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Pacific Northwest Tertiary benthic foraminiferal biostratigraphy framework—An overview

by

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Pacific Northwest Tertiary benthic foraminiferal biostratigraphic framework—An overview

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ABSTRACT

The benthic foraminiferal biostratigraphic framework for marine Tertiary strata of the Pacific Northwest, as it has developed over the past 30 years, has been fundamental to geologic mapping by the U.S. Geological Survey and the state of Washington. However, the refinement of foraminiferal zonation in this area varies considerably because foraminiferal faunas sometimes do not differ greatly throughout thick sequences or the available data from certain areas have been limited. Furthermore, correlations are most reliable within local areas because differences in benthic foraminiferal faunas are largely the result of paleoecologic variations through time, as well as over geographic area, rather than evolutionary change.

Studies, beginning in southwest Washington in the late 1940s and continuing into the 1950s, resulted in the initial correlation of Washington's Tertiary sequence with California foraminiferal stages and the establishment of provincial zones. This framework was later extended to the early and middle Tertiary rocks of northwest Washington. Refinements and additions were made in the 1960s in connection with Washington State and U.S. Geological Survey geologic mapping in the Grays Harbor basin. In western Oregon during much of the past 30 years, foraminiferal studies have also been an integral part of U.S. Geological Survey geologic mapping. California stages have been recognized and the local faunal distribution has been informally established. In the 1970s, foraminiferal studies and geologic mapping in several coastal areas of the Olympic Peninsula by both the U.S. Geological Survey and the state of Washington made it possible to present biostratigraphic and paleoecologic interpretations for the Tertiary rocks of that area.

As a result of these studies, eight foraminiferal zones, two informal subdivisions of a stage, and four distinctive assemblages from additional parts of the Pacific Northwest Tertiary sequence have been described. The characteristics of these early Eocene to Pliocene faunal divisions are summarized in this report.

INTRODUCTION

Over the past 30 years, foraminiferal studies have been conducted in conjunction with both U.S. Geological Survey and Washington State geologic mapping and other surveys in the Tertiary province of the Pacific Northwest. During this time geologic mapping has become fundamentally dependent upon foraminiferal biostratigraphy. Few and poorly exposed outcrops, relatively few continuously exposed sections, and substantial thicknesses of massive relatively uniform lithology have all contributed to the need for biostratigraphic control. Much of the foraminiferal data and biostratigraphic interpretations developed from these studies has been presented in various publications through the years. Thus, foraminiferal biostratigraphic concepts evolved from, and were built upon, a number of geologic investigations in different parts of the Pacific Northwest. It therefore seems appropriate to review and synthesize these studies for a better understanding of their contribution to Pacific Northwest foraminiferal biostratigraphy.

Limitations and Nature of Biostratigraphic Units

Because a foraminiferal biostratigraphic framework had already been established in California, early studies in western Washington and Oregon necessarily relied heavily on correlations with California biostratigraphy. However, it was soon recognized that although broad divisions, such as stages of Kleinpell (1938), could be generally recognized in western Washington and Oregon, the faunal characteristics of smaller California units, such as zones, were frequently unrecognizable (Rau, 1958). It therefore became necessary, when practical, to develop

local subdivisions or zones. The extent to which local subdivisions could be defined depended on several considerations. First, the stratigraphic variability of assemblages within a local area had to be considered. In some areas, for example, the Zemorrian Stage of Kleinpell (1938) is readily recognized, but its faunal character varies little throughout hundreds of metres of section. Thus, although it was desirable, in reality it was not practical to define local subdivisions of the stage, even though a substantial amount of data was available. In other areas and/or in parts of the Tertiary sequence, faunal characteristics were found to vary sufficiently so that local subdivisions of stages could be defined. In still other areas only a lower and upper part of a stage could be generally recognized with no finite boundary definable between. Some geologic studies were limited and did not provide extensive collections of foraminiferal material; in those cases only a broad framework, mainly of stages, was locally developed and utilized. For a number of reasons, then, and as is apparent in the following historical review, the refinement of foraminiferal biostratigraphy varies considerably from area to area in western Washington and Oregon.

Benthic foraminifers are relatively abundant and diverse in Tertiary rocks of the Pacific Northwest, whereas planktonic foraminifers are of rare or scattered occurrence; therefore, early uses of foraminifers for stratigraphic purposes were based largely on benthic rather than on planktonic taxa. The successful use of benthic faunas for stratigraphic purposes requires assessing the reality of ecologic control on faunal occurrence. Furthermore, the effects of ecological differences can be and are reflected stratigraphically as well as geographically. Thus, the stratigraphic distribution of benthic foraminifers in local sequences is perhaps far more the result of changing environment through time than it is the result of evolutionary change. The detailed characteristics of a local biostratigraphic unit can be recognized only as widespread as was the paleoenvironment of the geologic time that it represents. If a relatively uniform environment existed over a wide area during a given geologic time, that geologic time may be represented by a characteristic fauna throughout that same geographic area. As geologic time progressed, changes took place in ecologic conditions. Such changes reflect stratigraphic variations in faunas. These differences become the characteristics of local biostratigraphic zones. This concept of "dual environmental variablility" has been recognized in foraminiferal biostratigraphic studies of the Pacific Northwest (Rau, 1964, 1966, 1967, 1970) and is particularly apparent, for example, in the lower and middle Miocene strata of southwest Washington as is discussed in a following section of this report.

REVIEW OF EARLY PUBLICATIONS

Prior to the late 1940s, a few taxonomic reports were published on isolated collections from various rock units of the Northwest Tertiary sequence. Among these are reports by Hanna and Hanna (1924) and by Beck (1943) on the Eocene Cowlitz Formation of Washington Cushman and Frizzell (1943) on the Lincoln Creek Formation of Washington; and in Oregon, Cushman and Schenck (1928) described foraminifera from the Keasey and Bastendorff beds. In the late 1940s Detling (1946) described foraminifera from the lower Tertiary of Coos Bay; Cushman and others (1947, 1949) published on foraminiferal faunas from the Miocene Astoria Formation, Eocene Toledo and Coaledo Formations and Helmick Hills beds of Oregon, and the Pliocene Quinault Formation of Washington. Rau (1948a, 1948b, 1951) described an additional fauna from the Lincoln Creek Formation, a small Miocene assemblage from southwest Washington, and faunas ranging in age from Eocene to Miocene from a Tertiary section exposed in the Willapa Valley of southwest Washington.

