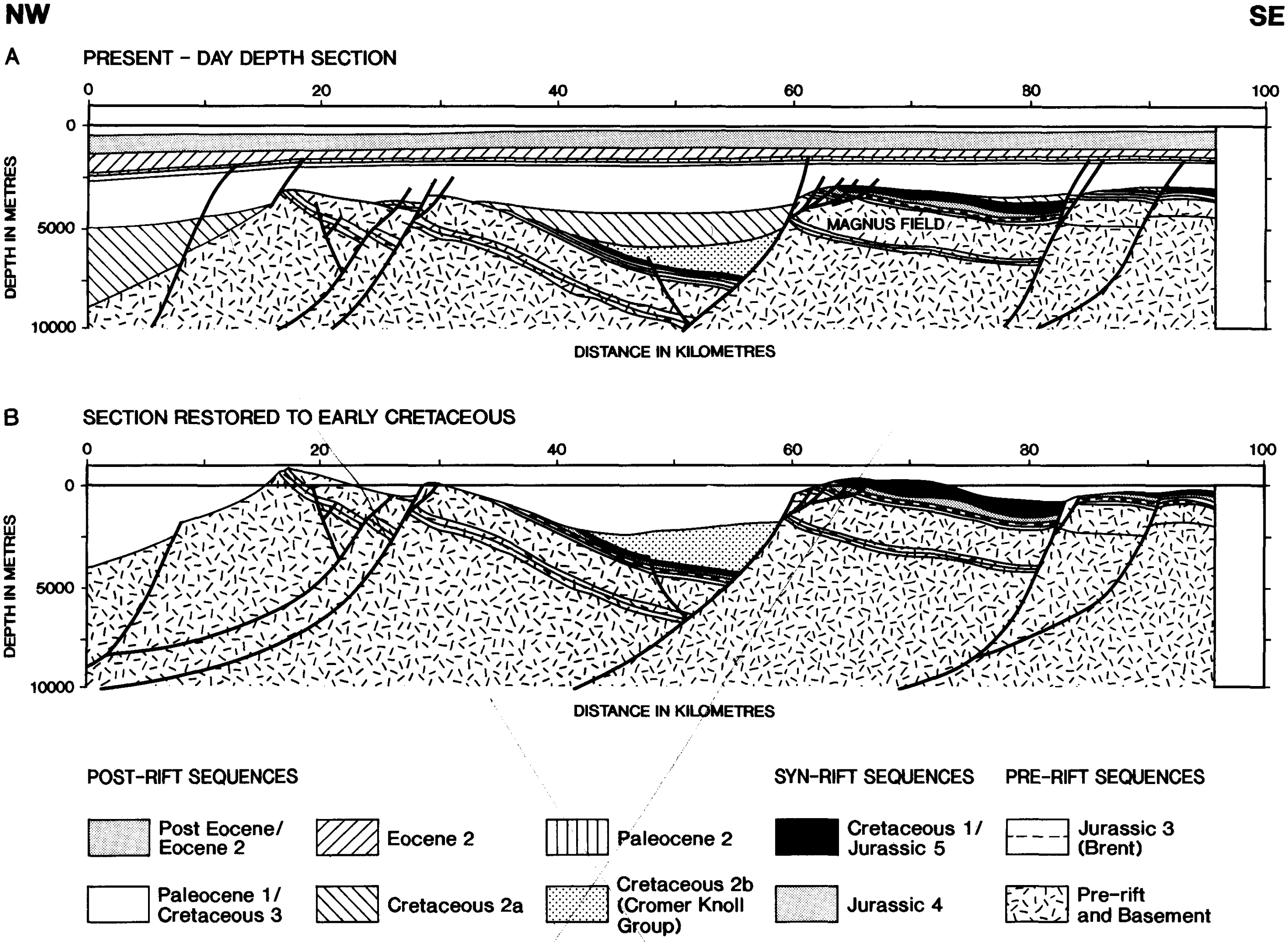

Figure 3. A: Present-day depth section across Shetland Trough. Magnus oilfield is indicated at crest of rotated fault block. B: Section as above, restored to Early Cretaceous time when sediments now forming Cromer Knoll Group were being deposited. Note subaerial exposure of Magnus Sandstone Member.

