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Exceptional crinoid occurrences and associated carbonates of the Keasey Formation (Early Oligocene) at Mist, Oregon, USA

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Abstract

An unusual concentrated zone of well-preserved fossil crinoids, corals, and other organisms exists with carbonates in an otherwise barren outcrop of fine-grained sandstone and siltstone of the Early Oligocene Keasey Formation at Mist, Oregon. The origin of this Lagerstätte has long puzzled paleontologists. Taxonomically similar modern isocrinids have a strong preference for indurated substrates; the Mist carbonates may have provided seafloor hardgrounds for the isocrinids, a physical limiting factor on the formation and distribution of the crinoid Lagerstätte. Other paleoenvironmental factors such as currents, sedimentation rates, and food flux also may have affected crinoid community development. Stable carbon and oxygen isotopic analyses of micritic slabs, concretions, and sparry veins in several lithologic units at Mist indicate that the carbonates formed in the zone of archaeal methanogenesis (enrichment in $^{13}C_{carbonate}$ with values as high as +9.5‰ VPDB). The carbonates may be a late diagenetic feature, entombing the faunal material following burial (depletion in $^{18}O_{carbonate}$ to −7.8‰ VPDB), and therefore have no temporal relation to the crinoids. Alternatively, the carbonates could have formed in the methanogenic zone deep in the sediment pile, later exhumed by erosion and colonized, again with no temporal affiliation to the epifauna. Finally, the carbonates at Mist could have precipitated in an unusually shallow zone of archaeal methanogenesis induced by seepage from the subsurface, resulting in availability of reduced organic compounds and bacterial consumption of sulfate near the sediment–water interface. In this case, the sulfate reduction zone must have been thin and the upward advection of deep-sourced, isotopically evolved fluids sufficient to impart negative $\delta^{18}O$ and positive $\delta^{13}C$ signatures to the carbonates forming possibly at only a few centimeters depth. Further evidence that supports a shallow methanogenic origin for the Mist carbonates includes: (1) presence of an infaunal low-oxygen and/or chemosymbiotic fauna; (2) pristine preservation of molluscan shell secreted in isotopic equilibrium with seawater bicarbonate; (3) lack of major erosional surfaces associated with the carbonates; and (4) the occurrence of reservoir rocks beneath Mist that were charged with natural gas during the Early Oligocene. Locally mapped faults and/or clastic dikes of this age may have conveyed methane to the near-surface, with

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crinoid growth occurring upon indurated, calcareous sediments that were intermittently exposed by minor current winnowing of the draping bottom silts.

Keywords: Crinoid Lagerstätte; *Isocrinus*; Methanogenic carbonate; Keasey Formation; Oligocene; Oregon

1. Introduction

Crinoid Lagerstätten are well known from Paleozoic and Mesozoic strata worldwide, but they are almost unheard of in Cenozoic sediments. Occurrences of Cenozoic crinoids typically consist of fragments or isolated crowns, and only a few examples of concentrated remains are known, such as from the Eocene La Meseta Formation of Seymour Island, Antarctica (Meyer and Oji, 1993; Blake and Aronson, 1998). The spectacularly well preserved, articulated crinoids of the genus *Isocrinus* in deep-water siltstones of the Early Oligocene Keasey Formation at Mist, Oregon (Fig. 1), first described by Moore and Vokes (1953), thus rank as a striking example. A few crinoids are found in other Cenozoic strata of the Pacific Northwest, but as isolated, commonly disarticulated individuals, or as columnals only (Burns and Mooi, 2003). At Mist, they are highly localized and abundant (Fig. 2A), an anomaly when compared to their rarity in the remainder of the Pacific Coast Cenozoic.

Burns and Mooi (2003) summarized previous paleontological studies conducted at Mist. In general, earlier workers attempted to explain this occurrence by inferring crinoid preservation as a function of depth, suggesting quiet, deep-water conditions below wave base, although not far from shore. However, the lack of other crinoid Lagerstätten in similar paleosettings in the Pacific Northwest suggests that exceptional paleoecologic and/or taphonomic circumstances were required for the preservation of the crinoid fossils at Mist.

Published observations and photographs of modern isocrinids indicate a common preference for hardground substrates (e.g., Fig. 2B; cf. Fujita et al., 1987; Hess et al., 1999, Figs. 235 and 236). Furthermore, abundant carbonate slabs and concretions at Mist, described herein, are found adjacent to the crinoid Lagerstätte and in a nearby association with in situ corals (*Flabellum hertleini*, Durham, 1942). This paper represents the first attempt to describe and assess potential spatial and temporal relations between these fossils and the carbonates, which occur in the same general stratigraphic level within the Keasey Formation.

Several scenarios could be presented to explain the formation of the carbonates at Mist. One, hypothesized by Burns and Mooi (2003), invokes seafloor methane seepage that subsequently led to formation of indurated lenses and pavements (cf. Schwartz et al., 2003). Fossil-rich methane seep-carbonates are common in Pacific Coast Cenozoic strata (summarized in Campbell et al., 2002), including a documented seafloor methane-seep deposit in the Keasey Formation at Vernonia-Timber Road, 22 km south of Mist (Figs. 1 and 3A,B; Campbell and Bottjer, 1993; Nesbitt et al., 1994; Campbell, 1995). Another possible origin for the Mist carbonates is early diagenetic mineral precipitation around organic remains (e.g., Fig. 3C) within fine-grained sediments. Concentrated shell layers also may have contributed bicarbonate from solution-reprecipitation that diffused into surrounding sediments during burial and diagenesis (cf. Hesse et al., 2004). Finally, carbonate can form in the subbottom in the zone of microbial sulfate reduction or methanogenesis (cf. Irwin et al., 1977; Mazzullo, 2000), as documented, for example, in Miocene subsurface seep deposits in California (Fig. 3D; Aiello et al., 2001). Herein, these mechanisms are further explored for the Mist carbonate and crinoid association, in the context of stratigraphic, sedimentologic, paleontologic, and stable isotopic data gathered for this study.

Fieldwork at Mist in 2003 investigated the spatial relation between the carbonate layers and the fossil-rich layers. Lithologic unit distribution was mapped as completely as possible, given exposure constraints, explained below. The removal of the crinoids by commercial fossil collecting activity in the 1980s required the use of material collected from this Lagerstätte in 1971 for our petrographic and stable isotopic

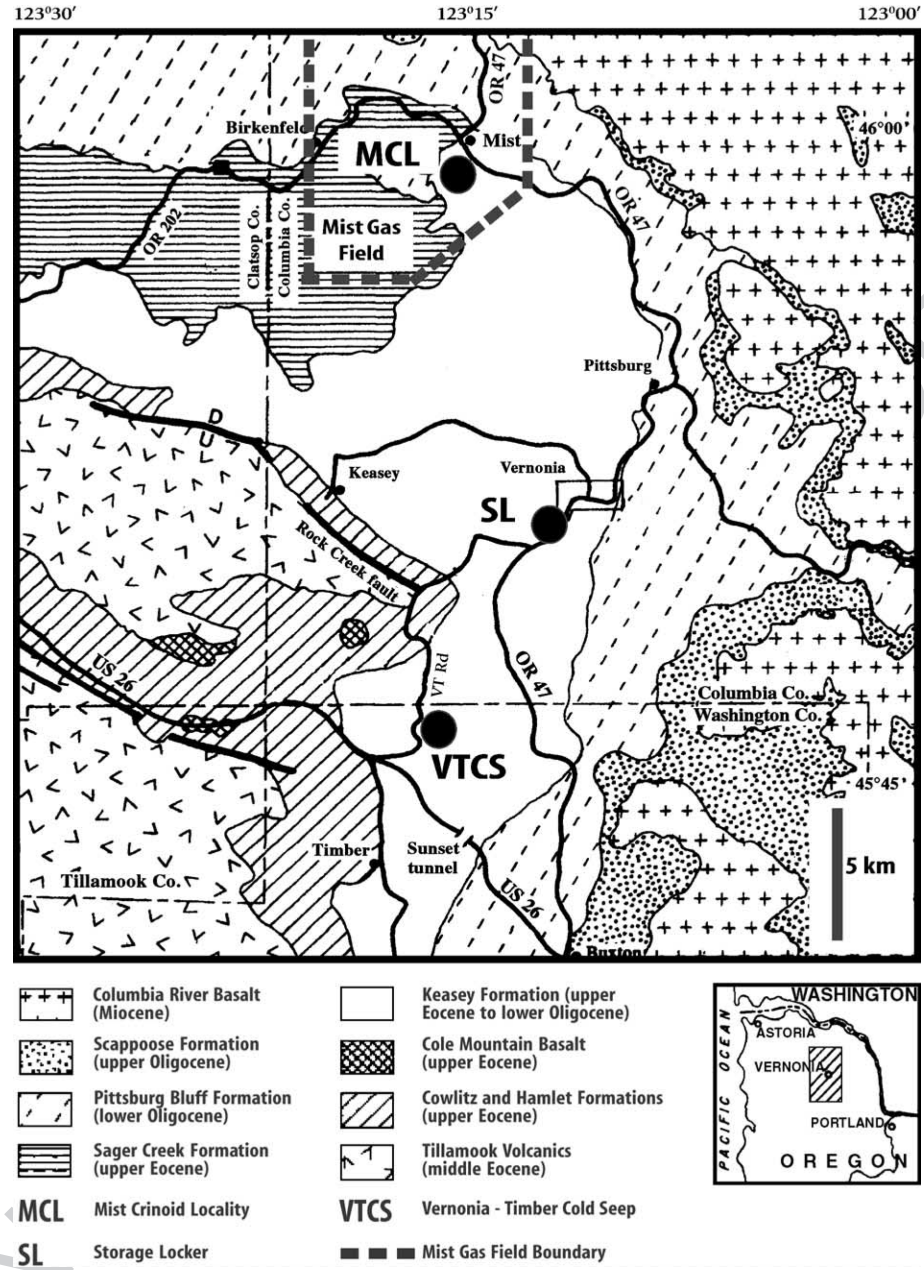

Fig. 1. Generalized geologic and locality map of the Nehalem River valley, northwestern Oregon adapted from Niem et al. (1994). MCL = Mist Crinoid locality; SL = Storage Locker; VTCS = Vernonia-Timber Cold Seep.

analyses. Samples taken during annual visits to the site since 1986 were useful for paleontologic analysis. Geochemical analyses show a range of stable carbon and oxygen isotopic signatures for carbonates at the site; most signals indicate methanogenesis and pore fluid input distinct from seawater. The temporal relations among organism activity, fluid flow, and cementation/diagenesis remain somewhat elusive at Mist, at least in part due to limited outcrop accessibility and scarcity of fossils at the site today.