FORAMINIFERAL BIOSTRATIGRAPHY, 1950-1979

The Willapa Valley study (Rau, 1951) was an early attempt to describe the foraminifera and to point out faunal differences in several stratigraphic units that occur in a major Pacific Northwest Tertiary sequence. Furthermore, suggested correlations to California stages—the Refugian of Schenck and Kleinpell (1936) and the Zemorrian and Saucesian of Kleinpell (1938)—was an early recognition of these units in the Pacific Northwest.

The first attempt to formally divide a Pacific Northwest Tertiary sequence into biostratigraphic units on the basis of foraminifers developed from U.S. Geological Survey foraminiferal studies and mapping in the Centralia-Chehalis area of southwest Washington (Fig. 1). In the resulting report Rau (in Snavely and others, 1958) defined 10 zones of Eocene and Oligocene age, the details of which are summarized in Figure 2. These divisions were not necessarily intended to be "Oppelian" zones in the strict sense, but rather they were designed to point out significant groups of species that occur in certain segments of local sections. With the exception of the *Cibicides hodgei* Zone, each faunal zone was assigned to a relatively distinct stratigraphic position within the local Tertiary section. The *C. hodgei* Zone is represented by a provincial shallow-water-facies fauna that locally occurs in the basal part of what is known today as the Lincoln Creek Formation (Beikman and others, 1967). Although this zone is in part equivalent to the *Sigmomorphina schencki* Zone, in places it extends higher in the section.

A continuation of geologic mapping by the U.S. Geological Survey both west and southwest from the Centralia-Chehalis area (Pease and Hoover, 1957; Roberts, 1958) prompted additional foraminiferal studies of a much larger area in southwest Washington. Some 13 surface sections and wells served as a base from which eight foraminiferal zones were proposed for the Tertiary strata of southwest Washington (Rau, 1958). Although these zones are fewer in number than those of the local Centralia-Chehalis area, their characteristics were presented in greater detail and correlations were more comprehen-

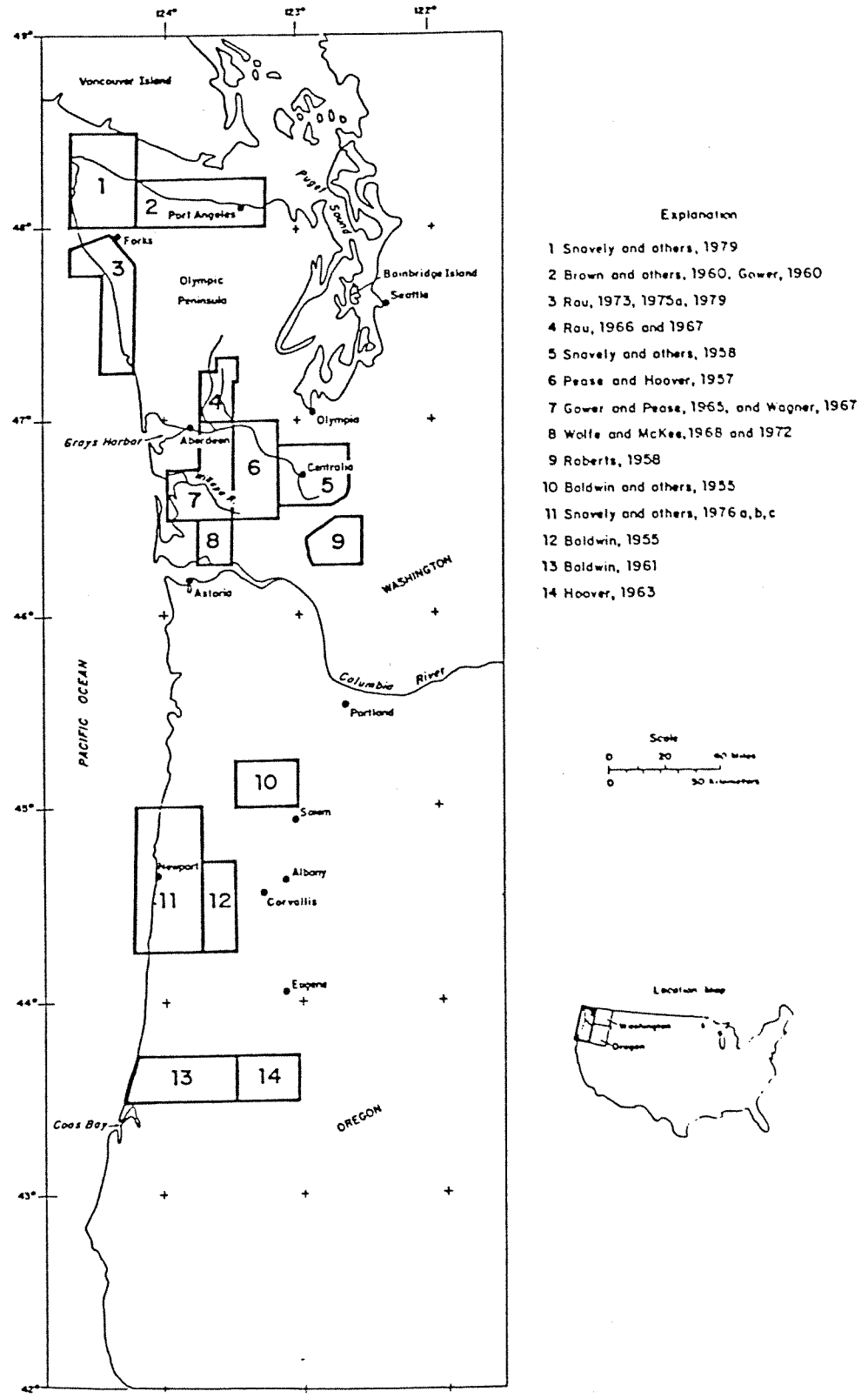


Figure 1. Index map showing areas discussed in this report.

