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**Cover photo:** Pysht Formation strata exposed along the Strait of Juan de Fuca, Washington State. Photo taken by Ruth A. Martin.

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# Cenozoic Marine Formations of Washington and Oregon: an annotated catalogue

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An annotated list of Cenozoic, fossiliferous marine formations from western Oregon and Washington State, U.S.A., and southwestern Vancouver Island, British Columbia, Canada, has been assembled. This chart is a product of the Eastern Pacific Invertebrate Communities of the Cenozoic (EPICC) Thematic Collections Network project that is digitizing over 1.6 million Cenozoic marine invertebrate fossils from the eastern Pacific margin (Alaska to Chile) housed in the network's museums. The chart includes formation names currently recognized by *Geolex*, the U.S. Geological Survey's National Geologic Map Database. Also included on the chart are prior names, original authors, biozonations, ages from the International Chronostratigraphic Chart (ICC), and references for the most recent age calls.

***Keywords:*** Cenozoic formations, marine fossiliferous, EPICC, biostratigraphic correlations, Oregon, Washington, Vancouver Island

## INTRODUCTION

Presented here is an annotated list of Cenozoic fossiliferous marine formations from western Oregon and Washington states and southwestern Vancouver Island, British Columbia. The chart of 70 formations was assembled for the Eastern Pacific Invertebrate Communities of the Cenozoic (EPICC) project (http://epicc.berkeley.edu/), funded through the National Science Foundation program, "Advancing the Digitization of Biological Collections (ADBC) Thematic Collections Network (TCN)." The EPICC project is currently digitizing over 1.6 million Cenozoic marine macroinvertebrate fossils from the eastern Pacific margin (Alaska to Chile) that are housed in the TCN's nine participant museums. Shelled mollusks make up the bulk of these invertebrate taxa, but echinoderms, brachiopods, corals, bryozoans, decapod crustaceans and barnacles are also included. The chart (Table 1) cites those formations recognized by the U.S. Geological Survey National Geologic Map Database (*Geolex*), the ages of the formations as Epochs, the International Chronostratigraphic Chart (ICC) Stages and, where possible, West Coast benthic foraminiferal stages. Molluscan biozonal schemes, discussed below, have not been included in Table 1 because they are geographically restricted and often facies-dependent. The most recent compilation of stages was published by Prothero (2001). References to age assignments are based on the most recent literature on macro- and microfossil data as noted in Table 1 for each stratigraphic unit.

Fossils were first reported from the Pacific Northwest by the United States Exploring Expedition, led by Lieutenant Charles Wilkes in 1841. Fossiliferous rocks in western Oregon and Washington were named and mapped by U.S Geological Survey (USGS) geologists in their quest for economically viable coalfields. Reports of these rocks, mapped by W. G. Dall, J. S. Diller and B. Willis were recorded in the USGS Eighteenth and Nineteenth Annual Reports (Walcott 1898a, 1898b). Arnold and Hannibal (1913) published a survey of Cenozoic formations from southern Vancouver Island to southern Oregon that contained marine fossils, with maps and cross sections. They divided the sequences into two, essentially biostratigraphic series, the older Tejon Series named after middle Eocene fossiliferous rocks in southern California, and younger Astoria Series that included Oligocene formations, overlain by the Miocene Monterey and Empire formations. Although not explicitly stated, they correlated fossiliferous units along the entire

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western U.S. margin. Schenck (1927) pointed out the misunderstandings that occurred when names and type localities were not correctly designated. In most early studies, Cenozoic marine units of western Washington and Oregon were mapped and named on their associated fossils. This is not surprising given the complexity of this tectonically active margin with extensive forest cover. Walking out beds or tracing sequential stratigraphy in outcrops was not possible in the majority of localities. In the 1930s the U.S. National Research Council directed members of the Geological Society of America to establish a series of stratigraphic correlation charts of Phanerozoic sedimentary formations in North America (Dunbar et al. 1942). At least 70 geologists and paleontologists were involved in this endeavor. These charts (some confined to a single period, some to a geographic area) were based on the stated protocol defined by Ashley et al. (1933), under the title *Classification and Nomenclature of Rock Units,* that the "most important modern document in American stratigraphy is a codification of good usage in matters of classification and stratigraphic nomenclature."

The first comprehensive stratigraphic chart and correlation of marine Cenozoic formations of western North America was published under the direction of Charles E. Weaver (Weaver et al. 1944), who was the first academic paleontologist at the University of Washington. Weaver worked with 21 collaborators, some of the most prominent paleontologists on the West Coast in the mid-twentieth century. This publication included Cenozoic marine formations that cropped out along the eastern Pacific margin from Baja California, Mexico, California, Oregon, Washington, and southern Vancouver Island, British Columbia. Weaver et al. (1944) stressed that the compilation of this chart involved two schools of thought: one based in macroinvertebrate fossil assemblages and one based on benthic foraminifera. This is because stratigraphically useful taxa are usually facies-related: the assemblage composition if invertebrate taxa changes with depth and they are much more common in subtidal and neritic depths (e.g., Hickman 1984) and benthic foraminifera are more commonly found from the shelf-slope break to bathyal depths (e.g., McDougal 1980). A further problem arose in attempting to correlate the formations into the current "standard sections" of Europe that became progressively less feasible after the warm global climate (greenhouse times) of the Eocene, and at higher latitudes. Weaver et al. (1944) emphasized that this West Coast correlation chart was established on the basis of local criteria and not attached to the European stage names and their stratigraphy.

The chart presented here (Table 1) includes the name of each Cenozoic marine fossiliferous unit in western Oregon and Washington that is included in the USGS lexicon of geological names for the United States (https://ngmdb.usgs.gov/Geolex/stratres/lexicons). Names for the Cenozoic marine units of Vancouver Island, British Columbia, are included as they are northern extensions of the same rock units found in Washington State. Also included are a few units that have been described in publications but not recognized by *Geolex*, as well as fossiliferous Pleistocene terraces because these are important geologic units for the EPICC project. The chart differs from the Macrostrat (https://macrostrat.org/) entries for these states and provinces, because this system is more inclusive with non-marine units and unofficial (unpublished) stratigraphic names.

There is a growing literature on formation names and descriptions that are not included within the USGS lexicon because they did not meet the combined standards of the Survey and the Association of American State Geologists schema (NCGMP09, 2016). Some of these are in unpublished theses and dissertations; some are on maps but are not described, and some are in state geological survey literature. Beaulieu (1971) listed, with short descriptions, all the formations of western Oregon, west of 121° 30' longitude using published and unpublished reports. Herein, Table 1 also includes prior names used for each formation, member and group names if applicable, with the author(s) and references to the original description. Ages of the units are based on the most recent publications, and notes indicate the sources of these age calls. Each unit is tied to Cenozoic Stages of the International Chronostratigraphic Chart where possible following Gradstein et al. (2012).