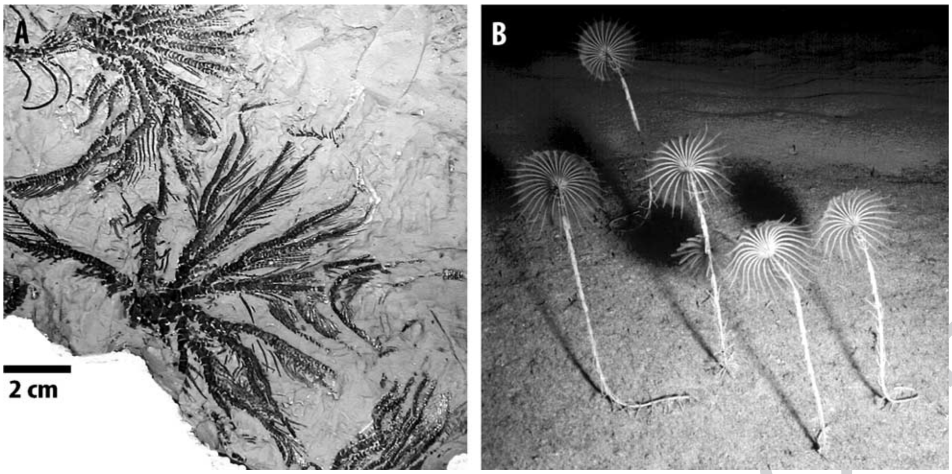

Fig. 2. Fossil and living crinoids. A. *Isocrinus oregonensis* slab collected in 1971 from the "bench" Lagerstätte (CR) deposit (OMSI IF-H-51) B. Modern isocrinids, *Neocrinus decorus*, on carbonate hardground, northeastern Straits of Florida, near Grand Bahama Island, 420 m depth. Stalk length approx. 35 cm. Note comatulid crinoid perched on stalk of one individual (photograph from the Johnson Sea Link submersible, courtesy C.G. Messing).

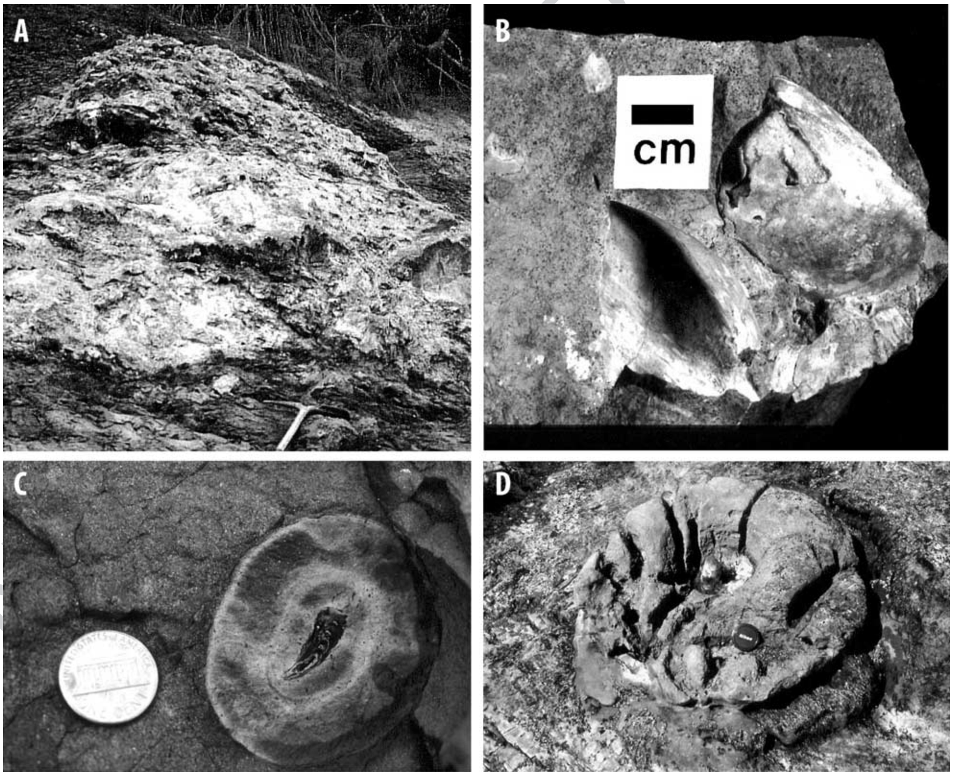

Fig. 3. Examples of different types of seep-carbonates for comparison with Mist carbonates. A. Vernonia-Timber Road seep mound carbonates. B. Vernonia-Timber Road seep *Conchocele* plus carbonate. C. Normal marine concretion around crab. Coin 18 mm in diameter. D. Subsurface concretions/fluid conduits. Lens cap 6.2 cm in diameter (Santa Cruz Mts., California).

Material examined in this study is housed at the Oregon Museum of Science and Industry (OMSI), Portland, Oregon; Condon Museum (CONDON), Eugene, Oregon; Oregon Department of Geology and Mineral Industries (DOGAMI), Portland, Oregon; Burke Museum of Natural History and Culture (UWBM), Seattle, Washington; Museum of Paleontology (UCMP), Berkeley, California; Humboldt State University Natural History Museum (HUM), Arcata, California; and Natural History Museum of Los Angeles County (LACM), Los Angeles, California.

2. Geologic setting and age of the Keasey Formation at Mist

The Keasey Formation, first described by Schenck (1927), consists of Late Eocene to Early Oligocene

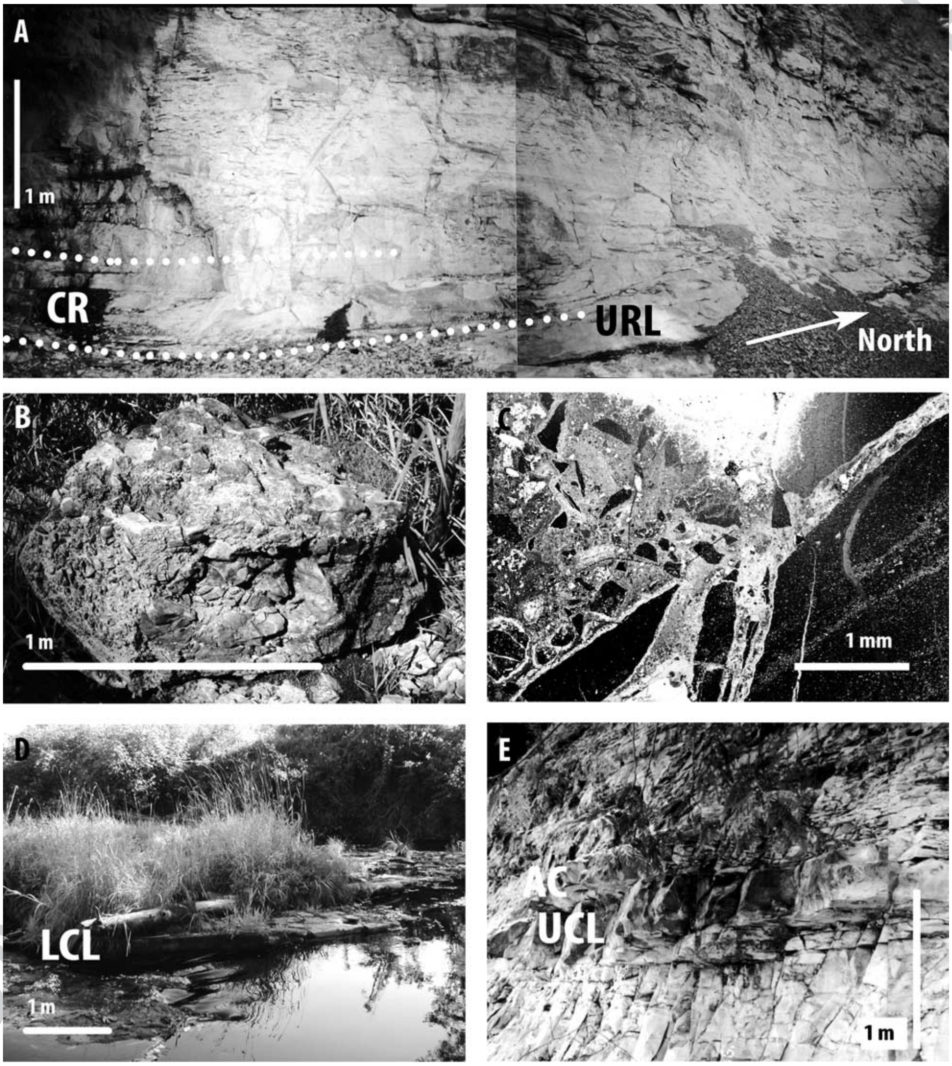

Fig. 4. Examples of outcrop and carbonate types at Mist. A. Crinoid Lagerstätte (CR)—1991 photo taken before the landslide, view to the west. The most crinoid-rich part of the outcrop lies between the lines of white dots. The underlying resistant layer (URL) is visible in the lower right of photograph. B. Brecciated boulders (BB)—width of view 1.5 m. C. Thin section detail of vein calcite in a brecciated boulder, transmitted light. D. Lower calcareous layer (LCL)—width of view (to east), 5 m. E. Upper calcareous layer (UCL) in section, view to the southwest. The *Acila*/coral (AC) layer occurs directly overlies this feature.

deep-water, concretionary, tuffaceous siltstones and clayey mudstones. It is exposed in the Nehalem River basin of northwestern Oregon, straddling the Washington, Columbia, and Tillamook counties area (Fig. 1). Warren and Norbisrath (1946) subdivided the Keasey Formation into three informal members and mapped the extent of its distribution (Warren et al., 1945). Additional researchers have attempted to refine the stratigraphy on the basis of lithology and paleontology, but most agree that the Keasey Formation was deposited in a near-shore shelf-slope setting and is composed of siliciclastic sediments weathered from nearby volcanic sources. On the basis of paleontological evidence, the Eocene–Oligocene boundary occurs