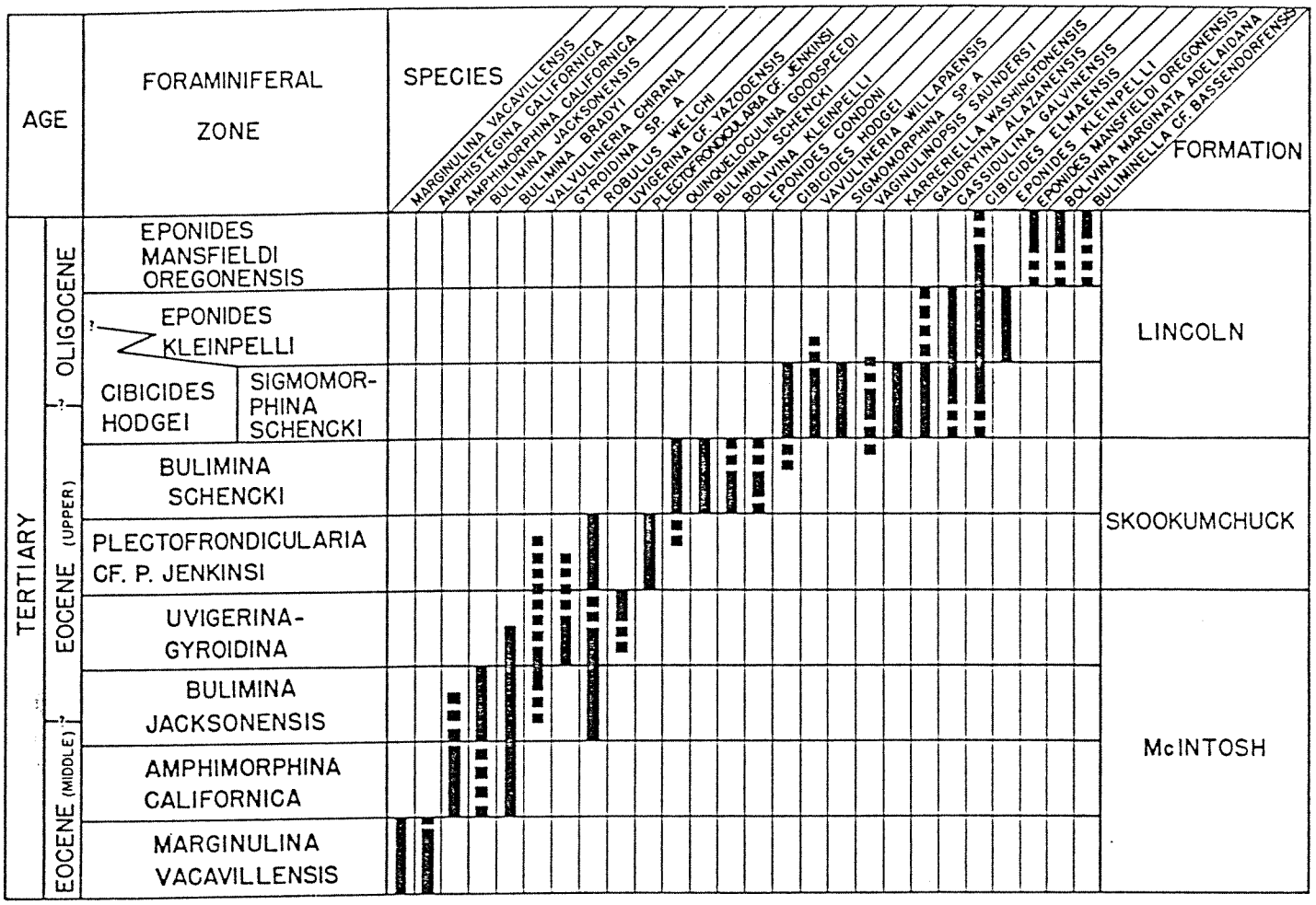


Figure 2. Foraminiferal zones and stratigraphic distribution of significant species in the Tertiary sequence of the Centralia-Chehalis area, southwest Washington, as originally applied in the 1950s. Changes have since been made in zonal concepts, zone names, and taxonomy. See text for discussion.

sive (Fig. 3). Furthermore, they are more nearly "Oppelian" in design because they are of chronologic as well as biostratigraphic significance and were constructed from substantial data from a number of Tertiary sequences over a relatively large area of the Pacific Northwest. Many of the zonal names were perpetuated or modified from usage in the Centralia-Chehalis area. The *Epistominella parva* Zone, broadly including the faunas of Miocene age and primarily representing the Astoria(?) Formation of southwest Washington, was added to the framework. Eocene zones were generally related to Laiming's (1940) Eocene zones of California on the basis of similarities in the stratigraphic occurrence of species. Furthermore, the California Refugian Stage of Schenck and Kleinpell (1936) and the Zemorrian and Saucesian Stages of Kleinpell (1938) were more formally recognized. It was not intended to imply a precise correlation to these stages but rather to point out that faunal sequences occurring in the Tertiary of California, at least to the stage magnitude, could also be recognized in the same chronologic succession in Tertiary strata of western Washington. The 1958 report of Rau constitutes the fundamental framework for benthic foraminiferal biostratigraphy in a major part of the Pacific Northwest Tertiary sequence. Additions and refinements have since been made, particularly in the Neogene, but most of the original zonal names remain the same and only minor conceptual changes have been made.