## HISTORY OF BIOSTRATIGRAPHIC ZONES

The oldest fossiliferous units in this region are part of the Umpqua Group, first described as the Umpqua Formation by Diller (1898) and are early Eocene in age. Later Baldwin (1974) and Thoms (1975) divided the Umpqua Group into formations and correlated the molluscan fossils with faunas from the Meganos and Capay formations in central California. Many early descriptions of fossiliferous units in the Pacific Northwest used names from fossiliferous California formations, for example the name Tejon for all middle Eocene formations and their faunas, leaving a confusing legacy. There was no difficulty in correlating Pacific Northwest early and middle Eocene fossils with those from California because of the extremely wide tropical and subtropical latitudinal zonation during the early Paleogene. However, as global temperatures dropped in the Oligocene, and latitudinal biozones shrank, it is more difficult to correlate Pacific Northwest faunas with those from California. Weaver (1916), in the first comprehensive description of Cenozoic marine faunas from western Washington, proposed three biozones for the Oligocene based on fossils from the Lincoln Creek and Blakeley formations: in stratigraphic order, the *Molopophorus lincolnensis* zone, *Turritella porterensis* zone, and *Acila gettysburgensis* zone. A definitive, three-part volume by Weaver (1943) described all the invertebrate fossil species known at that time from Washington and Oregon, and this text is still the most useful document for fossil identification. Schenck (1936) proposed three Oligocene biozones for Oregon and Washington based on species of the bivalve genus *Acila:* in stratigraphic order, the *A. nehalemensis, A. shumardi,* and *A. gettysburgensis* biozones.

Durham (1944) published a biostratigraphic scheme of six molluscan zones based on fossils from Oligocene rocks exposed in western Washington. His definitions followed Schenck's (1936) directive that each zone is best defined when both the next oldest and next younger faunas are known and when they contain related species. However, Durham (1944) correctly pointed out that this is the ideal condition and variations in sediment type and depositional environments affect the faunal associations. These six biostratigraphic zones (all placed in the Oligocene) were named after prominent gastropods in the assemblage and correlated with Weaver's (1937) formation names, from oldest to youngest: *Turcicula* (now *Bathybembix*) *columbiana* ("Keasey" stage), *Molopophous stephensoni, M. gabbi, Turritella porterensis*, (all within the "Lincoln" Stage), *Echinophora (*now *Liracassis) rex,* and the youngest *E. apta* zone ("Blakeley" stage). Weaver et al. (1944) used these units to define molluscan stages, but named them after lithostratigraphic units (formations) where they are best represented.

Armentrout (1975) proposed two molluscan stages based on taxa from the Lincoln Creek Formation, southwestern Washington: the latest Eocene Galvinian Stage and the early Oligocene Matlockian Stage. This stratigraphic system included biozones with designated type sections within the Lincoln Creek Formation and one in the Keasey Formation, Oregon. The Galvinian Stage was divided into lower *Bathybembix columbiana* zone, the *Liracassis dalli* zone and upper, *Liracassis fax* zone. The Matlockian Stage that was divided into the lower *Liracassis rex* zone and upper *Liracassis apta* zone. Armentrout (1975) correltated the molluscan Galvian and Matlockian stages wth the benthic foraminiferal Refugian Stage and lower Zemorian Stage respectively. All these molluscan zones have persisted in the literature in various forms and iterations.

Addicott (1976a, 1981) proposed and later modified six molluscan stages for Oregon and Washington to extend Armentrout's scheme to younger rocks of the lower Miocene through the Pliocene. Addicott (1981) restricted the Matlockian Stage to the early Oligocene and proposed the Juanian Stage for the late Oligocene, to avoid overlapping schemes. He proposed three Miocene stages, Pillarian, Newportian, and Wishkahan stages, largely represented by the presence of giant pectinid index taxa *Vertipecten fucanus*, *Patinopecten propatulus,* and *P. oregonensis* respectively. The Pillarian Stage was based on fossils from the Clallam Formation, Washington, the Newportian Stage on the Astoria Formation assemblages found around Newport, central Oregon, and the Wiskhanan Stage on the Empire Formation of Oregon and Montesano Formation of Washington. Armentrout (1981) summarized the known biostratigraphic zonal schemes to update Weaver et al. (1944) and greatly expanded it to tie boundaries with known radiometric dates, diatom and coccolith age calls and megafloral zonations. Moore and Addicott (1987) refined the Neogene chronostratigraphic nomenclature and correlated the stages with both molluscan and benthic foraminiferal stages in California: the Pillarian Stage equivalent to the late "Vaqueros" California molluscan stage, Newportian Stage to the "Temblor" California molluscan stage, and Wishkahan Stage to the "Margaritan" California molluscan stage.

There are very few reliable radiometric dates from fossiliferous marine formations in the Pacific Northwest on which to tether these biozones. Most age assignments in this region are based on benthic foraminifera because these are the most commonly published data for these units. These foraminiferal biozones (Table1) were all based on California benthic foraminiferal zones (Laiming 1940, Mallory 1959, Kleinpell 1938, Kleinpell 1980, McDougall 2008). Rau (1981) proposed foraminiferal zones that he correlated with the California scheme, particularly after the Eocene-Oligocene boundary. McDougall (1980) demonstrated that in Oregon and Washington the Paleocene, benthic foraminiferal zones are facies-dependent and that some stages are coeval. This is partially the result of depositional basins filling up and the fauna changing from deep water taxa to shallow water assemblages through time. In addition, comparison with the type California stages, those in the Pacific Northwest are time-transgressive (McDougall 1980). This is critical for the overlapping early Eocene Penutian and Ulatisian stages and for the Narizian and Refugian stages across the late Eocene and early Oligocene. The Eocene-Oligocene boundary is well represented in marine sections of Oregon, Washington and southwestern Vancouver Island. However, the Oligocene-Miocene boundary in Washington is difficult to pinpoint because of faunal provinciality and high morphologic variability in index taxa (Nesbitt et al. 2010). Tectonic activity along this eastern Pacific margin through the Cenozoic has resulted in very few continuous stratigraphic sections exposed for study today. Uplift and erosion here can best be described by Ager's (1973) general comment that "the stratigraphic record is a lot of holes tied together with sediment" (more gaps than record). Older stratigraphic schemes always incorrectly extended each biozone to cover the entire time between those above and below.

This was addressed by a series of studies, led by Donald Prothero, to obtain paleo-magnetostratigraphic signatures from some of these outcrops with key biozones. The first study pinpointed the Eocene/Oligocene boundary within the Lincoln Creek Formation (Prothero and Armentrout 1985) and investigations into many stratigraphic sections were published subsequently (e.g., Prothero and Hankins 2000, Prothero et al. 2008, 2009). Interpretation of the paleomagnetic signatures was based on micro- and macrofossil age calls and the studies utilized recent revisions of paleontological data for each rock unit. Difficulties with both molluscan and benthic foraminiferal zones in this region of the eastern Pacific margin are apparent. The lack of long stratigraphic sections, forest cover, and tectonic overprinting limits many of these studies. Additionally, index taxa used to define some Californian biozones do not occur in the northern parts of Washington and on Vancouver Island. Nevertheless, the use of Californian benthic foraminiferal stages has persisted. The results from these magnetostratigraphic studies did illustrate facies controls, the extensive temporal gap in some places, as well as temporal overlap in others. Most notably, the Wishkahan Stage is younger in Oregon (Empire Formation) than in Washington (Montesano Formation) and overlaps the Graysian Stage, originally designated as the next youngest stage (Prothero et al. 2001a), and that they were deposited in different water depths. In the stratigraphic chart (Table 1) presented here, the benthic foraminiferal biozones are noted for most of the formations, because they have proven more useful in correlation with other microfossil zonation systems and paleomagnetic data.

The most recent advance to obtaining numerical ages for Cenozoic rocks was compiled by Wells et al. (2014) and consists of new radiometric dates from the Siletzia large igneous province (Siletz River Volcanics, basalts of the Crescent Formation and the Metchosin igneous complex) and numerous intrusive units, e.g., Tillamook, Grays River, Yatchets, and Cascade Head volcanics. This Siletzia time-rock diagram extending from Vancouver Island, southern British Columbia, to the Roseburg area, southern Oregon, was placed onto the global timescale (Polarity Chrons and CP Zones) of Gradstein et al. (2012). These provide a stratigraphic framework for the marine sedimentary units where they intersect. This time-rock diagram was utilized for assigning ICC stages to the chart presented herein.