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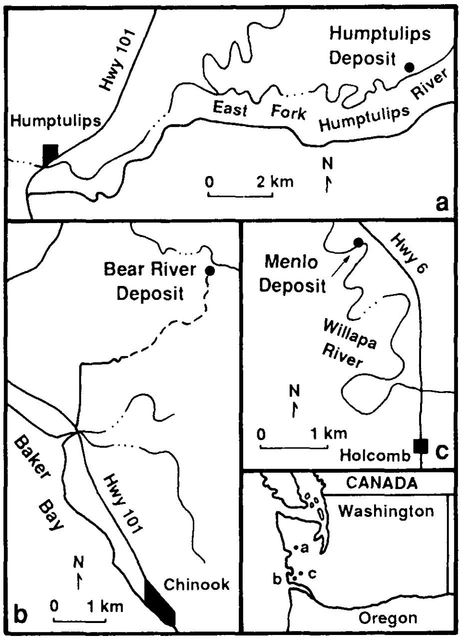

Figure 1. Location maps for three localized limestone deposits of Eocene age containing chemosynthetic communities related to subduction-related methane seeps, western Washington. a: Humptulips deposit. b: Bear River deposit. c: Menlo deposit.

Another type of tube (Figs. 2k, 2l), also in clusters, is circular, up to 5 mm in diameter, and 6 cm long and has an outer surface coincident with a black organic deposit. These tubes are most likely vestimentiferan worm tubes, and the black deposits are where the chitinous tube walls used to be. Some of the specimens are vertically oriented (Fig. 2l).

Bear River Deposit

The Bear River deposit is enclosed within deep-water siltstones mapped as being the siltstone of Cliff Point (Wells, 1989). The deposit is in an abandoned quarry on the south side of Bear River in SE¼SE¼ sec. 20, T. 10 N., R. 10 W., Chinook 7.5-minute quadrangle, Pacific County. The locality is equivalent to locality LACMIP 5802. In 1954, during the last active quarrying of the limestone, it was reported to be 15 m thick, 68 m in length, and 38 m wide (Danner, 1966).

Rock samples and fossils used in this study were collected in bulk (about 50 kg) from boulders on the quarry floor. The mytilid bivalve *Modiolus* forms dense concentrations (Figs. 2m, 2n) of juvenile to adult specimens. The vesicomyid bivalve *Calyptogena* (Figs. 2o, 2p) is less abundant and forms less dense concentrations of late juvenile to adult specimens as much as 10 cm long. Specimens of the small trochid archaeogastropod *Margarites* (*Pupillaria*) (Fig. 2q) show a growth series. The specimen of *Homalopoma*? sp. B (Fig. 2r) is broken but unabraded. Although only three specimens of the solemyid bivalve *Acharax* were found, they are uncommonly large. The largest specimen (Fig. 2s) is 13 cm long, including a 1-cm-long imprint of the fragile horny periostracum that extends beyond the anterior margin of the shell. Specimens of a pitarid bivalve show a growth series; some individuals are as much as 9 cm long (Fig. 2t). Specimens of the siliceous sponge *Aphrocallistes* (Fig. 2u) are, as noted by Rigby and Jenkins (1983), three-dimensional branching tubular forms.

Analyses of calcareous nannofossils and benthic foraminifera done during this study indicate a late Eocene age for a *Modiolus*-bearing thin siltstone bed enclosed by limestone and uncovered in a hand-dug trench in about the middle of the limestone quarry. The siltstone contained the calcareous nannofossil *Isthmolithus recurvus*, which has an extremely short range and allows the zonal assignment to the late Eocene CP15b Zone of Okada and Bukry (1980). The siltstone also contained the benthic foraminifer *Uvigerina cocoaensis*, which is diagnostic of the late Eocene part of the Refugian Stage (Rau, 1981). The age assignment for the Bear River limestone deposit indicates temporal correlation to the lower part of the widespread Lincoln Creek Formation of southwestern Washington, the age of which has been discussed by Prothero and Armentrout (1985). See Armentrout et al. (1983) for a chart showing the regional stratigraphic correlation of the Lincoln Creek Formation.