Geologic mapping in the late 1950s by the U.S. Geological Survey in the northern Olympic Peninsula area of Washington (Brown and others, 1960; Gower, 1960) required further expansion of Pacific Northwest foraminiferal studies to the Tertiary sequence of that area (Fig. 1). Over 40 species significant to correlation were illustrated and described, and correlations were made to the established biostratigraphic framework of southwest Washington, as well as other West Coast areas (Rau, 1964). References to Eocene stages of Mallory (1959) were made for the first time by the U.S. Geological Survey in Pacific Northwest Tertiary strata and were applied not only to the Eocene sequence of the northern Olympic Peninsula but to the Eocene zones of southwest Washington (Fig. 4). Foraminiferal assemblages were referred to stages ranging from the early Eocene Ulatisian Stage of Mallory through the early Miocene Saucesian Stage of Kleinpell. Because the observed stratigraphic range of many taxa varied appreciably from section to section, reliable correlations within

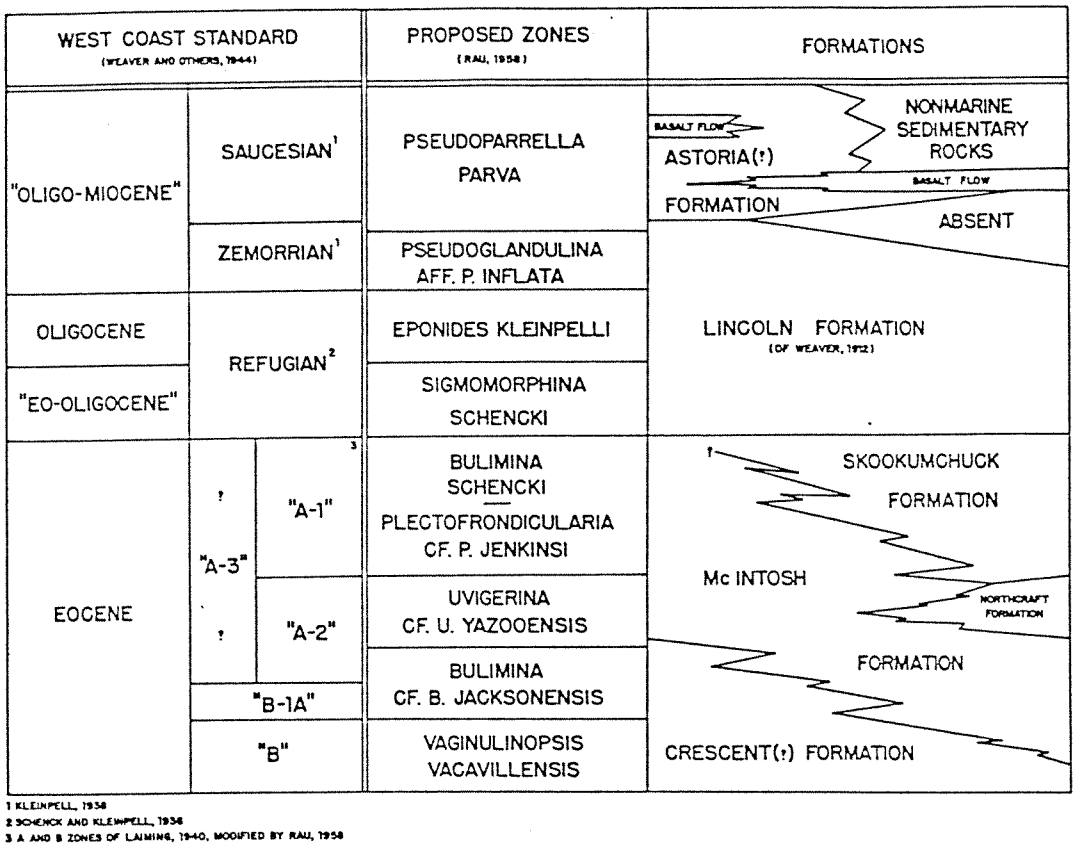


Figure 3. Foraminiferal zones and stratigraphy of southwest Washington as proposed by Rau in 1958. Subsequent changes in zonal nomenclature are discussed in the text.

the study area, as well as to other areas, were limited largely to the stage level of magnitude. The thick Twin River Formation was found to contain assemblages representative of the Narizian, Refugian, and Zemorrian Stages. A twofold division of the latter stage was recognized and informally referred to as "upper" and "lower" Zemorrian. Key taxa for each unit were noted as shown in Figure 5. Due to the growing need for paleoenvironmental analysis, a greater emphasis has been placed on paleoecologic interpretation in this study than in previous works.

Recent studies in the northern Olympic Peninsula have demonstrated that the Saucesian Stage is in part represented in the Twin River Formation (Rau, in Addicott, 1976b). The Zemorrian/Saucesian boundary is within the upper part of the formation and at least 45 m below the top of the molluscan "Blakeley" Stage of Weaver and others (1944) (= Matlockian Stage of Armentrout, 1975).

Geologic mapping and related research in western Oregon by the U.S. Geological Survey during the past 30 years have yielded extensive foraminiferal data, particularly from the Newport embayment (Snavely and others, 1976a, 1976b, 1976c), where foraminiferal studies were an integral part of the mapping project (Fig. 1). Extensive sampling from measured sections along the Yaquina and Siletz Rivers, as well as from sections along the shores of Alsea Bay, provided most of the basic biostratigraphic information concerning foraminiferal occurrences throughout this major Tertiary basin. Several reports were presented dealing with foraminiferal data (Rau, in Snavely and others, 1964, 1969), but the major use of these studies was as a direct aid to geologic mapping. Faunal characteristics of each formation of the local sequence were stressed rather than defining and describing new biostratigraphic zones. Suggested correlations were made to California foraminiferal stages and to some zones (Fig. 6). Rau (1975b) located and defined the Refugian/Zemorrian boundary in the type section of the Alsea Formation at Alsea Bay (Fig. 7) and suggested that faunas of this formation can be correlated to those of his *Cassidulina galvinensis* and *Pseudoglandulina* cf. *P. inflata* Zones of the southwest Washington sequence. Additional foraminiferal studies were made in support of geologic mapping in the Oregon Coast Range and the west side of the Willamette Valley, particularly for projects conducted by Baldwin (1955), Baldwin and others (1955), Baldwin (1961), and Hoover (1963) (see Fig. 1).