## COLD METHANE SEEP DEPOSITS

The distinctive depositional setting of cold methane seep sites are preserved in numerous marine Eocene though Pliocene formations in the Pacific Northwest. These are unique, calcite deposits within voluminous siliciclastics, and are characterized by a distinct assemblage of invertebrate taxa that inhabited methane-rich, oxygen-poor benthic environments. Seep fauna have been recorded from the Humptulips, Lincoln Creek, Keasey, Makah, Pysht, Blakeley, Astoria, Quinault, and Sooke formations (e.g., Goedert and Squires 1990, Squires and Goedert 1991, Campbell 1992, Goedert et al. 2003, Keil and Goedert 2007, Martin et al. 2007, Nesbitt et al. 2013, Hickman 2015). All the discrete seep sites are small and geographically restricted, consisting of cemented calcium carbonate blocks, lenses and chimneys, or are diffusely scattered nodules through sediment strata. Authigenic deposition of calcite, and subsequent silicification of the fossils, results in exceptional preservation of mollusks and the unusual preservation of more rare groups such as sponges, solitary corals and tube worms. Invertebrate taxa from areas of seepage are usually restricted to these benthic environments and are not normally useful for biostratigraphic correlations. Many seep sites have also yielded vertebrate fossils including early cetaceans, pinnipeds, desmostylids, "beach bear" (*Kolponomus*), plotopterid and pelagornithid sea birds, sharks and fish.

## ANNOTATIONS TO TABLE 1

Some of the formations listed in Table 1 require further annotation to clarify the history of name changes and age assignments. These formations are presented in time-stratigraphic order because older names have been used, and misused. Each annotated formation is listed with its sequential number from Table 1.

## MIOCENE

***Empire Formation and the Sandstone of Flores, Lake, OR [Table 1: 5, 6, 9]***—Fossiliferous strata that extend from northern Bastendorff Beach to South Slough in Coos Bay and south of Cape Blanco, Oregon were named Empire Formation by Diller (1903). Addicott (1983) applied the informal name Sandstone of Flores Lake to the basal Miocene beds of the Empire Formation south of Cape Blanco because the molluscan fauna are older than those in in the Coos Bay sections. Outcrops of the rocks along the sea-cliffs immediately south of Cape Blanco are structurally complex (Addicott 1983, figure 3) and include three fault-bounded units: a) basal unnamed Eocene sediments, b) Sandstone of Flores Lake, and c) Empire Formation. Thus, the name Empire Formation at this locality is restricted to the upper part of the unit described by Diller (1903). Molluscan fauna for the Sandstone of Flores Lake was correlated with the Newportian Stage (Addicott 1983) based on a similar fauna from the Astoria Formation in Oregon. A single-crystal plagioclase $^{40}$Ar/$^{39}$Ar date of 18.24±0.86 Ma was obtained on the plant-bearing tuff layer near the top of the Flores Lake section (Raymond et al. 2008) placing it within the ICC Burdigalian Stage.

The Empire Formation at Coos Bay, exposed along the edges of South Slough, was assigned to the Miocene by Howe (1922). The molluscan fauna is comparable to that of the Montesano Formation in Washington and formed the basis of the Wishkahan Stage of Addicott (1976a). Barron (1981) assigned the type section of the Empire Formation in Coos Bay to the North Pacific Diatom *Denticulopsis hustedtii* D-zone, Zones X11 through Xa, or middle late Miocene.

***Astoria Formation, OR and WA, and Clallam Formation, WA [Table 1: 8, 38, 39]***—Etherington (1931) gave an early history of fossil collections from rocks near Astoria (Clatsop County) and Newport (Lincoln County), Oregon, and similar fossil taxa collected from Wahkiakum County, southwest Washington and the northern Olympic Peninsula. Macroinvertebrate assemblages from the Clallam Formation, exposed on the northern Olympic Peninsula, Washington, were first recognized by Arnold (1906) and included within the geographically extensive Astoria Formation of Arnold and Hannibal (1913). Some of these original descriptions placed this “Astoria” fauna in the Oligocene, but other authors compared the taxa with Miocene species from Maryland and California.

Moore (1963) and Moore and Addicott (1987) described the middle Miocene Newportian Stage based on the molluscan fauna from the Astoria Formation in the Newport embayment Oregon. The Cape Foulweather Basalt, part of the Frenchman Springs Member of the Columbia River Basalt Group (Snavely et al. 1971, Wells 1989) overlies and interfingers with upper strata of the Astoria Formation. A radiometric date of 15.1 Ma places the upper limit of the Astoria sedimentary units here.

Etherington (1931) designated a reference section for the Washington outcrops of the Astoria Formation along the Clemons logging railroad in Grays Harbor, and pointed out that some authors used the name Clallam Formation for all Miocene fossiliferous horizons in Washington, and Astoria Formation for paleontologically similar Oregon units. He showed that the Astoria Formation molluscan fauna from southern Washington is equivalent to that from Astoria and from Yaquina Bay Oregon, and he considered that all were middle Miocene in age.

Outcrops of the Clallam Formation along the Strait of Juan de Fuca were designated by Addicott (1976a) as the type section of the early Miocene Pillarian Stage and its molluscan fauna was compared with the “Vaqueros” stage of California. Rau (1964) recorded benthic foraminifera from the Clallam Formation that are most similar to those from the lower Saucesian benthic foraminiferal Stage of California of Kleinpell (1938). The Clallam Formation consisting of sandstones and conglomerates conformably overlies the deeper water mudstones and turbidites of the Makah and Pysht formations. Coal seams at the top of the Clallam section record shallowing of the mid-Cenozoic marine depositional basin (Weaver 1937, Snavely et al. 1978, Addicott 1976b). Thus, the Pillarian Stage is defined by shallow-water molluscan taxa. Structural complexity of the Clallam and underlying Pysht formations that are exposed on the north side of the Olympic uplift and the south limb of the synclinal fold along the Juan de Fuca fault zone obscures the stratigraphic sequential patterns. Folds and numerous faults suggest that some of the sections exposed along the sea-cliffs are repeated (Nesbitt et al. 2010).

## OLIGOCENE

***Nye Mudstone, Yaquina Sandstone, Alsea Formation, OR [Table 1: 12, 13, 14]***—A thick sequence of marine sedimentary rocks (over 3,000 m) crops out along the shores of Yaquina Bay, south of Newport, Lincoln County, Oregon. Snavely et al. (1975 and references therein) mapped these three conformable formations showing their stratigraphic relationship and that of the underlying Nestucca and Yamhill formations. The names Moody Shale (member) and Toledo Formation had been used for parts of the Alsea Formation (Snavely et al. 1975), but detailed mapping showed that these names are no longer valid lithological units. These conformable formations comprise the thickest marine Cenozoic sequential outcrops in the Pacific Northwest (Snavely et al. 1969,

**Table 1.** Cenozoic, fossiliferous, marine formations of Oregon, Washington State and Vancouver Island, British Columbia Province, with authors and biostratigraphic ages and stages. UWBM is University of Washington Burke Museum.