Menlo Deposit

The Menlo deposit is enclosed within siltstone of the Lincoln Creek Formation (Wagner, 1967). W. W. Rau (1990, personal commun.), on the basis of benthic foraminifera, has assigned this siltstone to the foraminiferal upper Refugian Stage (late Eocene). The deposit is on the north bank of the Willapa River adjacent to the Chehalis-Raymond highway, in SW¼NW¼ sec. 24, T. 13 N., R. 8 W., Raymond 7.5-minute quadrangle, Pacific County. The locality is equivalent to locality LACMIP 12326.

Danner (1966) reported the deposit to be 2 m thick, 7.5 m long, and 3 m wide. Farther along the river are 20 or more small, thin, lenticular beds of limestone separated by shale.

In the Menlo deposit, *Modiolus* forms less dense concentrations than those found in the Bear River deposit. About 2 kg of rock samples were collected for this study.

ENVIRONMENT

The presence of articulated, juvenile to adult bivalves, as well as the unabraded condition of the bivalves, fragile worm tubes, siliceous sponges, and gastropods in the three limestone deposits indicate that the macrofossils have not undergone any kind of transport and are in situ communities. Although each community has a somewhat different taxonomic composition, they are all dominated by bivalves. They are very similar to modern-day assemblages associated with cool-fluid seepage at depths of about 2000 m in the subduction zone off the coast of Oregon (Suess et al., 1985; Kulm et al., 1986) and between 3800 and 6000 m at several locations along the landward slopes of the subduction-zone complex off the Pacific coast of Japan (Ohta and Laubier, 1987; Hashimoto et al., 1989). Surveys by submersible in these waters found localized colonies that typically consist of very dense aggregations of chitinous vestimentiferan and calcareous serpulid tube worms associated with *Calyptogena* and *Solemya* (a bivalve closely allied to *Acharax*). These soft-bottom colonies, which can be up to 30 m wide and 200 m long, are centered around cool-fluid seeps on the ocean floor where interstitial waters laden with methane and light hydrocarbons are discharged from underlying sediments. These subsurface sediments are being squeezed by tectonic forces associated with active subduction. The bivalves consume the methane and are sustained by symbiotic methane-oxidizing and/or sulfur-oxidizing chemoautotrophic bacteria that live in the gills of the bivalves. Like the Humptulips, Bear River, and Menlo communities, tax-

TABLE 1. CHECK LIST AND ABUNDANCE OF MACROFOSSILS IN SUBDUCTION-RELATED LIMESTONES IN SOUTHWESTERN WASHINGTON

Species	Hump-tulips	Bear Creek	Menlo
Acharax cf. *A. dalli*	1	3	-
Modiolus (M.) n. sp.	32	IN	15
Calyptogena n. sp.	3	60	2
Thyasira (Conchocele) folgeri	55	-	1
pitarid	9	3	-
Gastropods			
fissurellid? limpet	12	-	-
patelliform limpet	14	1	-
Margarites (Pupillaria) n. sp.	-	15	-
Homalopoma? sp. A	25	-	-
Homalopoma? sp. B	-	1	-
naticid	30	5	1
buccinid?	-	1	-
Scaphopod			
Dentalium sp.	1	-	-
Sponge			
Aphrocallistes polytretos	?	40	-
Worm tubes			
vestimentiferan?	IN	3	-
serpulid	IN	-	-
Other			
decapod parts	5	-	-
wood fragment	-	1	-
fish bone	-	1	-

IN = Innumerable.

onomic composition of the modern communities is highly variable and specific diversity is very low. The specific diversity appears to be low in modern seep communities because of the extraordinarily high densities of *Calyptogena*. There is no specific predator. Opportunistic suspension feeders such as the bivalves and worms concentrate in the vicinity of the seeping waters (Ohta and Laubier, 1987) where there is a significantly greater food supply than is typical for deep-sea depths (Suess et al., 1985). The very small limpets, trochids, and turbinid gastropods in some of the Washington limestones were probably grazers of bacteria that lived on the surfaces of bivalves and worm tubes. Similar gastropods have been observed in modern cold-water seep communities off Florida (Paull et al., 1984).

It is important to mention that the modern Oregon chemosynthetic communities are associated with methane-derived authigenic carbonate deposition (Kulm et al., 1986). This mode of formation of calcium carbonate was most likely responsible for the presence of bodies of limestone around the three late Eocene Washington communities.