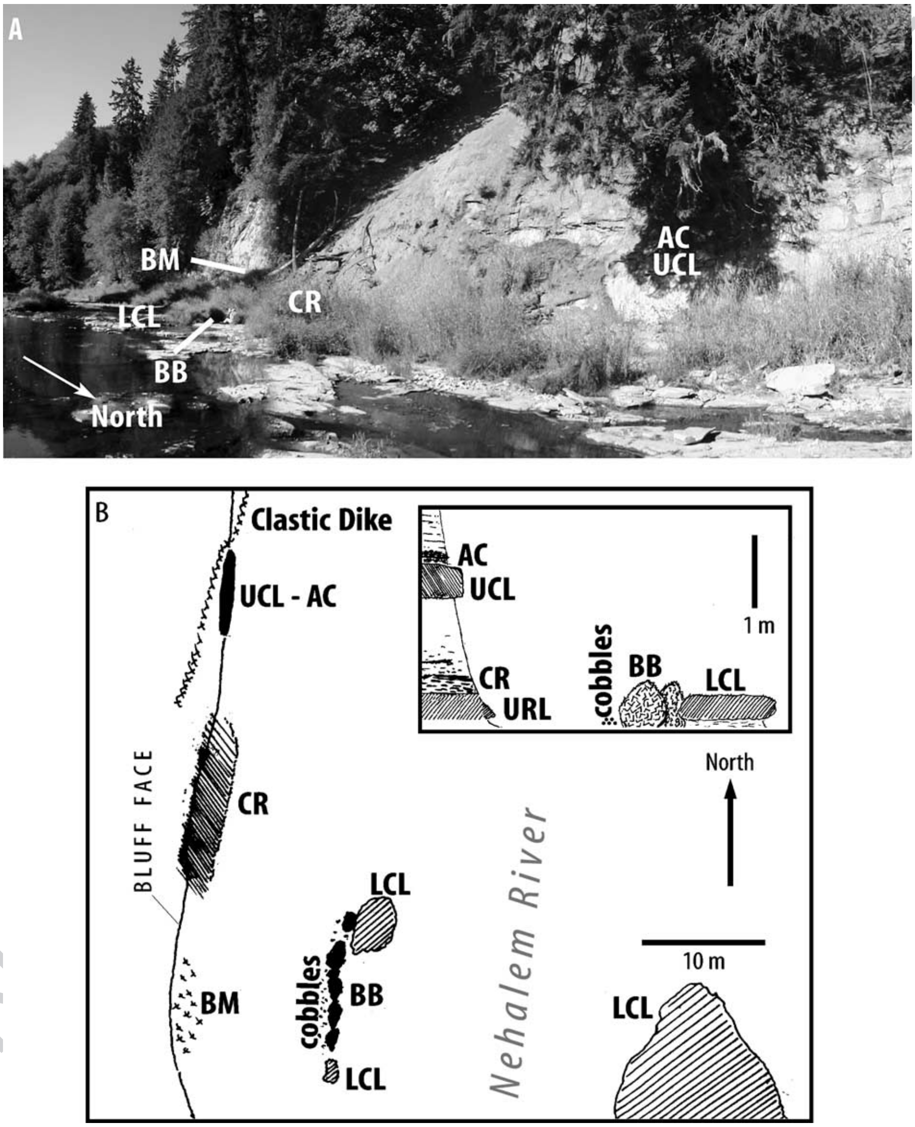

Fig. 5. The Mist crinoid locality. A. General stratigraphic overview of the Mist locality, view to the south. B. Plan view of the locality showing spatial relations of the different rock units. Inset shows lateral and vertical relations between units. CR area includes a "bench," that has been removed by past commercial quarrying. The remaining CR deposit exists only along the bluff face. URL = underlying resistant layer; LCL = lower calcareous layer; BB = breccia boulders—the dots represent the loose concretionary cobbles containing *Acila*; BM = "*Brisaster*" beds; UCL = upper calcareous layer; AC = *Acila*/coral layer.

near the top of the middle member (Hickman, 1980; McDougall, 1980), which is where Moore and Vokes (1953) stratigraphically placed the Mist deposit. Hankins and Prothero (2000) refined the age of the Keasey Formation using magnetostratigraphy of a section along Oregon Highway 26 and determined the age of three additional localities in the Keasey Formation including the Mist crinoid site. Their results place the Mist crinoids in Chron 13n, corresponding to an age of 33.0–33.5 Ma, or earliest Oligocene.

The Mist crinoid locality occurs at the base of a prominent bluff approximately 900 m long and 90 m high exposed along the Nehalem River just south of the town of Mist in Columbia County, Oregon; it is approximately 850 m south of the junction of Oregon Highways 47 and 202 (Fig. 1). Except for the units described below that contain carbonates and fossils (Figs. 4–8), most of this outcrop consists of undifferentiated, unfossiliferous, tuffaceous siltstone that is gray where fresh and weathers beige; it contains uncommon concretions and few recognizable sedimentary structures. The study outcrop is concealed in places by talus and vegetation (Fig. 5A). Access to the Mist site is usually limited by high river water level to the dry summer months, when frequent rockfalls from the high bluff render collecting hazardous.

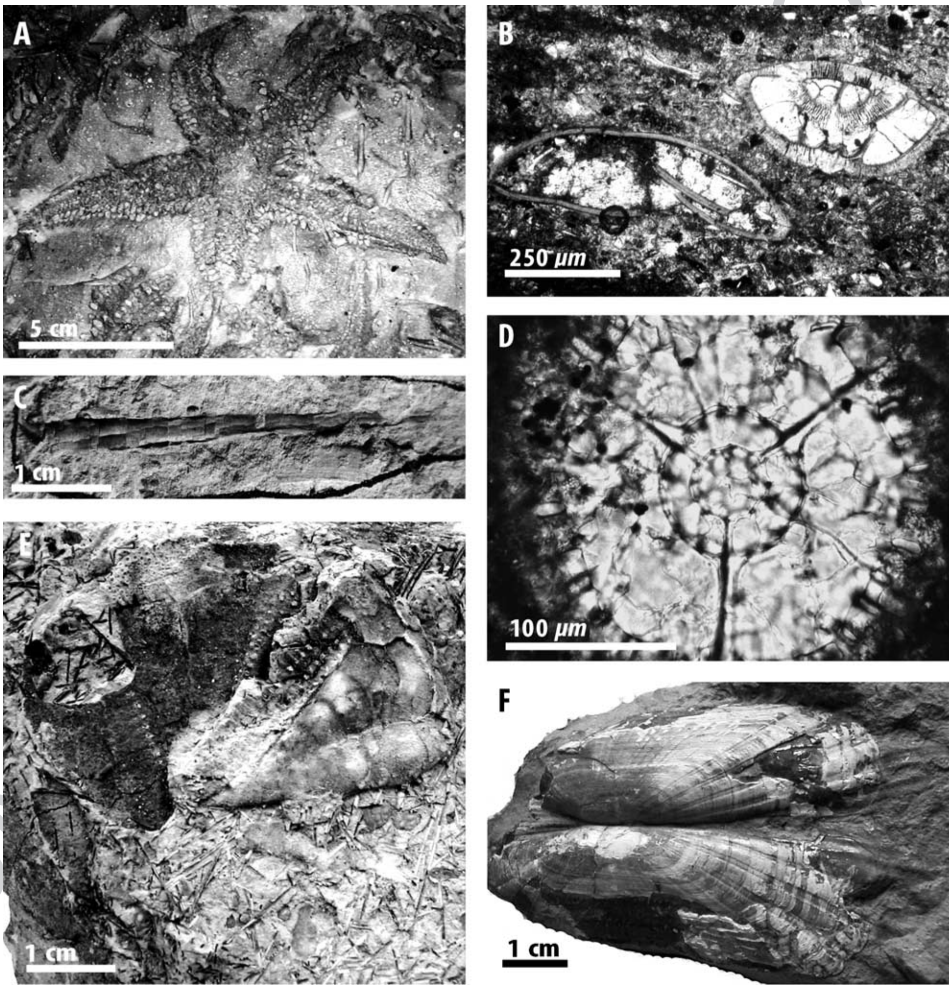

Fig. 6. Fossil taxa from Mist locality. A. Seastar from bench CR Lagerstätte (CONDON F36,432). B. Foraminifera and crushed micromollusk from AC. C. *Dentalium*, incorrectly identified as pogonophoran by Adegoke (1967), from BM (UCMP 12151) D. Actinommid radiolarian from LCL. E. “*Brisaster*” *maximus* from BM (UWBM 97640). F. *Acharax willapaensis* from CR packstone (OMSI IF-H-77).