| | Geolex Name | State / Province | Other names used in literature | First published description & redefinitions | Geolex recognized Member and/or Group names | Informal name | Epoch | International Chronostratigraphic age | Correlation with California benthic foraminiferal stages | References for age determinations |
|---|---|---|---|---|---|---|---|---|---|---|
| | **OREGON** | | | | | | | | | |
| **1** | Pleistocene terraces at Cape Blanco | OR | | Addicott (1964) | | No offical name | Late Pleistocene | | | Addicott (1964) mollusks |
| **2** | Coquille Formation | OR | Whiskey Run Terrace | Baldwin (1945) | | | Pleistocene | | | Baldwin (1945) on geologic structure |
| **3** | Elk River Formation | OR | | Diller (1902), Baldwin (1945) | | | Pliocene-Pleistocene | Zanclean-Piacenzian | | Addicott (1964) mollusks |
| **4** | Port Orford Formation | OR | | Baldwin (1945) | | | Pliocene | Zanclean-Piacenzian | | Addicott (1983) mollusks |
| **5** | Empire Formation south of Cape Blanco | OR | | Diller (1896) | Coos Conglomerate | | Pliocene-Miocene | | | Addicott (1983) mollusks |
| **6** | Empire Formation in Coos Bay | OR | Coos Conglomerate | Diller (1903) | | | early-middle Miocene | Serravillian-Tortonian | Mohinian | Barron (1981) North Pacific Diatom *Denticulopsis hustedtii* D-zone |
| **7** | Scappoose Formation | OR | | Warren and Norbisrath (1946) | | | early Miocene | | | Van Atta and Kelty (1985) interfingering with with Frenchmans Springs Member, Columbia River Basalts at Yaquina Head, 15.5 Ma (Barry et al. 2013) |
| **8** | Astoria Formation | OR | Astoria Shales; *Aturia* beds | Dall and Harrison (1892); Etherington (1931) | | | early-middle Miocene | Burdigalian-Langhian | Relizian | Dall (1909) and Moore (1963) mollusks; Wells et al. (1983) radiometric date on overlying Cape Foulweather Basalt at 15.1-15.7 Ma |
| **9** | Sandstone at Flores Lake | OR | | Addicott (1983) | | Informal | early-middle Miocene | Aquitanian-Burdigalian | | Addicott (1983) mollusks; Raymond et al. (2008) radiometric date |
| **10** | Scotts Mills Formation | OR | Butte Creek beds | Miller and Orr (1986) | Marquam Member, Abiqua Member, Crooked Finger Member | | late Oligocene | Chattian | | Miller and Orr (1986) mollusks |
| **11** | Pittsburg Bluff Formation | OR | Pittsburg Bluff Sandstone | Hertlein and Crickmay (1925) | | | Oligocene | Chattian | Zemorrian | Moore (1976) mollusks; D. Bukry in Niem and Niem (1985) calcaeous nannofossils |
| **12** | Nye Mudstone | OR | *Acila* Shales | Smith (1926) | | | Oligocene/ Miocene boundary | Chattian-Aquitanian | Zemorrian/ Saucesian boundary | McKeel and Lipps (1975) and W.A. Berggren in Prothero et al. (2001b) foraminifera |
| **13** | Yaquina Formation | OR | Yaquina Sandstone | Schenck (1927) | | | late Oligocene | Rupelian | Zemorrian | Rau (1975) benthic foraminifera; W.A. Berggren in Prothero et al. (2001b) foraminifera |

**Table 1.** Cenozoic, fossiliferous, marine formations of Oregon, Washington State and Vancouver Island, British Columbia Province, with authors and biostratigraphic ages and stages. UWBM is University of Washington Burke Museum (continued).

| | Geolex Name | State / Province | Other names used in literature | First published description & redefinitions | Geolex recognized Member and/or Group names | Informal name | Epoch | International Chronostratigraphic age | Correlation with California benthic foraminiferal stages | References for age determinations |
|---|---|---|---|---|---|---|---|---|---|---|
| **14** | Alsea Formation | OR | Moody Shale; partially Toledo Formation; Silstone of Alsea | Harrison and Eaton (1920); Snavely et al. (1975) | | | Eocene/ Oligocene boundary | Priabonian-Rupelian | Refugian-Zemorrian | Schenck (1927) mollusks; Snavely et al. (1975) benthic foraminifera; McKeel and Lipps (1975) planktonic foraminifera; Warren and Newell (1980) calcaeous nannofossil zone CP16 |
| **15** | Tunnel Point Formation | OR | Arago beds, Coaledo Formation in part, Tunnel Point Sandstone | Dall (1898) | | | Oligocene | Priabonian-Rupelian | Refugian | Weaver et al. (1944) mollusks; Tipton (1975) benthic foraminifera |
| **16** | Eugene Formation | OR | *Acila* Shales | Schenck (1927) | | | Eocene/ Oligocene boundary | Priabonian-Rupelian | Refugian | Hickman (1969) mollusks; McDougall (1975) benthic foraminifera |
| **17** | Bastendorff Shale | OR | Foraminiferal shales of Arago beds | Diller (1896); Schenck (1927) | | | Eocene/ Oligocene boundary | Priabonian | Refugian | Vokes et al. (1949) and Tipton (1975) benthic foraminifera; McKeel and Lipps (1972, 1975) planktonic foraminifera |
| **18** | Keasey Formation | OR | Keasey Shale | Schenck (1927) | | | late Eocene-early Oligocene | Priabonian-Rupelian | late Narizian-Refugian | Weaver (1937) and Hickman (1980) mollusks; McDougall (1975) benthic foraminifera |
| **19** | Silstone of Oswald West | OR | | Wells et al. (1983) | | Informal | late Eocene - early Miocene | | Refugian-Saucesian | Wells et al. (1983) |
| **20** | Nestucca Formation | OR | | Snavely and Vokes (1949) | | | late Eocene | Bartonian-Priabonian | lateNarizian-Refugian | Snavely and Vokes (1949) mollusks; McDougall (1975) benthic foraminifera; Bukry and Snavely (1988) calcaeous nannofossil zone CP15b |
| **21** | Cowlitz Formation | OR | | Warren et al. (1945) | | | middle Eocene | Bartonian | late Narizian | Warren et al. (1945) and Van Atta (1971) mollusks |
| **22** | Hamlet Formation | OR | | Niem and Niem (1985) | | | middle Eocene | Lutetian-Bartonian | | UWBM unpublished data mollusks; Niem and Niem (1985) calcareous nannofossil zone CP14 |
| **23** | Coaledo Formation | OR | Arago beds, Arago Formation | Diller (1896, 1899); Turner (1938) | Lower, Middle, Upper | | middle Eocene | Bartonian | late Narizian | Turner (1938) mollusks |
| **24** | Spencer Formation | OR | | Turner (1938) | | | middle Eocene | Bartonian | late Narizian | Baldwin et al. (1955); McKeel and Lipps (1975) planktic foraminifera |

**Table 1.** Cenozoic, fossiliferous, marine formations of Oregon, Washington State and Vancouver Island, British Columbia Province, with authors and biostratigraphic ages and stages. UWBM is University of Washington Burke Museum (continued).