Reports of ancient examples of subduction-related communities are rare and so far have been confined to Miocene and Pliocene deposits in Japan (Kanno et al., 1989; Niitsuma et al.,

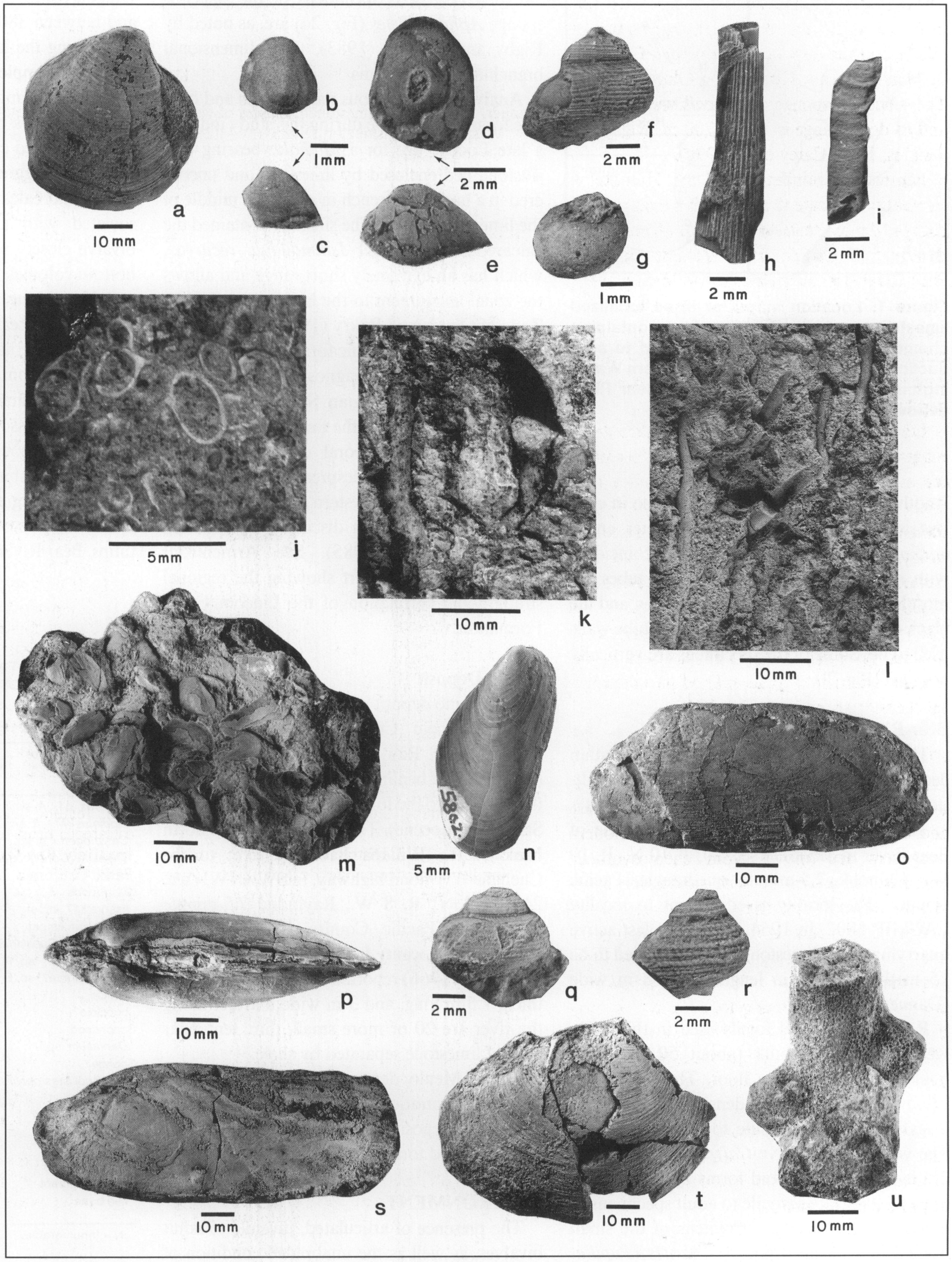

Figure 2. Photos a–l: Humptulips deposit; a—*Thyasira* (*Conchocele*) *folgeri* Wagner and Schilling, hypotype, LACMIP 8339, right valve of articulated specimen; b, c—patelliform limpet, hypotype, LACMIP 8340, dorsal and lateral view; d, e—fissurellid? limpet, hypotype, LACMIP 8341, dorsal and lateral view; f—*Homalopoma*? sp. A, hypotype, LACMIP 8342, abapertural view; g—naticid, hypotype, LACMIP 8343, abapertural view; h—*Dentalium* sp., hypotype, LACMIP 8344, lateral view; i—serpulid worm tube, hypotype, LACMIP 8345, lateral view; j—serpulid worm tubes (colonial specimens), hypotype, LACMIP 8346, lateral view; k, l—vestimentiferan? worm tubes, hypotypes, LACMIP 8347-8348, lateral views. Photos m–u; Bear River deposit; m, n—*Modiolus* (*Modiolus*) n. sp., hypotype, LACMIP 8349, cluster of specimens and hypotype, LACMIP 8350, right valve of articulated specimen; o, p—*Calyptogena* n. sp., hypotype, LACMIP 8351, left valve of articulated specimen and hypotype, LACMIP 8352, dorsal view of internal mold of articulated specimen; q—*Margarites* (*Pupillaria*) n. sp., hypotype, LACMIP 8353, apertural view; r—*Homalopoma*? sp. B, hypotype, LACMIP 8354, abapertural view; s—*Acharax* cf. *A. dalli* (Clark), hypotype, LACMIP 8355, right valve of internal mold of articulated specimen; t—pitarid, hypotype, LACMIP 8356, right valve of articulated specimen; u—*Aphrocallistes polytretos* Rigby and Jenkins, hypotype, LACMIP 8357, lateral view.

1989) and Miocene-Pliocene deposits in southwestern Washington. The limestones of late middle to late Eocene age in southwestern Washington, therefore, contain the earliest examples to date of subduction-related communities.