In the 1960s Washington State began stratigraphic studies on the northern flank of the Grays Harbor basin, mainly in tributaries of the Wynoochee and Satsop River valleys (Rau, 1966; see Fig. 1). The project was initiated for the purpose of conducting detailed biostratigraphic studies where the Refugian and Zemorrian Stages are well represented in the thick and widespread Lincoln Creek Formation. Modifications and refinements were made

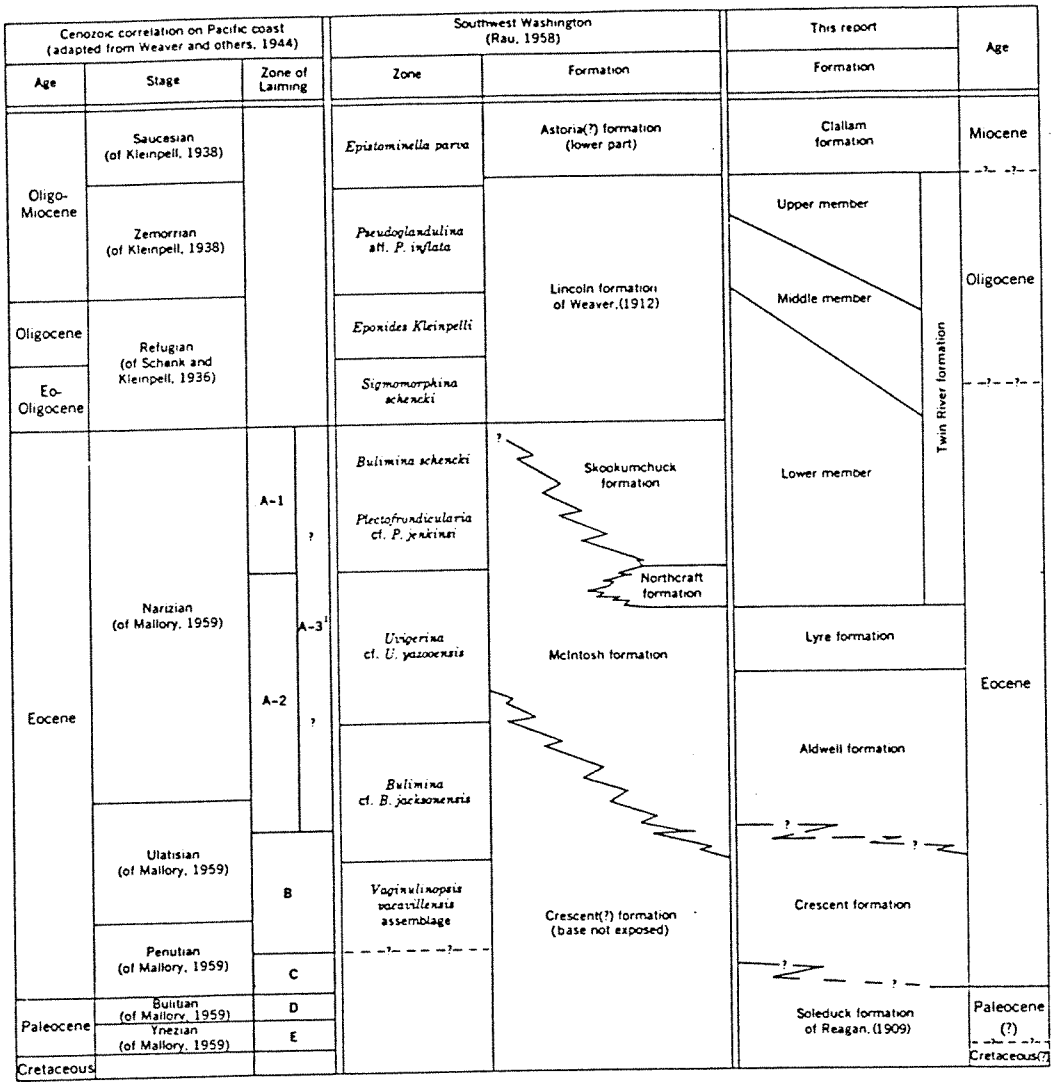


Figure 4. Stratigraphic relations—northern Olympic Peninsula, southwest Washington, and a West Coast standard as proposed by Rau in 1964. Subsequently, the zone name *Eponides kleinpelli* has been changed to *Cassidulina galvinensis*, and the single *Epistominella parva* Zone has been divided into three newly named zones (see text).

especially to faunal definitions for provincial subdivisions of the Refugian and Zemorrian Stages. The previously named *Eponides kleinpelli* Zone (Rau, 1958) of the Refugian Stage was renamed the *Cassidulina galvinensis* Zone because the latter species was found to be more widely distributed (Fig. 8). In addition, a twofold division of the Zemorrian Stage was recognized. These subdivisions were not given formal names, mainly because faunal characteristics are gradational between them without a precise boundary. Concurrent ranges of several long-ranging species not restricted to the Zemorrian Stage characterize these subdivisions. The two parts of the Zemorrian Stage were regarded as general correlatives of two previously recognized subdivisions of the stage in the northern Olympic Peninsula area.