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|---|---|---|---|---|---|---|---|---|---|---|
| **25** | Yamhill Formation | OR | Rickreall Limestone Member | Baldwin (1955) | | | middle Eocene | Ypresian-Lutetian | Ulatisian-Narizian | Baldwin et al. (1955) mollusks; Bukry and Snavely (1988) calcaeous nannofossil zones CP13c and CP14a |
| **26** | Bateman Formation | OR | | Baldwin (1974) | | | middle Eocene | | Ulatizian | Baldwin (1974) |
| **27** | Tyee Formation | OR | Pulaski Formation, Tyee Sandstone, Burpee Formation, Lorane Shale Member of Spencer Formation | Diller (1898) | Baughman, Elkton Siltstone, Hubbard Creek, Lorane Shale, Tyee Mountain | | late Paleocene-early Eocene | Ypresian-Lutetian | Ulatizian-Narizian | Thoms (1975) and Miles (1981) benthic foraminifera; Bukry and Snavely (1988) calcaeous nannofossil zone CP12b. |
| **28** | Flournoy Formation | OR | | Baldwin (1974) | Umpqua Group | | early Eocene | Lutetian | Ulatisian | Thoms (1975) mollusks; Miles (1981) planktonic foraminiferal zone P10 and calcaeous nannofossil zones P14-CP12 |
| **29** | Lookingglass Formation | OR | | Baldwin (1974) | Umpqua Group; Bushnell Rock, Olalla Creek and Tenmile members | | early Eocene | Ypresian | Ulatisian/ Penutian | Baldwin (1974) on mollusks; Miles (1981) planktonic foraminifers zone P8. |
| **30** | Roseburg Formation | OR | Umpqua Formation | Baldwin (1974) | Umpqua Group | | early-middle Eocene | Ypresian | Ulatisian/ Penutian | Turner (1938) and Vokes et al. (1951) mollusks equivelent to "Capay" California molluscan stage in California. Miles (1981) planktonic foraminifers Zones P7-8 |
| **31** | Salmon River Formation | OR | | Snavely (1991) | | | early Eocene | Ypresian | | Snavely (1991) mollusks and calcareous nannoplankton zone CP11 |
| **32** | Siletz River Volcanics | OR | Metchosin Volcanics | Snavely and Baldwin (1948) | Kings Valley Siltstone Member | | Eocene | Ypresian | Ulatisian/ Penutian | Snavely and Vokes (1949) benthic foraminifera; D. Bukry in Wells et al. (2014) calcareous nannoplankton zones CP9 and CP11; Wells et al. (2014) radiometric dates, 56-49Ma. |
| | **WASHINGTON STATE** | | | | | | | | | |
| **33** | Pleistocene terraces in Pacific County | WA | | | | No official name | Pleistocene | | | |
| **34** | Puget Sound glacial-marine deposits | WA | | | | No official name | Pleistocene | | | Balzarini (1983) mollusks and benthic foraminifera indicate Everson Interstade, 13,000-11,000 years |

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|---|---|---|---|---|---|---|---|---|---|---|
| **35** | Quillayute Formation | WA | Quileute | Reagan (1909) | | | Pliocene | | | Dall (1922) and UWBM unpublished data, mollusks |
| **36** | Quinault Formation | WA | Quinaielt, Cape Elizabeth beds, Point Granville beds | Arnold (1906) | | | early Pliocene | Zanclean-Piacenzian | Delmontian-Repettian | Arnold (1906) mollusks; Rau (1970) and Campbell and Nesbitt (2000) benthic foraminifera |
| **37** | Montesano Formation | WA | | Weaver (1912) | | | late Miocene | Tortonian | Mohnian-Delmontian | Fowler (1965) and Rau (1981) benthic foraminifera; Barron (1981) diatom assemblage |
| **38** | Astoria Formation | WA | Astoria Shales; Clallam; Wakhiakum; Bald Ridge Unit (Unit III) | Etherington (1931) named the Astoria Fm in Washington State. | | | early Miocene | Burdigalian-Langhian | Relizian | Rau (1948, 1981) benthic foraminifera; Moore (1963) and Moore and Addicott (1987) mollusks |
| **39** | Clallam Formation | WA | Astoria | Arnold (1906) | | | early Miocene | Aquitanian | Saucesian | Weaver (1937) and Addicott (1976a) mollusks; Rau (1964) benthic foraminifera |
| **40** | Lincoln Creek Formation | WA | Lincoln Formation; Knappton beds, Porter Formation; Porter, Galvin, Chehalis beds; Gries Ranch beds | Weaver (1912); Beikman et al. (1967) | | | latest Eocene-early Miocene | Priabonian-Aquitanian | | Rau (1958, 1966) and Beikman et al. (1967) benthic foramnifera; Armentrout (1975) mollusk; Prothero and Armentrout (1985) magnetostratigraphy |
| **41** | Blakeley Formation | WA | Seattle Formation | Weaver (1912, 1937) | Orchard Point and Restoration Point Members | | Oligocene | Chattian | Zemorrian | Arnold (1906) mollusks; Rau (1970) and Campbell and Nesbitt (2000) benthic foraminifera |
| **42** | Marrowstone Shale | WA | Upper Unit of Lyre Formation | Durham (1944) | | | early Oligocene | Rupelian | Refugian | Durham (1944) mollusks; Armentrout and Berta (1977) benthic foraminfera |
| **43** | Quimper Sandstone | WA | | Durham (1942) | | | Eocene/ Oligocene boundary | Priabonian/ Rupelian | Refugian | Durham (1944) mollusks; Armentrout and Berta (1977) benthic foraminfera; Prothero et al. (2009) magnetostratigraphy |
| **44** | Siltstone of Cliff Point | WA | | Wells (1989) | | | late Eocene | | Refugian | Goedert and Squires (1990) mollusks |
| **45** | Pysht Formation | WA | Gettysburg beds; Seattle Formation; Twin River Formation | Snavely et al. (1978) | Twin River Group | | Oligocene | Chattian | Zemorrian | Rau (1964) benthic foraminifera; Nesbitt et al. (2010) foraminifera and mollusks |
| **46** | Makah Formation | WA | Baada Point Member, Carpenter Creek Member, Dtokoah Point Member, Jansen Creek Member, Klachopis Point Member, Third Beach Member | Snavely et al. (1978) | Twin River Group | | Oligocene | Bartonian-Chattian | Narizian-Zemorrian | Snavely et al. (1980) mollusks and benthic foraminifera |

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| **47** | Hoko River Formation | WA | | Snavely et al. (1978) | Twin River Group | | Eocene | | Narizian | Snavely et al. (1978) benthic foraminifera |
| **48** | Gries Ranch Formation | WA | Grecco Ranch beds | Dickerson (1917); Weaver (1937) | | | late Eocene | Priabonian | | Dickerson (1917) and Effinger (1938) mollusks |
| **49** | Silstone on Bolton Peninsula | WA | | Spencer (1983) | | Informal | middle Eocene | | Narizian | Spencer (1983) benthic foraminifera |
| **50** | Townsend Shale | WA | | Durham (1942) | | | middle Eocene | | Narizian | Durham (1942) mollusks; Armentrout and Berta (1977) benthic foraminifera |
| **51** | Toutle Formation | WA | | Roberts (1958) | | | middle Eocene | Priabonian | | Dickerson (1917) and Armentrout (1975) mollusks |
| **52** | Unit A of Wolf & McKee | WA | | Wolfe and McKee (1968) | | Informal | middle Eocene | | late Ulatizian-early Narizian | Rau (unpublished UWBM collections) benthic formanifera |
| **53** | Unit B of Wolf & McKee | WA | | Wolfe and McKee (1968) | | Informal | middle Eocene | | late Ulatizian-early Narizian | Rau in Wolfe and McKee (1968) and Rau (unpublished UWBM collections) benthic foraminifera |
| **54** | Siltstone of Shoalwater Bay | WA | | Wells (1989) | | Informal | middle Eocene | | late Ulatizian-early Narizian | Wells (1989) considered it to be lateral equivalent of Unit B of Wolfe and Mckee (1968) |
| **55** | Siltsone of Skamokawa Creek | WA | | Wells (1989) | | Informal | middle Eocene | Bartonian | Narizian | Wells and Sawlan (2014) benthic foraminifera |
| **56** | Cowlitz Formation | WA | Tejon Formation, Olequah Creek Formation, Chehalis Formation | Weaver (1912); Henriksen (1956); Wells (1981) | | | middle Eocene | Bartonian | Narizian | Weaver (1912, 1937) and Henriksen (1956) mollusks; Irving et al. (1996) raiodmetric dates; Wells and Sawlan (2014) radiometric dates on interfingering Grays River Volcanics |
| **57** | Tukwila Formation | WA | | Waldron (1962) | Puget Group | | middle Eocene | Bartonian | Narizian | Nesbitt (1998) mollusks |
| **58** | Raging River | WA | | Vine (1962) | Puget Group | | middle Eocene | Lutetian-Bartonian | Ulatizian-Narizian | MacNeil in Vine (1962) mollusks; Rau in Vine (1962) benthic foraminifera |
| **59** | Skookumchuck Formation | WA | | Snavely et al. (1951a) | Puget Group | | middle Eocene | Bartonian | Narizian | Rau (1958); Beikman et al. (1967) benthic foraminifera |
| **60** | McIntosh Formation | WA | Tenino Formation, Stillwater Creek Member of Cowlitz Formation | Snavely et al. (1951b); Wells (1981) | Puget Group | | middle Eocene | Lutetian-Bartonian | Ulatizian-Narizian | Snavely et al. (1951b) and Rau (1974) benthic foraminifera; Wells and Sawlan (2014) and Wells et al. (2014) calcareous nannplankton zones CP14a and CP13 |
| **61** | Carbonado Formation | WA | | Willis (1898) | Puget Group | | middle Eocene | | | Bukovic (1975) mollusks |