The exact depth of water in which the Humptulips, Bear River, and Menlo limestones formed is uncertain. All the identifiable molluscan genera are extant, but their depth ranges are very broad. Except for *Calyptogena* and *Thyasira*, they range from intertidal or nearshore to about 3300 m (Keen and Coan, 1974; Okutani, 1974). The depth range of *Calyptogena* is 500 to 6000 m (Keen and Coan, 1974; Ohta and Laubier, 1987), and the depth range for *Thyasira* is 5 to 9100 m (Keen and Coan, 1974; Okutani, 1974). The siliceous sponge *Aphrocallistes* is extant, and its depth range is 28 to 2700 m (Rigby and Jenkins, 1983; Carey et al., 1990).

Benthic foraminifera from the Humptulips Formation indicate that deposition took place in bathyal depths (150 to 2500 m) (Rau, 1986). Benthic foraminifera from a siltstone within the Bear River deposit include the following extant genera: *Uvigerina*, *Gyroidina*, *Pullenia*, *Eponides*, *Bulimina*, *Nonion*, *Cibicides*, and *Lenticulina*. All range from shelf to bathyal depths except *Nonion*, which is primarily from shelf depths (Murray, 1973).

On the basis of (1) the modern-day depth ranges of the macrofauna and benthic foraminifera and (2) the fact that subduction is a relatively deep-water phenomenon, it is likely that the ancient Washington communities formed in bathyal depths around 500 to 2000 m and most certainly above the calcite compensation depth (CCD). The Pacific Ocean CCD was about 3200 m during most of the late Eocene, and it lowered to about 3400 m at the close of the Eocene, when cold water entered into the abyssal ocean (van Andel et al., 1975).

CONCLUSIONS

The regional subduction-zone setting, the petroliferous lime mud surrounding in situ fossils, and the high numbers of fossils whose modern congeners are known from chemosynthetic communities associated with subduction zones clearly indicate that the three localized limestones of late middle to late Eocene age in southwestern Washington formed in the same way that bivalve- and tube worm–rich carbonate sediments are forming today in the subduction zone off the coast of Oregon. On the basis of depth ranges of extant genera in the fossiliferous deposits and CCD considerations, the depth of water in which the communities lived was probably between 500 and 2000 m. These Eocene assemblages are the earliest examples of subduction-zone–related communities known anywhere in the world.

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