Subsequent geologic mapping southward into the main valleys of the Wynoochee and Satsop Rivers, where large areas of the Miocene Astoria(?) Formation and Montesano Formation are exposed, provided the opportunity to determine the stratigraphic occurrence of Miocene foraminifers of the Grays Harbor basin (Rau, 1967). Three zones, all occurring within rocks of the Astoria(?) Formation and broadly referred to as the *Pseudoparella parva* Zone of Rau (1958) were named and described from bottom to top as the *Siphogenerina kleinpelli* Zone, *Baggina washingtonensis* Zone, and *Rotalia becki* Zone (Fig. 8). It was emplasized that the faunas of the three zones actually reflect differences in depositional environments through time within a given geographic area. The local basin of deposition apparently was deepest during the early part of the Miocene and is represented by the relatively deep-water, perhaps bathyal, faunas of the *Siphogenerina*

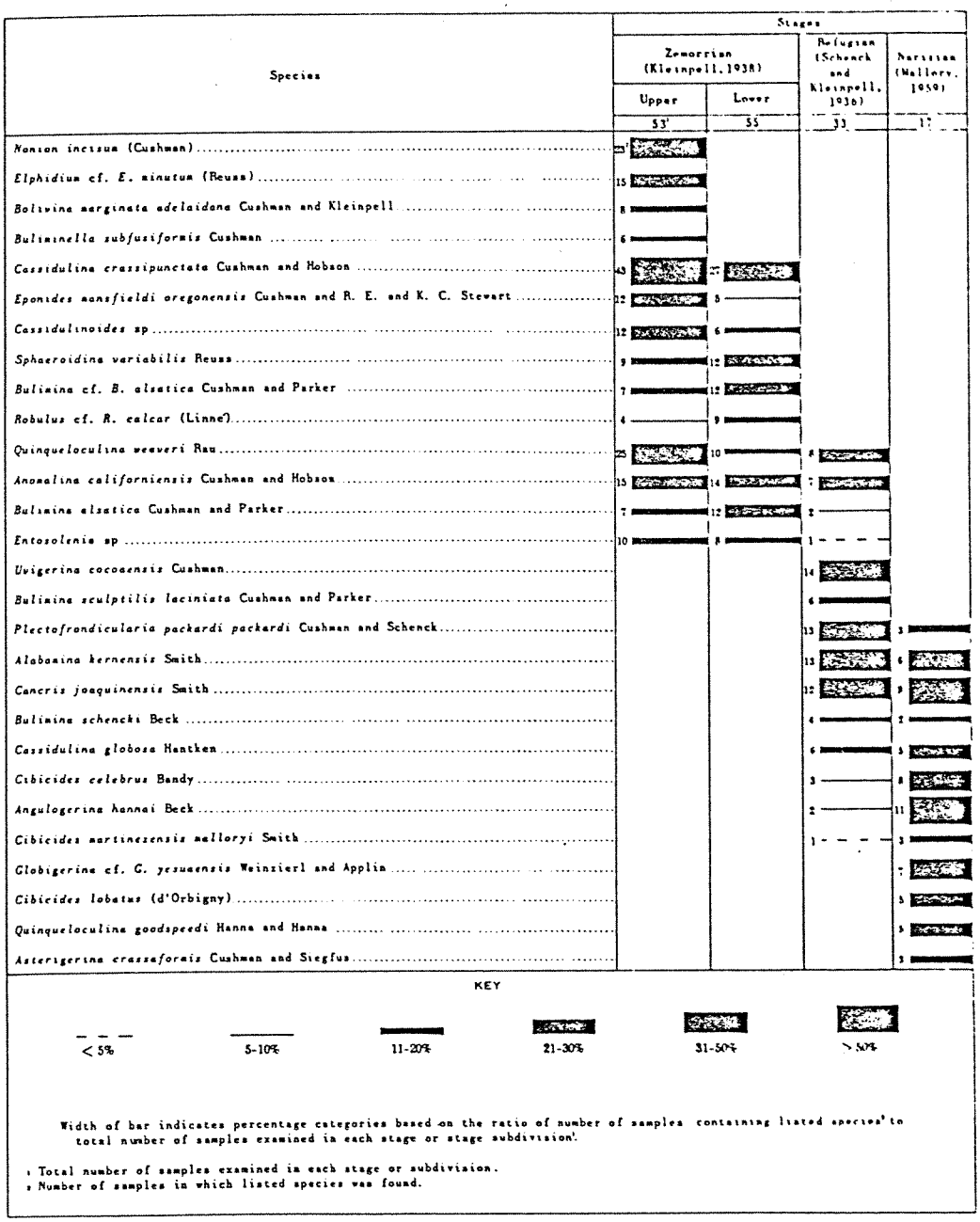


Figure 5. Frequency of occurrence of selected species of foraminifera in the Twin River Formation as presented by Rau in 1964.

kleinpelli Zone. As the basin became shallower, faunal characteristics changed to those of the *Baggina washingtonensis* Zone and eventually to those of the relatively shallow-water shelf faunas of the *Rotalia becki* Zone. Thus, within the basin of deposition for the Astoria(?) Formation, deep-water faunas are essentially restricted to the lowest part, whereas the upper part of the Astoria(?) Formation contains only shallow-water taxa. Even though shallow-water faunas are more widespread in the upper part of the sequence, they are not necessarily confined to the upper part because they presumably existed as basin margin features throughout the depositional cycle.

The *Siphogenerina kleinpelli* Zone was correlated to the lower part of the Saucesian Stage, the *Baggina washingtonensis* Zone to the upper part of the Saucesian Stage and probably the lower part of the Relizian Stage, and the *Rotalia becki* Zone, largely on the basis of superposition, to an upper part of the Relizian Stage and possibly a part of the Luisian Stage.

Foraminifera of the Montesano Formation were collected only from key areas as a means of identifying the formation. No attempt was made to conduct detailed biostratigraphic or paleoecologic studies with foraminifers of these rocks. Foraminifers of the Montesano Formation were broadly referred to the upper Miocene undifferentiated Mohnian and Delmontian Stages of Kleinpell