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|---|---|---|---|---|---|---|---|---|---|---|
| **62** | Aldwell Formation | WA | Boundary Argillite | Brown et al. (1960) | | | middle Eocene | Lutetian-Bartonian | Narizian | Rau (1964) benthic foraminifera; Wells and Sawlan (2014) corrrelated with McIntosh and Yamhill formations to zone CP14a |
| **63** | Lyre Formation | WA | | Weaver (1937); Brown et al. (1956) | | | middle Eocene | Lutetian | Narizian | Rau (1958, 1981) benthic foraminifera |
| **64** | Humptulips Formation | WA | | Rau (1984) | | | middle Eocene | Lutetian | Ulatisian | Rau (1984) benthic foraminifera; Prothero et al. (2001d) planktonic foraminiferal zone P10-11 |
| **65** | Crescent Formation | WA | Metchosin Volcanics | Arnold (1906) | | | early-middle Eocene | Ypresian | Ulatisian | Brown et al. (1960) bentihc foraminifera; Rau in Wells and Sawlans (2014) foraminifera |
| | **VANCOUVER ISLAND** | | | | | | | | | |
| **66** | Fraser lowland glacial-marine deposits | BC | | | | No official name | Late Pleistocene | | | Balzarini (1983) mollusks and benthic foraminifera in Everson Interstade, 13,000-11,000 years |
| **67** | Sooke Formation | BC | | Richardson (1876-1877); Clapp and Cook (1917) | Carmanah Group | | late Oligocene | Chattian | Zemorrian | Clark and Arnold (1923) and Prothero et al. (2008) mollusks |
| **68** | Hesquiat Formation | BC | Carmanah | Jeletsky (1975b) | Carmanah Group | | Oligocene | Rupelian-Chattian | Refugian-Zemorrian | Clapp and Cook (1917) and Jeletzky (1975b) mollusks; Cameron (1980) benthic foraminifera |
| **69** | Escalante Formation | BC | Carmanah | Bancroft (1937) | Carmanah Group | | Eocene/ Oligocene boundary | Bartonain-Priabonaian | Narizian-Refugian | Clapp and Cook (1917) and Jeletzky (1954, 1975a) mollusks; Cameron (1980) benthic foraminifera |
| **70** | Metchosin Volcanics | BC | | Clapp and Cook (1917) | | | late Paleocene-early Eocene | Thanetian-Ypresian | | Wells et al. (2014) stratigraphic correlation with Crecent and Siletz River volcanics |

1975). Planktonic foraminifera from the middle Alsea Formation were referred to the uppermost P17 zone (Warren and Newell 1980), and benthic foraminifera indicate Refugian and Zemorrian stages, however, the critical biozonal boundary is covered in the type section (Rau 1981). These fossil assemblages and their assigned ages in the Pacific Northwest are discussed in Warren and Newell (1980) and in Prothero et al. (2001b). Benthic foraminiferal assemblage from the Yaquina Formation is Zemorrian in age and a Zemorrian/Saucesian age was assigned for the Nye Mudstone (W.A. Berggren and P. Pearson in Prothero et al. 2001b). Vertebrate fauna from the Alsea Formation includes cetaceans, and from the Nye includes shark, turtle, “beach bear” (*Kolponomos*), cetaceans, pinnipeds and pelagornithid birds.

***Blakeley Formation, WA [Table 1: 41]***—The Blakeley Formation was defined by Weaver (1912) and the name was also used for his late Oligocene molluscan biozone (Weaver 1916, Weaver et al. 1944). The type section was designated as outcrops on the wave-cut platform of southeastern Bainbridge Island and adjacent northeastern Kitsap Peninsula. These strata dip steeply and occasionally are overturned as they trace the east-west trending Seattle Fault zone (Blakely et al. 2002). Fulmer (1975) presented a detailed stratigraphic section and divided the formation into sequential members. However, the tectonic effects of the still-active Seattle fault that has generated folds and internally faulting, makes this stratigraphy unreliable. Weaver (1912) considered the Blakeley invertebrate fauna to be lower Miocene in age, and he included within the Blakeley Formation the fossiliferous strata exposed in Seattle (that he called the Seattle Formation), in the Newcastle Hills on the eastside of Lake Washington, and around Cathcart in Snohomish County. The Blakeley was later considered late Oligocene in age (Weaver 1916, Weaver et al. 1944) and the term Seattle Formation was discontinued. A recent mapping program and re-evaluation of the fauna from the Cathcart area, including that from the Fiddlers Bluff methane seep site, indicates that Weaver’s Blakeley beds here are older than those of the type section. They are equivalent to molluscan fossils from the Galvinian Stage of the Lincoln Creek Formation, and are therefore Refugian in age (Allen et al. 2017).

## EOCENE/OLIGOCENE BOUNDARY

The Eocene/Oligocene Epoch boundary, represented by the benthic foraminiferal Refugian/Zemorrian Stage boundary, is present in numerous units but is not easy to pinpoint in outcrops. Prothero and Armentrout (1985) placed the boundary within the lower paleomagnetic reversed polarity Chron C12r. However, in the more recent correlation chart of Vandenberghe et al. (2012) the Eocene/Oligocene boundary is placed within paleomagnetic reversed polarity Chron C13, at the extinction of the planktonic foraminiferal species *Hankenina alabamensis*. In Washington, the boundary was placed within the Lincoln Creek Formation, the Quimper Formations, and the Twin River Group (Prothero and Armentrout 1985, Prothero et al. 2009, Nesbitt et al. 2010). In Oregon, the Refugian/Zemorrian benthic foraminiferal Stage boundary occurs in the Alsea, Bastendorff, Eugene, and Keasey formations (see annotations below). On Vancouver Island, the Refugian Stage is recorded in the Hesquiat Formation (Cameron 1980).