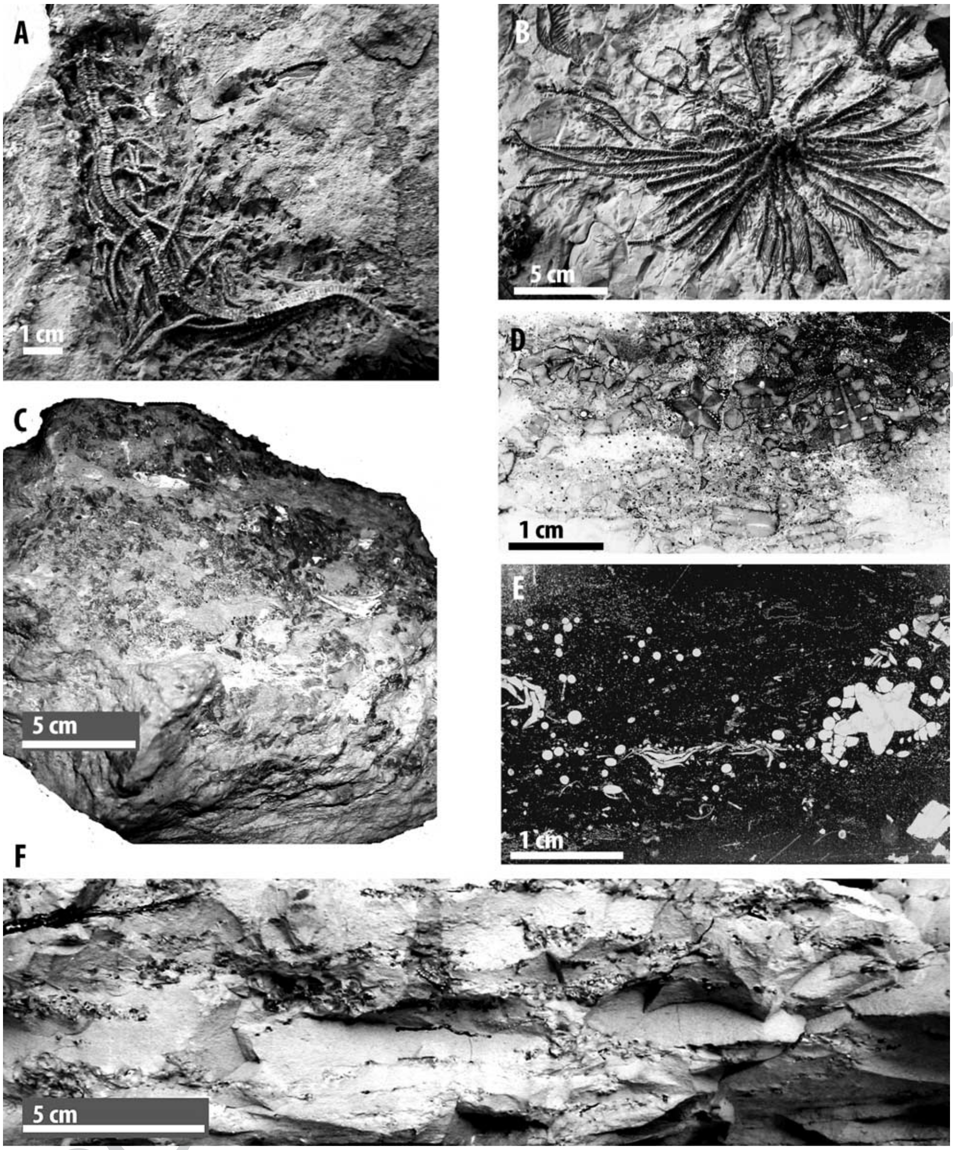

Fig. 7. Crinoid taphonomy at Mist. All specimens from original bench CR Lagerstätte: A. Crinoid stalks with cirri; length of stalk 18 cm (HUM 953). B. Crinoid in outstretched filtration fan posture; maximum width 21 cm (CONDON F34,481). C. Packstone slab (OMSI IF-U-70); width of view 20 cm. D. Packstone, thin section in plane polarized light (OMSI IF-U-70). Note abundance of columnals. E. Lagerstätte, thin section in transmitted light. F. Lagerstätte slab showing bedding characteristics (CONDON F34,481).

The crinoid- and other fossil-bearing deposits are localized and typically covered by talus, making it difficult for collectors unfamiliar with this site to locate the fossil-bearing strata.

A seep-carbonate deposit was described (Campbell and Bottjer, 1993; Nesbitt et al., 1994; Campbell, 1995) at another Keasey Formation locality, the Vernonia-Timber Road site, 22 km to the south (Fig. 1). These Vernonia-Timber carbonates (1) consist of nodular, irregular pod- and lens-shaped bodies (to 2 m thick) and have diffuse sedimentological boundaries (Fig. 3A); (2) contain glauconite-rich micrite and fibrous cements; (3) enclose abundant, in situ thyasirid bivalves (e.g., Fig. 3B); and (4) yield depleted

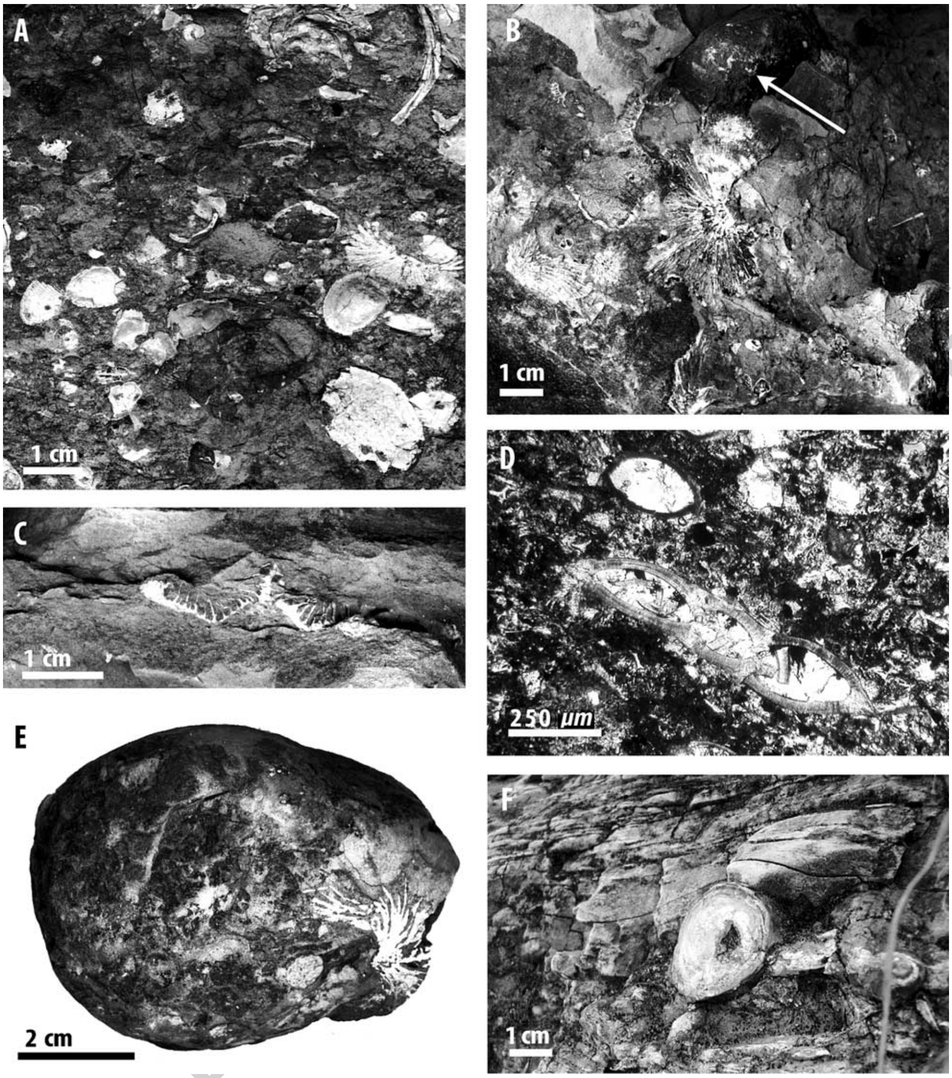

Fig. 8. Fossils and sedimentology of the *Acila*/coral layer (AC). A. Bivalves in AC; view of bottom surface of slab (UWBM 97632). B. Coral *Flabellum hertleini* collected from top of AC; view of upper surface of slab; arrow points to a carbonate concretion (UWBM 97633). C. *Flabellum* in AC in life position, collected 1 cm above contact with UCL (UWBM 97634). D. Uniserial foraminifera and micromollusks; thin section in plane polarized light. E. Concretion partially enclosing *F. hertleini* coral from top of AC (UWBM 97635). F. Concretion layer at top of AC.

carbonate-carbon signatures (to δ^{13}C $-53.7‰$ VPDB, Campbell, unpublished data). Therefore, they are considered to represent seafloor methane-derived seeps sensu stricto. In contrast, the Mist carbonates are characterized by (1) sharp-bounded, horizontal, calcareous siltstone beds (from 30 to 60 cm thick; Figs. 4A,D,E and 5A); (2) subspherical carbonate concretions of homogenous micrite (Fig. 8F) and abundant detrital siliciclastic grains; or (3) uncommon micrite breccia with veins of a yellow-white, coarse spar (Fig. 4B,C). Many modern seep-carbonates are described in the literature as homogeneous micritic slabs and lenses or containing sparry veins (summarized in Campbell et al., 2002, Table 4), quite similar to the Mist material. Furthermore, the Mist crinoid locality is situated on the eastern half of the commercially producing Mist Gas Field (Fig. 1), which taps a reservoir sand that has been charged with methane since the Eocene and that underlies the Keasey Formation throughout the area (Niem et al., 1994). Carbonates are more abundant at Mist than in other portions of the Keasey Formation and are spatially associated with the fossil-bearing units (Figs. 4A and 5).

3. Stratigraphy and lithological units of the Mist deposit

Moore and Vokes (1953) treated the Mist deposits (Fig. 5A) as one collecting site (U.S. Geological Survey locality 15318), and they also used the University of California's locality register (UCMP A-5018) for the same geographic locale. All subsequent authors have referred to one undifferentiated (i.e., stratigraphically and sedimentologically) collecting site, except for Adegoke (1967), who recorded one additional fossil locality (UCMP B-5218) 90 m south of the crinoids in a paper about pogonophoran tube-worms in the Keasey Formation. We have divided the calcareous and/or fossiliferous strata at Mist into seven informal units corresponding to specific sedimentologic and/or paleontologic features. We have differentiated the units stratigraphically, vertically and laterally (Fig. 5B), with the aim of revealing taphonomic circumstances that led to the presence and preservation of the crinoids. Although talus, vegetation, and weathering of the rock to a uniform color and texture obscure some of these units in most places (e.g., Figs. 4A and 5A), one upper calcareous layer is a reliable marker bed for local correlation.

The relevant units described below are crinoid Lagerstätte (CR) and the associated underlying resistant layer (URL); brecciated boulders (BB); lower calcareous layer (LCL) and associated float cobbles, both containing the bivalve *Acila*; upper calcareous layer (UCL), 1.5 m above the Lagerstätte; coral-bivalve layer (AC), including small concretions just above the corals; and beds containing the schizasterid "*Brisaster*" *maximus* (Clark, 1937), representing a possible paleo-debris fan (BM) marginal to CR, ~10 m to the south. The spatial, stratigraphic, lithologic, and paleontological characteristics of these seven informal units are illustrated in Fig. 2A and Figs. 4–8.