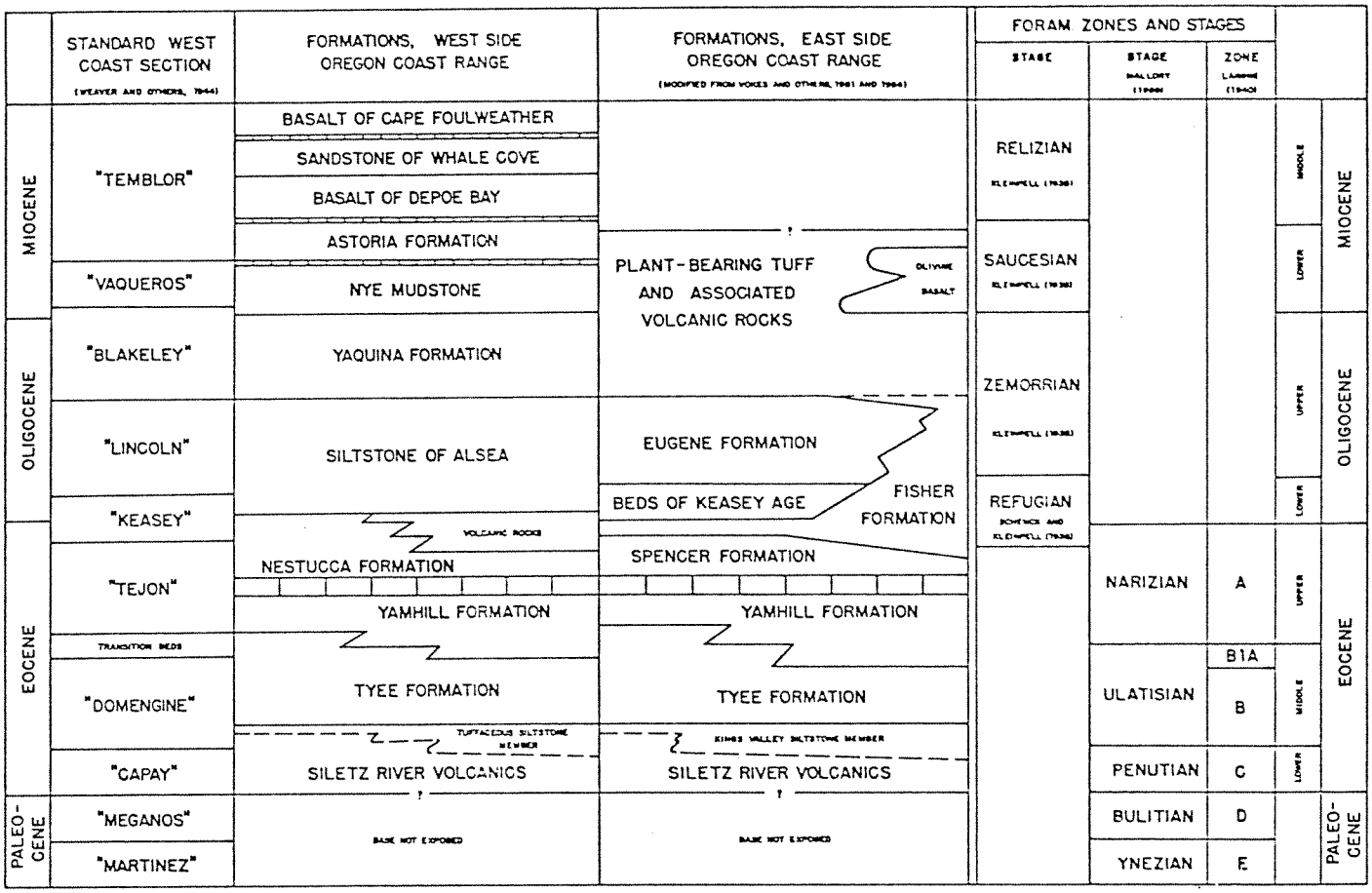


Figure 6. Correlations—west and east sides of Oregon Coast Range (Snavely and others, 1969). The Eocene/Oligocene boundary has been placed variously on the diagrams of the present report with respect to the base of the Refugian Stage of Schenck and Kleinpell (1936). The authors of this diagram considered the Eocene/Oligocene boundary to be with the Refugian Stage at that time.