***Lincoln Creek Formation, WA [Table 1: 40]***—Oligocene fossiliferous rocks south of the Olympic Mountains were first described as the Lincoln Formation (Arnold and Hannibal 1913) and numerous sections have been given different names (Table 1). Rocks of the Lincoln Creek Formation cover the largest span of geologic time of any single formation in western Washington, from late Eocene through early Miocene, and fossil faunas have been utilized to establish biozonal schemes. Armentrout (1975, 1981) defined regional molluscan stages and zones based on faunas from the Lincoln Creek Formation, and used these for interpreting the first paleo-magnetostratigraphic study in the area (Prothero and Armentrout 1985). Calcareous nannofossils established that the Refugian benthic foraminiferal Stage is equivalent to the calcareous nannofossil zone NP19-20 (Prothero et al. 2001c, McDougall 2008). On the global ICC stratigraphic Paleogene timescale, this places it within the latest Eocene Priabonian Stage (Vandenberghe et al. 2012).

The youngest $^{40}Ar/^{39}Ar$ dates from the Grays River Volcanics that underlie the Lincoln Creek Formation is 36.64+0.40 Ma and this provides a maximum age for the Lincoln Creek in the Willapa Hills area (Chan et al. 2012, Wells et al. 2014). Macro- and micro-fossiliferous strata within the of the Canyon River and the Satsop River Middle Fork sections of the Lincoln Creek extend the age of this unit to the earliest Miocene, Aquitanian in age (Armentrout 1981, Rau 1981).

An unusually high diversity of silicified invertebrate fauna and rare vertebrates have been collected from methane seep sites on the Washington side of the Columbia River, known as the Knappton locality. Complex geologic structure shows that several different fossiliferous strata occur within both the Lincoln Creek and overlying Astoria formation here (Moore 1984, Goedert and Squires 1993, Squires and Goedert 1994).

***Eugene, Bastendorff and Keasey formations, OR [Table 1: 16, 17, 18]***—The Eocene/Oligocene boundary deposits indicated by the Refugian/Zemorrian boundary (Tipton 1975, McDougall 1975, 1980) and index planktonic foraminiferal taxa (McKeel and Lipps 1975) occur in the Bastendorff and Keasey formations in Oregon. The Bastendorf Shales were named by Schenck (1927) for the fine-grained rocks overlying the Coaledo Formation that yield rich benthic foraminiferal assemblages described by Tipton (1975). The Keasey Formation overlies the Cowlitz Formation in northwestern Oregon and is the depositional equivalent of the lower Lincoln Creek Formation in Washington, across the Columbia River. Invertebrate fauna described by Hickman (e.g., 1980, 2014, 2015) from the Keasey include chemosymbiotic assemblages from methane seep depositional settings. This fauna was the basis for the lower Matlockian molluscan stage (Armentrout 1975, 1981) but is entirely facies-restricted. The fault-bounded Mist Gas Field is situated within Keasey Formation strata and the source of the gas may be the underlying Cowlitz Formation (Meyer and Niem 2002).

The Eugene Formation includes well-preserved molluscan fauna (Hickman 1969) and the strata interfinger with the non-marine, leaf-bearing Fisher Formation. The Eugene Formation includes the Eocene/Oligocene boundary strata. $^{40}$Ar/$^{39}$Ar radiometric dates of 34.85 ±0.2 Ma of the Bond Creek Tuff, preserved within the Eugene and Fisher formations, and 31.86 ±0.82 Ma for the Buck Mountain Tuff near the top of the both formations (Myers et al. 2002, Retallack et al. 2004) constrains these units. The Fisher Formation was defined by Schenk (1927) as the leaf-bearing, non-marine strata and associated tuffs that interfinger with the marine Eugene strata. Thus, the Fisher Formation is not included in Table 1.

***Pysht, Makah and Hoko River formations (Twin River Group) WA [Table 1: 45, 46, 47]***—The history of unit names for the Twin River Formation, and its elevation to Twin River Group is complex and confusing (see Nesbitt et al. 2010). Arnold and Hannibal (1913) described the Twin River fossiliferous locality but did not designate a type area. They considered that these rocks overlie the "Seattle Formation" rocks as part of their "Astoria series". The Twin River Formation was re-mapped numerous times by Brown and Gower (1958), Brown et al. (1960), Gower (1960) and Snavely et al. (1978). The formation comprised three distinct lithologic members that were elevated to formation status: Hoko River, Makah and Pysht formations within the Twin River Group by Snavely et al. (1978). The youngest unit, the Pysht Formation, is rich in macrofossils and almost all the invertebrate specimens in museum collections labeled as "Twin River Formation" are from the Pysht Formation. Outcrops of the Pysht Formation indicated deposition within a diffuse area of methane seeps (Nesbitt et al. 2013), and the fauna is often well preserved because of associated calcium carbonate precipitates. Unusual fossils from the Makah and Pysht outcrops include molluscan-inhabited wood-falls, whale-falls and a diversity of rare cetaceous fossils (e.g., Goedert et al. 2003, Kiel and Goedert 2007, Marx et al. 2015). A revision of benthic foraminiferal and molluscan fauna from the Pysht Formation (Nesbitt et al. 2010) found that index fossils used in prior biozonal definitions were not reliable. Microfossils indicate the Zemorrian Stage (late Oligocene). However, there are some early Miocene taxa, and the Oligocene/Miocene boundary may occur at the top of the Pysht section below the lithological contact with the Clallam Formation. Faunal provincialism does not allow correlation with this boundary, as the definitive foraminiferal index taxa that characterize the Oligocene/Miocene boundary in Californian are not present in northernmost Washington assemblages.

***Sooke, Hesquiat and Escalante formations (Carmanah Group), BC [Table 1: 67, 68, 69]***—Muller et al. (1981) formally defined the Carmanah Group to include the Sooke, Hesquiat and Escalante formations that crop out along the southern and southeastern margins of Vancouver Island. Cameron (1980) and Muller et al. (1981, table 8) note that the name Carmanah Formation has been used for various non-contiguous outcrops of different ages. Based on benthic foraminiferal assemblages, the Escalante Formation spans the Narizian/Refugian boundary and the Hesquiat Formation extended from the Refugian into to Zemorrian. Molluscan fossils are not common but where present are most similar to those from the Lincoln Creek Formation, and the faunal assemblages span the Galvinian, Matlockian and Juanian Stages (Jeletzky 1954, 1975a, 1975b, Cameron 1980).

Southernmost outcrops of the Sooke Formation yield macroinvertebrate fossils that indicate inner neritic to rocky intertidal settings (Clark and Arnold 1923, Prothero et al. 2008) and are conspecific with very shallow water assemblages from Blakeley Formation. Foraminifera are rare in these outcrops but deeper water benthic foraminifera that indicate cold methane seep settings are

Zemorrian in age (Nesbitt et al. 2010).

## MIDDLE EOCENE

***Cowlitz Formation, WA and OR, and Hamlet Formation, OR [Table 1: 56, 21, 22]***—The Cowlitz Formation was first named by Weaver (1912) and his early collections on the Cowlitz River Bend, near Vader, Washington were part of the first Burke Museum collections with reliable and accurate locality data. Weaver et al. (1944) correlated the Cowlitz, Coaledo (Arago Beds) and Spencer Formations with those from the Tejon Formation in southern California. In Oregon and Washington, this biostratigraphic interval has subsequently been named the "Coaledo-Cowlitz" Fauna (Armentrout 1981). Henriksen (1956) remapped the rocks in the eastern Willapa Hills region (Lewis County) and erected four members of the Cowlitz Formation: the type Olequa Creek Member, Stillwater Creek Member and two volcanic units. Wells (1981) redefined the Cowlitz formation, restricting it to the Olequa Creek Member and referred the Stillwater Creek Member to the underlying McIntosh Formation. To the south of the type section in Cowlitz County, Weaver (1912) mapped the Cowlitz Formation along Coal Creek, west of Longview. Most of the abundant fossils from these strata are from marginal marine and rare fresh water deposits and are similar to those from the Stillwater Creek outcrops. Weaver (1937) suggested that the Coal Creek fauna may be older than the type section fauna. However, the molluscan assemblages, and the Narizian benthic foraminiferal fauna from the full-marine facies do not differ across the entire formation. The Narizian Stage covers a long time-span, from 42.7 to 36.8 million years (McDougall 2008) when the region was uniformly warm. Radiometric dates indicate that the type section of the Cowlitz was deposited 38 million years ago (Irving et al. 1996). In addition Grays River Volcanics intruding into the Cowlitz Formation in Washington yielded dates of 39.35 +0.36 and 40.01 ±0.35 Ma (Chan et al. 2012).