Three fossiliferous units (CR, AC, BM) are distinct in both lithology and paleontologic composition, which allowed us to reliably determine the units from which specimens were taken for several fossil collections made by earlier workers.

3.1. Crinoid Lagerstätte and underlying resistant carbonate

A unit that is 125 cm thick and approximately 3 m in exposed width comprises the "classic" Mist crinoid locality (Fig. 4A, CR). These strata are the least accessible and most difficult to analyze, except by historic collections and photographs made before 1996 (e.g., Fig. 7). This unit once consisted of a north-trending erosion-resistant bench approximately 1.5 m high, 2 m wide, and 9 m long (original position of CR indicated in Fig. 5B). This bench consisted of fossiliferous, indurated calcareous siltstone, exposed at the base of the bluff. From this, several slabs were collected in 1970–1973 by the first author. Moore and Vokes (1953), probably collected their type material from this unit, and they commented on the hardness of the rock and the difficulty of preparation, compared with "traditional" midwestern U. S. crinoid material familiar to Moore. Indeed, preparation of the crinoids collected in 1970–1973 required the use of an air hammer and detailed work with an air abrasive unit using aluminum oxide or silicon carbide abrasive. Some of the slab material was too indurated to respond to this treatment.

Commercial fossil collecting in the 1980s removed all of the bench, leaving only weathered layers in the bluff face at the site (Fig. 4A) from which a few weathered specimens of *Isocrinus* have been collected with great difficulty. Float from these weathered layers, containing several partial and complete crowns, has been salvaged during frequent visits over the past 30 years. In 1996, a landslide covered these fossil-rich layers. However, photographs taken in 1991 indicate that the crinoid Lagerstätte (CR) lies stratigraphically above a differentially eroding, calcareous layer (underlying resistant layer, or URL) greater than 40 cm in thickness (Fig. 4D).

Crinoids from the CR unit are spectacularly well preserved. The crinoid stereom is blue-black (Fig. 2A), but it rapidly weathers reddish-orange. Similar specimens in rock similar to the bench layers are deposited at DOGAMI, LACM, and UWBM and are common in private collections (Moore and Vokes, 1953, p. 113). On the basis of various museum and private specimens, observed densities of the crinoids on a single bedding plane range up to 100 individuals per square meter. In the remaining weathered layers in the cliff west of the former bench deposit (Fig. 4A), the densities are considerably less, ranging up to 50 individuals per square meter. Within 2 m to the north of this area, the density of individuals rapidly diminishes. A few isolated individuals have been found in beds stratigraphically equivalent to this unit as far as 15 m north.

Moore and Vokes (1953) were the first to described the crinoids from the Keasey Formation at Mist, naming two species: *Isocrinus oregonensis* and *Isocrinus nehalemensis*. Burns and Mooi (2003) reviewed the taxonomy of these species, preferring to keep the original placement pending further revision of the Isocrinidae. *Isocrinus* has been found at a number of other Keasey Formation localities, including an excavation 1 km south of Vernonia, in an unnamed basaltic gritty sandstone at Yachats, Oregon, and in the Lincoln Creek Formation, Washington (Burns and Mooi, 2003). In contrast to Mist, the crinoids elsewhere in the Pacific Northwest occur as rare, disarticulated individuals or columnals only. At the other Keasey Formation crinoid localities, calcareous layers like those at Mist have not been observed.

Occurring with the articulated crinoids at Mist are uncommon seastars (Fig. 6A) described by Blake (1973), undescribed ophiuroids currently under study by G. Hendler (LACM), well-preserved entire leaves (Moore and Vokes, 1953, plate 22-2), wood with *Teredo*-borings, Foraminifera and micromollusks (Fig. 6B), radiolarians, and fish scales (David, 1956). Moore and Vokes (1953) reported one spinose ophiuroid attached to a crinoid stem. The seastars are intact and outstretched, suggesting rapid burial in place.

The crinoids at Mist exhibit a number of preservation modes (Fig. 7), ranging from individuals or groups arranged in life position with outstretched filtration fans (Fig. 7B) to specimens indicating arm regrowth (Moore and Vokes, 1953, plate 21-2) and to individuals with autotomized arms. A few isolated autotomized arms are known. Stalk sections also are found with fully articulated stalks and cirri still clinging to the substrate (Fig. 7A). These observations suggest that the Mist deposits represent a deep-water obrution taphofacies that resulted from frequent pulses of sediment that both killed and preserved the echinoderms in situ (cf. Brett et al., 1997). Preservation of entire seastars (e.g., Fig. 6A) and ophiuroids also supports this inference. Furthermore, interspersed with the articulated crinoid layers are layers as much as 10 cm thick consisting primarily of disarticulated crinoid remains dominated by columnals and representing a skeletal packstone or grainstone (e.g., Fig. 7C,D; cf. Brett et al., 1997, p. 160). A sample of a well-preserved crinoid packstone from the original bench Lagerstätte was removed from an unprepared slab (OMSI IF-U-70) for thin section (Fig. 7D) and stable isotope analysis. This packstone, collected stratigraphically near the bottom of the bench in 1972, is well indurated (Fig. 7C). Although mollusks are uncommon in the articulated crinoid layers, they are common in the packstone layers, are unabraded, and include delicate taxa such as weakly hinged articulated bivalves and thin-shelled gastropods (e.g., *Scaphander*) that are unlikely to have survived transport. The crinoid debris consists of individual and stacked columnals and cirri that are unabraded. The mollusks include a few seep-suspect taxa, including rare solemyids (Fig. 6F) and thyasirids. Other mollusks are *Dentalium*, *Nuculana*, gastropods, and additional bivalves (Table 1). Periods of low sediment input may have resulted in formation of these accumulations of detrital crinoid debris through winnowing and/or sediment starvation, with the mollusks inhabiting the shelly debris layers on the seafloor. The thin sections reveal no evidence of extensive dissolution that might be expected if the crinoids or packstones had served as the source of carbonate for the surrounding strata.

Observations of living crinoids (Fujita et al., 1987; Meyer, 1997; Hess et al., 1999; Mooi, personal observation) suggest an apparently common requirement by isocrinids for some sort of hardground substrate. As these crinoids lack a holdfast or “root,” they can only grip the substrate with cirri along the stalk (e.g., Fig. 2B showing cirri grasping an indurated substrate beneath a thin veneer of soft sediment). Cirral anchoring is also observed among extant stalked isocrinids (Mooi, personal observation). The taphonomic evidence provided by the articulated crinoids at Mist

Table 1
Fossils found at Mist by unit

Unit	CR	CR-P[a]	AC	BM	LCL	<LCL[b]
Taxa						
Echinoderms						
Isocrinus	×	×	×	×		×
Starfish of Blake (1973)	×			×		
"*Brisaster*" *maximus*				×		
Salenia schencki		S[c]	S	×		S
Ophiuroids	×					
Corals						
Flabellum hertleini			×	×		
Bivalves						
Acila		×	×	×	×	×
Crenella				×		
Delectopecten		×	×	×		×
Erycina		×	×	×		
Isognomen		×	×	×		
Litorhadia		×	×	×		
Minormalletia			×	×		
Nemocardium		×	×	×		
Nucula		×	×	×		
Poroleda		×		×		
Propeamussium				×		
Acharax	×	×				
Tellina	×	×	×	×		×
Conchocele	×					
Teredo	×	×	×	×		
Yoldia		×	×	×		
Gastropods						
Acmaea				×		
Argobuccinum				×		
Bathybembix?		×		×		
Bonnelita		×	×			×
Conomitra				×		
Exilia		×				
Ficus		×	×			
Fulgarofusus		×		×		
Fusinus				×		
Fusitriton			×	×		
Limpets		×		×		
Naticids		×	×	×		×
Parasyrinx		×				
Pteropods	×			×	×	
Scaphander		×	×	×		×
Turricula		×	×			
Other mollusks						
Dentalium		×	×	×		
Fustiaria (scaphopod)		×	×	×		×
Aturia (cephalopod)		×	×			
Other fossils						
Decapods		×	×	×		
Shark teeth of Welton (1979)	×	×	×	×		
Fish scales of David (1956)	×	×	×	×		×
Leaves	×		×	×		

Notes to Table 1:
[a] CR-P—crinoid packstones.
[b] <LCL—from sediments 2.5 m west of BB and 30 cm stratigraphically below LCL.
[c] S–spines only.

suggests little or no transport, consistent with the presence of a "crinoid-friendly" substrate, perhaps a seafloor hardground. The erosion-resistant layer (URL) situated beneath the crinoids might have initially provided a hardground, allowing establishment of the crinoid population in this location. Similarly, localized packstone accumulations of well-preserved crinoid remains in debris shed by the population could have provided firm substrates upon which subsequent populations might have flourished. Ultimately, development and preservation of the Lagerstätte may have been controlled by localized hardground formation by cementation of silts with micritic cements, which could have arisen by several possible mechanisms, discussed below.

3.2. Brecciated boulders and lower calcareous layer

Fieldwork during low river levels in the summer of 2003 revealed the presence of a number of previously unrecognized carbonate features at the site that are in general stratigraphic association (within 11 m laterally and 1 m vertically) with the crinoid Lagerstätte (Fig. 5). One structure consists of north-trending aligned concretionary masses of in situ, resistant, calcareous siltstone (Fig. 5, labeled BB). Portions of these concretions are brecciated, with veins filled by vuggy, yellowish-white calcite spar. These masses are referred to here as the breccia boulders (BB; Fig. 4B,C).

A siltstone unit, or lower calcareous layer (LCL), lies at the northern margin of the BB features. Nonetheless, the LCL is clearly an erosional remnant (Fig. 5B); other portions of the unit are exposed in the river bottom at the southern end of the mapped area (Fig. 5B). A larger remnant of the LCL occurs across the river 12 m to the east (Fig. 4D). Old photographs show that the LCL is a lateral equivalent of the resistant layer (URL) beneath the crinoid Lagerstätte (14 m laterally to the northwest, Fig. 5B). However, erosion by the Nehalem River has removed any evidence of the relation between the LCL and the resistant layer (URL) below the crinoid Lagerstätte.