The Cowlitz Formation in northwestern Oregon is exposed in the Nehalem Basin, underlying the Keasey Formation. The informal Clark & Wilson Sandstone of the Cowlitz Formation was the natural gas reservoir for the Mist Gas fields within the overlying Keasey Formation (Niem et al. 1994). Warren and Norbisrath (1946) interpreted the contact between these two based on molluscan and benthic foraminiferal faunas. Van Atta (1971) divided the Cowlitz Formation here into two sedimentary members that interfinger with the Goble Volcanic member. Based on lithological evidence Van Atta (1971) originally assigned the mapped upper mudstone unit to the lower Keasey Formation. The Hamlet Formation was described and mapped by Niem and Niem (1985) and both formations underlie and interfinger the Cowlitz strata in the Nehalem Basin. *Geolex* does not recognize the Hamlet Formation, and the molluscan fauna is scarce; however, these strata are distinct and the formation is recognized by the Oregon Department of Geology and Mineral Industries.

***Coaledo Formation, OR [Table 1: 23]***—Diller (1896) first applied the name Arago Beds to a thick section of sedimentary rocks that crop out near Cape Arago and north along the coast to Astoria. In 1899, Diller subdivided the Arago Beds into two units, 1) the coal-bearing beds named the Coaledo Formation, and 2) the overlying marine sandstones and shales he named the Pulaski Formation. This definition of the Coaledo formation included the overlying shales at Bastendorf Beach, and the sandstone at Tunnel Point. Allen and Baldwin (1944) report that the Pulaski Formation name is preoccupied, and that these marine rocks are equivalent to the described Umpqua and Tyee formations. Thus, the name Arago Formation did not apply to any rocks in this area was no longer a valid stratigraphic name for Oregon.

***Tukwila, Raging River, Skookumchuck, McIntosh and Carbonado Formations (Puget Group), WA [Table 1: 57, 58, 59, 60, 61]***—Formations of the Puget Group are largely non-marine and brackish-water deposits, including coal beds that were of economic importance in the early to mid-1900s. The Puget Group was first named by White (1888) for coal deposits along the margins of the Puget Sound lowland. Undifferentiated Puget Group rocks, in the central part of this depositional basin, yield a diverse flora and very limited fauna. Marine strata within the Carbonado, Skookumchuck and Tukwila formations contain invertebrate fauna and benthic foraminifera correlative with those in the Cowlitz Formation. The McIntosh Formation has few fossiliferous units and benthic foraminifera indicate that these rocks are older than Cowlitz Formation, and span the Ulatisian/Narizian boundary (Rau 1981, Armentrout 1981). In the foothills of Mount Rainier, the Carbonado Formation contains scattered fossiliferous marine and brackish water strata that are correlated with both the Cowlitz and the McIntosh formations (Bukovic 1975, University of Washington Burke Museum collections).

***Nye, Yaquina and Alsea Formations, OR [Table 1: 12, 13, 14]***—A thick sequence of marine sedimentary rocks that crop out along the northern edge of Yaquina Bay were assigned to three formations, the Alsea, Yaquina and Nye formations. The Alsea Formation was described by Snavely et al. (1975) from rocks in Alsea Bay that were previously mapped as the Moody Shale, part of the Toledo Formation and the siltstone of Alsea Formation. These deep-water deposits conformably grade into the Yaquina Formation. The benthic foraminifera from the Alsea Formation are Refugian in age (Rau 1975). Schenck (1927) named the Nye Mudstone for the "Acila Shales" and noted the need to designate formation names that are independent of the fossil components of the rocks. Snavely et al. (1975) assigned strata previously called the Toledo Formation to the Nestucca, Alsea, and Yamhill formations.

***Yamhill Formation, OR [Table 1: 25]***—Boggs et al. (1973) studied the Rickreall Limestone unit of the Yamhill Formation and from planktonic foraminifera determined a lower Lutetian age for this member. McWilliams (1973) placed the Rickreall Limestone in the Siletz Volcanic Series of Snavely and Baldwin (1948), but *Geolex* continues to keep it within the Yamhill Formation. Rau (1974) published a rebuttal of McWilliams age data, stating that the foramiferal assemblages from the Yamhill are comparable to the informal Sacchi Beach beds of the McIntosh Formation in Washington, which are uppermost Ulatisian and lowermost Narizian in age. Bukry and Snavely (1988) support this age designation by assigning calcareous nanonplankton from this unit to zones CP13c and CP14a (Lutetian–Bartonian age).

***Flournoy, Lookingglass and Roseburg formations (Umpqua Group) OR [Table 1: 28, 29, 30]***—The Umpqua Group, named as a formation by Diller (1898), yields the oldest Cenozoic marine fossils in the Pacific Northwest, of late early Eocene to early middle Eocene age. Baldwin (1974) divided the rocks into three formations and mapped their geographic extent. Thoms (1975) also noted that there is no evidence of an unconformity between the Lookingglass and Flournoy as interpreted by Baldwin (1974). Thoms (1975) described the molluscan faunas, and included the "Glide Fauna" in the Lookingglass Formation and correlated it with the "Capay" Stage in California, early and middle Eocene in age. Miles (1981) assigned planktonic foraminifera and calcareous nannofossils from Flournoy Formation to Zone P10, Lutetian age, and the Lookingglass Formation to Zones P7/8 and NP12 and CP10, middle Ypresian age. The middle Eocene Tyee Formation lies unconformably on top of the Flournoy Formation. Molenaar (1985) in a study of depositional relationships of these formations rejected Baldwin's (1974) nomenclature and these names. He did not address paleontological resources, and returned all the formations to the Umpqua Formation (with four lithological members) and the Siletz River Volcanics. However, Prothero et al. (2009) used the three formation names of the Umpqua Group, and museum paleontological collections from the Umpqua Group retain the three names. For these reasons, this study adheres to the Baldwin (1974) nomenclature and stratigraphy.

***Siletz River, Crescent and Metchosin volcanics, OR, WA, BC [Table 1: 32, 65, 70]***—These three units comprise the Siletzia Terrane that undies all the Cenozoic units in western Oregon (north of the Klamath terrane), Washington and southernmost Vancouver Island. They are Paleocene and Eocene tholeitic and alkalic basaltic sequences of a large oceanic igneous province that accreted to the North American continent in the Eocene (see Wells et al. 2014 and references therein). Parts of this terrane have been uplifted and exposed in northwestern Oregon and most extensively on the Olympic Peninsula, Washington. Rare marine invertebrate fossils are found within interbedded sedimentary units in the Siletz Volcanics and Crescent Formation. Radiometric dates from basalt flows in the Siletz and Crescent volcanics range from 56 to 49 Ma (Wells et al. 2014). No fossils have been recorded from the Metchosin but this unit is included here as it is the northern extent of the accreted terrane.

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