The LCL is absent 5 m south of the former erosion resistant bench (CR/URL). The top of the LCL, as well as its eroded cross-section, was examined carefully for the presence of crinoids and other fossils. However, only pteropods were found in one sample, and radiolarians with framboidal pyrite (Fig. 6D) were noted in thin section. Siltstone stratigraphically below the CR and URL at the lowest river level also was examined for macrofossils ("<UCL" in Table 1). In the vicinity of the BB and toward the position of the bench Lagerstätte (CR/URL), a few discontinuous layers of fossiliferous siltstone contain abundant mollusks and some disarticulated crinoid debris, indicating that crinoids were in the area earlier than the deposition of the Lagerstätte. Similar fossiliferous layers occur for about 10 m to the north, but taper in abundance away from the BB. These layers superficially resemble the "*Brisaster*" beds described below.

Among the BB and around the margins of the LCL are loose cobbles of resistant, brittle, carbonate-cemented siliciclastics occur that contain articulated and somewhat recrystallized *Acila nehalemensis* (Schenck, 1936). The cobbles are found nowhere else at Mist and emit a faint petroleum odor when broken. None of these cobbles were found in situ. A survey 100 m upstream (south) and of streamside gravel banks on the opposite shore resulted in the discovery of only rare concretion float blocks. Samples were removed for petrographic and isotopic analysis from the BB, LCL, and the associated loose cobbles.

Due to erosion by the Nehalem River, landslide talus, and commercial fossil collecting activities, we may never be able to confirm the precise relation among the BB, LCL, CR, and URL (Fig. 5B).

3.3. Upper calcareous layer and coral-bivalve layer

An evidently intact coral paleocommunity occurs at Mist 15 m north of and 1.5 m above the CR. This unit is designated herein as UCL-AC (Figs. 4E and 5). UCL refers to a resistant, upper calcareous layer that underlies a 10- to 15-cm-thick layer of calcareous sandy siltstone containing concentrations of *F. hertleini* and dense accumulations of single valves of *A. nehalemensis* (AC unit; Fig. 8A–C,E). This layer also contains other mollusks and Foraminifera (e.g., Fig. 8D), crustaceans, organic matter, and sparse broken crinoids (see Table 1). The AC layer grades upward into a 5- to 10-cm-thick layer of carbonate concretions (Fig. 8F). Corals and other macrofossils from the AC layer are commonly partially or fully encased by these concretions (Fig. 8E), clearly demonstrating the post-coral timing of concretion formation.

The UCL is a lens-shaped deposit of resistant calcareous siltstone approximately 0.5 m thick and 5 m in length. It grades into the adjacent siltstone to the south. At present, UCL-AC represents the only accessible carbonate-rich deposit with an associated coral paleocommunity that can be examined in situ at Mist. It contains intact autochthonous to parautochthonous invertebrate fossils, similar to those found with the crinoids.

To the north, a vertical clastic dike of loose sand strikes 15° east, forming the northern terminus of the UCL, and extends up into the bluff for several meters (Fig. 5B). To the north, this dike is traceable on the river terrace for more than 50 m. No other carbonates are observed associated with this feature. Samples were collected of the UCL, AC, and mollusks for petrographic and stable isotope analyses.

3.4. "*Brisaster*" beds

Approximately 10 m south of the crinoid Lagerstätte occur numerous float blocks of friable, fossiliferous, noncalcareous siltstone derived from the cliff above. These blocks contain two common echinoids—*Salenia schencki* (Zullo et al., 1964), preserved with articulated spines and lanterns intact (see Zullo et al., 1964), and "*Brisaster*" *maximus* (Fig. 6E; see Burns and Mooi, 2003 for a discussion of this taxon). Also present are somewhat common clusters of *F. hertleini*, mollusks, plant matter (including well-preserved entire leaves), and abundant disarticulated crinoid remains. Because it is float that may have sampled different stratigraphic layers, it is unclear if this material, termed here the "*Brisaster*" *maximus* deposit (BM, Fig. 5), had any original stratigraphic relation to the coral layer or the crinoid Lagerstätte, or if it could represent a sampling of both AC and CR. However, the lack of carbonate cementation in these fossiliferous BM blocks suggests a more complex (and now obscured) association with, or even no stratigraphic relation to the "classic" Mist fossils at the cliff face nearby.

The burrowing schizasterid "*Brisaster*" *maximus*, common in these blocks, is found nowhere else at Mist. These fossils suggest that these layers were a "burrower-friendly" paleoenvironment, i.e., a depositional softground. This inferred habitat is in contrast to the crinoid Lagerstätte ~10 m to the north, where these echinoids are conspicuously absent and is consistent with the possibility of "burrower-resistant" hardgrounds at CR. The disarticulated crinoid remains common in the BM unit also allow for the possibility that these deposits represent a soft-bottom association once marginal to the crinoid paleocommunity. The "*Brisaster*" echinoids are rarely found as entire individuals (e.g., Fig. 6E), more frequently as isolated and disarticulated plates.

4. Possible origins of the carbonate–crinoid and –coral associations at Mist

We consider below several paleoecological, sedimentological, and geochemical aspects of the Mist carbonate-invertebrate concentrations that provide clues to formation mechanisms of the Lagerstätte. One hypothesis is that these crinoid/coral communities aggregated upon hardgrounds developed as methane-derived carbonates (sensu stricto) at the seafloor (Burns and Mooi, 2003; Goedert and Peckmann, in press). A second hypothesis is that the carbonates formed around shelly debris by solution-reprecipitation and recrystallization during burial and diagenesis. The carbonates would have to have been eroded from depth to be exposed to epifaunal colonization. A third hypothesis is that the carbonates precipitated at depth in the sediment pile in the zone of anaerobic methane oxidation (cf. Irwin et al., 1977; Aiello et al., 1999, 2001) and were later exhumed by significant erosion. A fourth hypothesis is that the carbonates developed in subbottom sediments in the zone of archaeal methanogenesis (cf. Mazzullo, 2000; Hesse et al., 2004), either at depth or near the sediment–water interface, fed by advecting methane from below. This fourth process would produce subsurface seep-carbonates sensu lato, designated here as methanogenic carbonate. The first three hypotheses can be excluded on isotopic and sedimentologic grounds. The methanogenic carbonate origin is consistent with the isotope data, although the subbottom depth at which this process may have occurred requires further consideration, detailed below.

4.1. Isocrinid hardground community paleoecology

The unusual occurrence of well-preserved Cenozoic crinoids at Mist piqued the curiosity of paleontologists. Moore and Vokes (1953) concluded that the crinoids at Mist were deposited in deep water below the limit of effective wave or current action in a near shore setting. Other works (David, 1956; Zullo et al., 1964; Welton, 1979) contributed little to the paleoenvironmental interpretation of this locality, other than to agree with and refine the initial depth estimates.

The exceptional preservation and abundance of the Mist crinoids has yet to be rivaled by discoveries in Cenozoic strata elsewhere. Autochthonous clusters of as many as 20 *Metacrinus* individuals, preserved as crowns, have been described from the Eocene of Antarctica (Blake and Aronson, 1998). Two recently discovered Lagerstätten from the Cenozoic of Japan, one containing approximately 100 comatulid crinoid individuals and another characterized by mostly *Isselicrinus* stalks are currently under study (T. Oji, written comm., 2004), but they still rank below Mist in terms of the abundance of individuals. We conservatively estimate that more than 7500 individual *Isocrinus* crowns have been removed from the Mist locality.

An understanding of possible controlling factors leading to or inhibiting the preservation of the crinoid Lagerstätte might help explain the uniqueness of this occurrence. A first requirement is presence of suitable substrates upon which crinoids could flourish. Secondly, currents must be sufficient to provide a constant suspension flux, but not so strong as to scour the sediment. A third requirement is frequent sedimentary inputs adequate to cause rapid burial of some individuals without overwhelming the entire population. Finally, inhibition of bioturbators through cementation of the substrate or some other factor must be present.

A number of volumetrically less spectacular Cenozoic echinoderm Lagerstätten such as brittle star and seastar beds have been described from the Pacific Northwest and California (Burns and Mooi, 2003; Blake and Allison, 1970; Blake, 1975). However, brittle stars and seastars are mobile echinoderms that utilize a variety of substrates, including soft bottom settings.

On the basis of observations of modern faunas, isocrinid crinoids are sessile organisms that typically exploit hard substrates for the purchase they afford to the cirral attachment mechanism. This hardground association is evidently one of the factors controlling distribution of fossil isocrinids in general, perhaps limiting their distribution and therefore that of their geologic record. With this in mind, our fieldwork at Mist focused on the location of possible hardground candidates and identifying their derivation. At issue is whether the Mist calcareous carbonates represent hardgrounds that were contemporaneous with, and available to, the crinoids.

Carbonate structures of similar scale and volume to Mist are lacking at a stratigraphically equivalent, fossil-rich site 1 km south of Vernonia, known as the "Storage Locker" site (Fig. 1; UWBM Loc. B6552) of Burns and Mooi (2003). Crinoids occur commonly at Storage Locker as disarticulated individuals (Burns, personal observations), suggesting at first glance that Keasey Formation crinoids may not have had an exclusive hardground requirement. Other invertebrates commonly found at Storage Locker include "*Brisaster*" *maximus*, *F. hertleini*, mollusks, crustaceans, brachiopods, and some plant debris. One 2-cm-thick packstone layer is exposed at this locality. Hexactinellid sponges, generally recognized from twisted root tufts, also occur in abundance with the crinoid debris. In 2000, careful field examination of this site (Burns and members of the Northwest Paleontological Association) revealed that the sponges are widespread, mostly intact, and represent a heretofore unrecognized primary faunal element.

In the modern oceans, hexactinellids serve as firm substrates for attachment in many epibenthic communities that include crinoids (Beaulieu, 2001). Therefore, the presence of abundant fossil hexactinellids at the Storage Locker site might explain the occurrence of the crinoids there. Despite the otherwise excellent preservation of other taxa at Mist, hexactinellids have been identified only as rare, isolated basal root tuft elements in the "*Brisaster*" blocks (BM).

Eocene basalts might represent an additional hardground substrate for crinoids in Pacific Northwest strata. Moore and Vokes (1953) reported the presence of *Isocrinus* columnals in gritty sandstones atop the basalt at Yachats, Oregon. Burns and Mooi (2003) identified two similar instances, one at the Oakville Quarry site at the contact between the Crescent Formation and the overlying Lincoln Creek Formation, and at another locality in the McIntosh Formation, both in southwest Washington. Scoured surfaces and basalt cobbles/clasts at these basalt/sediment contacts indicate a fairly high-energy erosional environment that might inhibit the formation of a Lagerstätte. Modern isocrinids have been observed to depend upon currents ranging from 5 to 20 cm/s to supply a constant plankton flux for filter feeding (Meyer, 1997). These populations enhance their filtration by positioning themselves at a point of enhanced or maximum current flow, such as at the shelf break of a carbonate platform (Meyer, 1997). Crinoids and scaphopods are commonly aligned in some layers at Mist. Convex-up orientation of single *Acila* valves has been noted in the AC unit (Fig. 8A; view from underside of slab). These data support the presence of considerable currents at Mist, in contrast to the claim by Moore and Vokes (1953) that the deposits accumulated in quiet water.

Preservation of the articulated crinoids in the Mist Lagerstätte closely resembles the "Crawfordsville" type multiple obrution facies of Brett and Seilacher (1991), indicating repetitive sedimentary pulses/input that would partially smother a population (Brett et al., 1997). Repopulation mechanisms might include regrowth by surviving members of the community, especially among higher tiered individuals. An important factor in the preservation of "Crawfordsville" type facies is the lack of an infaunal element that might disrupt the articulated remains. This circumstance would be consistent with paleoenvironmental factors detrimental to an infaunal benthos, but promoting Lagerstätte formation. Such factors could include (1) a decreased survival rate at the bottom tier in obrution events, as compared to higher tiered crinoids; (2) presence of indurated sedimentary layers beneath the crinoid community that would exclude burrowers; and/or (3) intermittent, shallow burial of crinoids by silt, followed by their rapid enclosure in carbonate precipitating within a near-surface zone of methanogenesis (discussed below). The resulting taphonomic signature would be articulated crinoids that were not necessarily confined to single bedding planes and a complete lack of burrowers or bioturbation. Some of the larger calcareous slabs from the Lagerstätte at Mist contain crinoids (Fig. 7F) that appear to be randomly distributed within the slabs with respect to bedding, suggesting differing survival rates among individuals during each event. Burrowers and evidence of bioturbation are lacking in these deposits, compared to elsewhere at Mist (e.g., BM unit). Thus, preservation of the crinoid population over time may reflect a fortuitous convergence of an appropriate rate of sedimentation and factors that inhibited burrowing and allowed episodic carbonate cementation to take place (see below).

4.2. Carbonate–faunal associations

Our fieldwork revealed that the associated carbonates are the only potential hardground substrates for the crinoid/coral paleocommunities, especially the URL/LCL and UCL beneath CR and AC (Fig. 5). Therefore, it became important to examine possible mechanisms for carbonate formation at Mist. Because methane-derived seep-carbonates sensu stricto are known in Pacific Northwest Cenozoic strata, including elsewhere in the Keasey Formation, we first evaluated any possible paleoecological signatures of seafloor hydrocarbon seepage for the Mist locality. In general, ancient methane-derived carbonates are confirmed as such by spatial associations with chemosymbiotic taxa, concurrent bioturbation by seep-associated organisms, as well as by distinctive sedimentologic and isotopic data (cf. Campbell et al., 2002 and references therein; Campbell and Nesbitt, in press; Nesbitt, in press).

The Keasey Formation at Mist has long been recognized as containing a diverse and unusually well preserved fauna (Table 1). This is in contrast to the generally low diversity, but locally dense biotic associations of chemosymbiotic and low-oxygen taxa in seep-carbonates sensu stricto of the Keasey Formation (e.g., lucinacean–solemyid–vesicomyid associations; cf. Hickman, 1984; Campbell, 1995; Little et al., 2002). There is no strong seep biotic signature at Mist, although a few taxa known to occur at seafloor methane-seeps have been collected within the crinoid coquina packstone layers, as well as in the coral/bivalve layer. Such taxa include *Acharax willapaensis* (Weaver, 1942; Fig. 6F) and *Conchocele bisecta* (Conrad, 1849), as first reported by Moore and Vokes (1953). Worm tubes also were described from Mist by Adegoke (1967). However, Adegoke's type material was re-examined and found to be either scaphopods or pteropods. Vesicomyids have not been found at Mist. The scattered occurrence of these taxa at Mist could reflect either low-oxygen conditions or diffuse H_2S- or CH_4-seepage.

Crinoids are seldom recorded at modern, active hydrocarbon-seep sites. However, echinoderms are known from a few such settings, both modern and in the fossil record (Gaillard et al., 1992; Sahling et al., 1997). Their presence suggests that any possible seafloor seep activity would be intermittent or that mixing with seawater would dilute the seep signal, given the poisonous effect that seep fluids have on the metabolism of many non-chemosymbiotic marine invertebrates (cf. Van Dover, 2000). Sahling et al. (1997) invoked an enhanced food particle supply to explain living crinoid aggregations around active cold-seeps in the eastern Aleutian trench. Goedert and Peckmann (in press) also cited increased local nutrient availability to justify coral associations with seafloor hardgrounds of ancient methane-derived carbonates in the Pacific Northwest. Some non-chemosymbiotic brachiopods also are opportunistic colonizers of seep-carbonate hardgrounds (e.g., terebratulid *Laqueus* aggregations at some seeps in Monterey Bay, California; Campbell, personal observations), probably to access the increased volume of bacterial suspensate. Therefore, crinoids probably would not seek out seeps for a biochemical or physiological benefit, but rather as indurated substrates or high points upon which an established population could best take advantage of ambient current flow for suspension feeding in areas with a steady particulate food supply.

4.3. Stable isotopic and sedimentologic considerations—shallow or deep zone of methanogenesis?

In order to assess potential origins of the various carbonates preserved at the Mist crinoid locality, as well as to more formally test the methane-derived seafloor hardground hypothesis, we conducted a pilot study to measure carbon and oxygen stable isotopes from representative calcareous units and shelly fossils (10 samples; Table 2). Powdered samples were reacted with orthophosphoric acid for 10 min in a Europa Carbonate Automatic Preparation System

Table 2
Stable carbon and oxygen isotope data for pilot study of Mist carbonates, including description of carbonate type, mineralogy and depositional unit from which samples were collected

Sample number	δ^{13}C‰ (VPDB)	Standard deviation	δ^{18}O‰ (VPDB)	Standard deviation	Description, mineralogy[a]; unit[b]
LAG-1	+8.32	0.05	−7.24	0.04	Micrite of crinoid packstone, HMC[c]; CR
LAG-2	+5.11	0.06	−4.02	0.04	Crinoid columnals in packstone, HMC; CR
LCL-1	+7.09	0.07	−0.24	0.06	Micrite, dolomite; LCL
SM-1	+3.22	0.09	−6.59	0.10	Micrite associated with *Acharax*, HMC; packstone of CR
BA1-1	+4.89	0.05	−4.80	0.04	Micrite, HMC; BB
BA1-2	+9.52	0.06	−7.82	0.01	Spar in vein, HMC; BB
UCL-1	+5.25	0.05	−6.14	0.02	Micrite, HMC; UCL
MCO-1	+5.55	0.04	−6.07	0.00	Micrite, HMC; AC
FL2-1	−17.70	0.07	+0.97	0.06	Micrite in rounded float cobbles, HMC; among LCL and BB
D1	+1.68	0.07	+0.93	0.06	*Dentalium* shell, aragonite; AC micrite

Carbon-13 and oxygen-18 isotope values are presented in delta (δ) notation, normalized, and expressed in per mil (‰), relative to Vienna Peedee belemnite, VPDB (Coplen, 1988, 1994).

[a] X-ray powder diffraction system comprises Philips PW 1130 high voltage generator with Cu anode X-ray tube and Philips PW 1050/25 goniometer fitted with curved graphite crystal monochromator and proportional detector; controlled by Sietronics Sieray 112 stepper motor and control unit. Operating conditions were 40 kV, 20 mA, 2° 2θ/min scanning speed and 0.02°/step size. Diffraction Technology VisXRD and Traces V4 software were used for acquisition/processing of diffractograms, with search/match compared to JCPDS and PCDFWIN databases.

[b] See text for lithological unit descriptions.

[c] High magnesian calcite; samples herein range from 10 to 13 mol.%.

using the individual acid dosing or 'drip' method. The evolved CO_2 product was frozen onto a dedicated cold finger, and water was removed during the reaction by passing the gas through a loop that was maintained at −90 °C. Each CO_2 sample was analysed in a Europa Geo 20-20 mass spectrometer, where gas pressures were balanced and the sample gas was compared to an internal reference gas calibrated daily. External precision for replicate analyses of the reference gas was better than 0.04‰ for both carbon and oxygen. Stable isotope values of $^{13}C_{carbonate}$ and $^{18}O_{carbonate}$ (Table 2) are presented in delta (δ) notation, normalized, and expressed in per mil (‰), relative to Vienna Peedee belemnite (VPDB) (Coplen, 1988, 1994).

Most Mist carbonate samples (Table 2) displayed positive carbon values (δ^{13}C range from +3.22‰ to +9.52‰ VPDB) and negative oxygen values (δ^{18}O range from −7.82‰ to −0.24‰ VPDB). Samples include (1) detrital-rich micrite consisting of high-magnesian calcite or dolomite sampled from the CR packstone, LCL, UCL, AC, and BB; (2) columnals of high-magnesian calcite from the CR packstone; and (3) coarse, yellow-white, high-magnesian calcite spar associated with the BB.

In addition, distinctly different isotopic signatures were obtained from (1) a concretionary float cobble associated with BB that emits a faint fetid odor upon breakage (δ^{13}C −17.70‰ VPDB, δ^{18}O+0.97‰ VPDB) and (2) an aragonitic scaphopod shell (*Dentalium*) from AC (δ^{13}C +1.68‰ VPDB, δ^{18}O +0.93‰ VPDB). The scaphopod carbonate-carbon signal indicates shell secretion in isotopic equilibrium with seawater inorganic carbon, and its δ^{18}O value and unaltered shell mineralogy imply no diagenetic modification (cf. Anderson and Arthur, 1983). The fetid cobbles concentrated among the BB and LCL appear to be typical of marine concretions formed during early burial diagenesis (e.g., Irwin et al., 1977); sedimentary organic matter mineralization there yields carbonate-carbon values ranging from δ^{13}C −15‰ to −35‰ VPDB (Deines, 1980). In seep fields worldwide, similar isotopic values are occasionally reported (reviewed in Campbell et al., 2002, Fig. 16, Table 4) and attributed to mixing of carbon derived from methane and carbon derived from dissolved marine bicarbonate or to carbonate formation by anaerobic oxidation of methane (cf. Aiello et al., 1999, 2001). The oxygen isotopic value of the fetid float cobble is similar to that of the scaphopod shell and suggests formation in low temperatures at the seafloor or in the shallow subsurface.

The remaining carbonates sampled at Mist (Table 2) display negative oxygen isotopic signatures that could have various origins, including advection of burial pore fluids that had elevated temperatures and/or connate fluid sources, input of porewaters with meteoric compositions, gas hydrate formation, or alteration of volcanic ash (cf. Anderson and Arthur, 1983; Veizer, 1983; Land, 1989; Hesse et al., 2004). Given the geologic setting and burial/uplift history of the Keasey Formation, we do not consider meteoric input a plausible explanation for the depletion of carbonate and oxygen at Mist. These low isotopic signals were obtained from a variety of carbonate materials at this locality and could be interpreted as pervasive overprinting of original oxygen isotopic compositions during late diagenesis. However, most fossils with preserved shell at Mist appear to be pristine (e.g., aragonitic scaphopods and nacreous *Acila* bivalves). The siltstones at Mist are no more tuffaceous than many other Oligocene formations in Oregon and Washington, and so devitrification of volcanic glass (cf. Hesse et al., 2004) cannot be the only source of isotopically light oxygen in Mist carbonates. A more plausible explanation for the negative oxygen values is tapping of deep, warm fluids during syndepositional faulting. Such a process was proposed to account for unusually depleted ^{18}O in modern seep-carbonates from the Oregon deformation front (Sample et al., 1993; Sample and Reid, 1998; cf. Campbell et al., 2002, Fig. 16). Furthermore, in Monterey Bay, active canyon formation has exposed at the seafloor some seep-carbonates that have low oxygen values that must have originally developed deeper in the sediment pile (Stakes et al., 1999). Correction of $^{18}O_{carbonate}$ values at Mist for their magnesium content or aragonite mineralogy yields pore fluid temperatures between 30 and 60 °C (J. Greinert, personal communication).

Those Mist carbonates with low oxygen signals also display high carbon values (Table 2) that are unusual compared to most reported seafloor hydrocarbon-seep deposits (cf. Campbell et al., 2002, Fig. 16, Table 4). For example, typical thermogenic or biogenic methane sources range from $\delta^{13}C$ ~ −30‰ to −110‰ VPDB (Deines, 1980; Anderson and Arthur, 1983; Roberts and Aharon, 1994). Isotopic mixing of carbon derived from methane and carbon derived from marine bicarbonate or input of oil fractions may lead to relative ^{13}C enrichment (cf. Deines, 1980; Roberts and Aharon, 1994). However, positive carbonate-carbon values ($\delta^{13}C$ +5‰ to +15‰ VPDB) have been reported from seep and non-seep deep-sea settings and are indicative of cementation by ^{13}C-enriched residual CO_2 produced during archaeal methane formation (in the methanogenesis zone; cf. Irwin et al., 1977; Deines, 1980; Hesse et al., 2004). This process occurs in the subsurface from a few centimeters to hundreds of meters below the seafloor (Mazzullo, 2000; Hesse et al., 2004), where methanogenesis produces residual CO_2 enriched in ^{13}C (cf. Boehme et al., 1996). Dolomite and calcite can form in such organic-rich sediments, in many places co-occurring with pyrite (Mazzullo, 2000).

As outlined above, strongly ^{13}C-enriched carbonate indicates microbial methanogenesis (e.g., Irwin et al., 1977; Budai et al., 2002). We attempted to determine whether methanogenesis occurred at Mist at or near the seafloor (shallow, early diagenesis) or in a deeper portion of the sedimentary pile (deep, late diagenesis). Based on our assessment of sources for negative ^{18}O values (above), this signal at Mist most likely suggests elevated fluid temperatures during burial (late) diagenesis and/or input of deep fluids distinct from seawater compositions (Campbell et al., 2002, and references therein). However, the unusual stable isotope signatures (depleted in ^{18}O, enriched in ^{13}C) at Mist are less likely to be a late diagenetic feature because erosional structures are absent that might be indicative of major exhumation. Moreover, late diagenetic cementation of the shelly material is not a favored interpretation because molluscan shell-oxygen isotopic values have not been overprinted, and shell dissolution features are lacking. Hence, we are left with an explanation for the isotope results of unusually shallow methanogenesis.

If the methanogenesis zone at Mist was near the sediment–water interface, reduced organic compounds had to be available and sulfate reduction would have occurred in a thinned zone in the shallow subsurface (cf. Mazzullo, 2000; Hesse et al., 2004). Subbottom seepage could produce such an effect as long as subsurface migration pathways could advect methane upward (Hesse et al., 2004). In the Mist area, syndepositional faulting during the Early Oligocene charged structural traps with natural gas from a source in the underlying Clark and Wilson Sand of the Eocene Cowlitz Formation (Niem et al., 1994). A prominent, uncemented sandstone dike is present at Mist (Fig. 5B), which resembles the fossil fluid-conduit features reported from Paleocene seep systems of Panoche Hills, California (cf. Schwartz et al., 2003). These sandstone dikes (>20 km in extent) are also uncemented. Stratigraphic, sedimentologic, paleontologic, and isotopic relations indicate that these dikes were fluid plumbing features, that fed seafloor methane-seeps sensu stricto (Schwartz et al., 2003). Hence, dikes and/or faults are likely fluid migration conduits at Mist, and could have delivered methane episodically to near-surface sediments. Minor current winnowing of these silts then could have concentrated crinoid debris and exposed indurated layers for crinoid/coral occupation. Subsequent burial and rapid development of methanogenic carbonate in the shallow subsurface may have preserved their remains as Lagerstätte units. Gaillard et al. (1992) reported an echinoid-seep relationship in Jurassic carbonate deposits formed in subbottom, fine-grained siliciclastic sediments from Beauvoisin, France. In these strata, $\delta^{13}C_{carbonate}$ values values as high as +15‰ VPDB were measured, similar to those at Mist, and were inferred to be sourced from methanogenesis (Gaillard et al., 1992; cf. Whiticar et al., 1986). A sparse fauna of irregular echinoids (*Tithonia*) and lucinid bivalves together with $^{18}O_{carbonate}$ enrichment (Gaillard et al., 1992; Peckmann et al., 1999) indicate that these Middle Oxfordian carbonates formed close to the seafloor. Gaillard et al. (1992) suggested the term 'pseudobioherm' to indicate their early diagenetic development *within* Beauvoisin sediments (i.e., they are also seep-carbonates sensu lato). Finally, spatial links between methanogenesis and seafloor methane seepage have been established for other Cenozoic seep limestones from the Olympic Peninsula, Washington; the limestones contain late carbonate phases that formed during methanogenesis (Peckmann et al., 2002).

Further geochemical study of the Mist carbonates is warranted. Because fluids can migrate through sedimentary piles during all phases of diagenesis, it is essential to establish criteria for recognition of temporal–spatial relations between seafloor communities and carbonate cementation in general and in seep fields in particular (cf. Hesse et al., 2004; Campbell and Nesbitt, in press). Future multi-proxy research on Mist carbonates to better pinpoint such relations should include fluid inclusion analysis, elemental composition studies, and Sr isotope assessment.

5. Conclusions

1. Detailed field studies at the Early Cenozoic crinoid Lagerstätte from Mist have revealed a stratigraphic association between these fossils and carbonate slabs and concretions. This association is virtually unknown in other parts of the faunally depauperate siltstones of the Late Eocene to Early Oligocene Keasey Formation. Moreover, crinoid Lagerstätten are extremely rare in Cenozoic strata worldwide.
2. The Mist locality is famous for its articulated crinoid, seastar, and echinoid remains, but it also preserves a diverse fauna of coral, bivalves, gastropods, scaphopods, leaf fossils, radiolarians, and Foraminifera, many in a pristine taphonomic and mineralogic state. In addition, seep-related taxa including thyasirid and solemyid bivalves, are present in low abundances.
3. Paleoecologic and taphonomic analyses of Mist fossils from museum and other collections, as well as comparison with living isocrinids, suggest a hardground association to explain the concentration of fossil crinoids. Preservation with outstretched filtration fans and cirri still clinging to the substrate demonstrates that these crinoids were rapidly buried in situ. The abundance of crinoids, the minor alignment of other fossils, the lack of burrowing echinoids, and the bedding geometry within the Lagerstätte indicate ideal conditions for the crinoids in terms of substrate, current, food flux, and sedimentation rates.
4. Mist carbonates occur as micritic slabs and concretions of high-magnesian calcite or dolomite or as sparry veins, similar to some modern seep-carbonates. However, they are isotopically unusual: most samples exhibit enriched carbonate ^{13}C and depleted ^{18}O. The positive carbonate-carbon signal can be explained by cementation in the zone of methanogenesis, in either shallow (early diagenetic) or deep burial (late diagenetic) conditions. In the

former situation crinoids could utilize indurated slabs exposed on the seafloor for hardgrounds. The latter scenario would temporally separate the living crinoid community from later, deep-burial carbonate development. Negative oxygen isotopic signatures likely imply that warm "burial" fluids reached the seafloor by faults or dikes. Other sources of negative $\delta^{18}O$ include alteration of volcanic ash in sediments, gas hydrate formation, and/or late-diagenetic overprinting of original fossils and sediments. However, our pilot isotope data indicate preservation of unaltered shell material secreted in equilibrium with seawater. Either diagenesis was patchy or methane was delivered episodically to the Mist seafloor from depth to drive shallow methanogenesis.

6. Uncited references

Campbell and Nesbitt, 2004
Nesbitt and Campbell, 2004

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