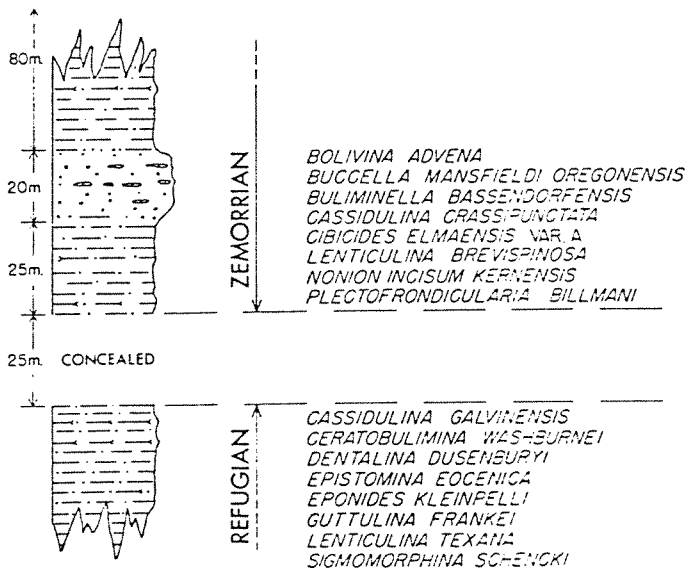


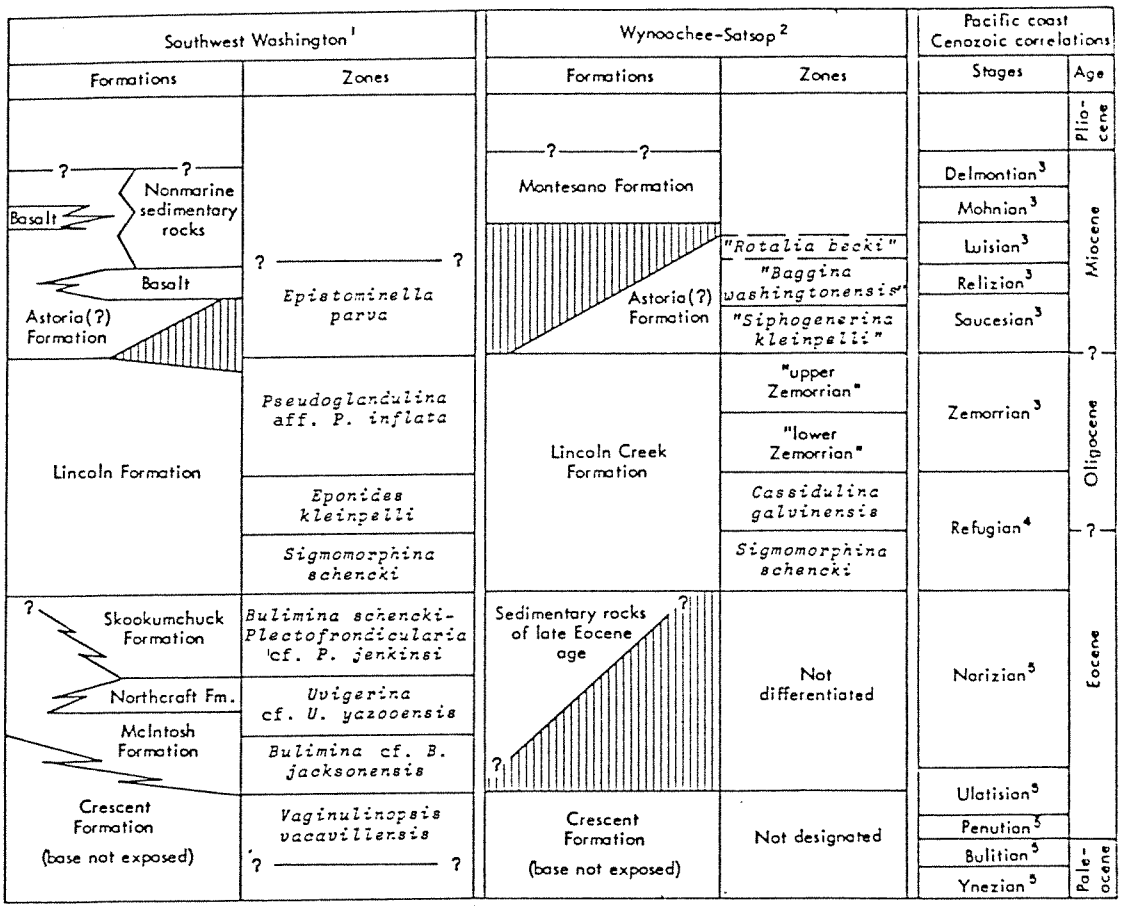
Figure 7. Foraminifera used in recognizing the Refugian/Zemorrian boundary, type section of Alsea Formation, north shore of Alsea Bay, Oregon (Rau, 1975b).

(1938). Fowler (1965) presented considerable detail on the stratigraphic and paleoecologic significance of foraminifers of the Montesano Formation.

Also in the 1960s, cooperative state and federal geologic mapping was conducted in the Grays River area of the extreme southwestern part of Washington (Wolfe and McKee, 1968). This project provided additional foraminiferal information and allowed an extended application of the foraminiferal zonation of southwest Washington (Rau, in Wolfe and McKee, 1972).

Support of U.S. Geological Survey geologic mapping in the western part of the Grays Harbor basin (Gower and Pease, 1965; Wagner, 1967) further extended the foraminiferal biostratigraphy of Washington to this area (see Fig. 1).

Increasing interest in offshore exploration in the late 1960s prompted Washington State to begin stratigraphic studies of the onshore Olympic coastal area. The project began with detailed biostratigraphic studies of the Pliocene Quinault Formation (Rau, 1970) in which four major surface sections were carefully measured, sampled, and described (Fig. 9). Foraminifers from these sections were described and illustrated, and their stratigraphic and paleoecologic significance discussed. Correlations were suggested to other West Coast Pliocene sequences. Formal



[1] Adapted from report by Pease and Hoover, 1957; Snavely and others, 1958; Rau, 1958.

[2] Includes area of report by Rau, 1966.

[3] Of Kleinpell, 1938.

[4] Of Schenck and Kleinpell, 1936.

[5] Of Mallory, 1959.

Figure 8. Correlations—southwest Washington and the Wynoochee-Satsop area as presented by Rau in 1967. See text regarding differences in zonal nomenclature, southwest Washington, 1958, versus Wynoochee-Satsop area, 1966 and 1967.

biostratigraphic subdivisions were not presented for the Quinault sequence because stratigraphic relations between each section were uncertain (Fig. 10). However, paleoecologic studies suggested that the Quinault Formation may have been deposited under shoaling conditions beginning with upper bathyal depths and terminating at littoral depths. Thus, the deepest water foraminifers may be confined largely to the oldest Quinault strata and the youngest beds should contain only relatively shallow-water faunas, a depositional model similar to that previously suggested for the early and middle Miocene Astoria(?) Formation of the Grays Harbor basin.

Continuing stratigraphic studies along the western flank of the Olympic Mountains in pre-Pliocene coastal rocks (Rau, 1973, 1975a, 1979) have shown that it is difficult to conduct detailed biostratigraphy in these rocks because faunas are sparse and structures are complex (Fig. 1). Stage-level assignments have been made to faunas from isolated outcrops mostly of Oligocene and Miocene age. A few older assemblages of both middle and late Eocene age have been recorded. However, available sections are not sufficiently complete to adequately verify that the stratigraphic order of occurrence of these faunas coincides with that of the West Coast stages.

Perhaps equally significant to relative age and correlation of these coastal strata have been the paleoecologic data that the contained faunas have produced. Almost all foraminiferal assemblages indicate substantial water depths in an oceanic environment—an environment distinct from that indicated by the shelf faunas that occur in most of the rocks of the Grays Harbor basin and northern Olympic Peninsula area of Washington. This evidence in itself supports the currently employed concept that most of the Tertiary rocks of the Olympic Mountains and west coastal area have been accreted to the North American plate from the oceanic plate and are therefore of a different ecological province than rocks of roughly the same age that flank the Olympic Mountains to the north, east, and south (Rau, 1973; Cady, 1975; Snavely and others, 1977; Tabor and Cady, 1978).

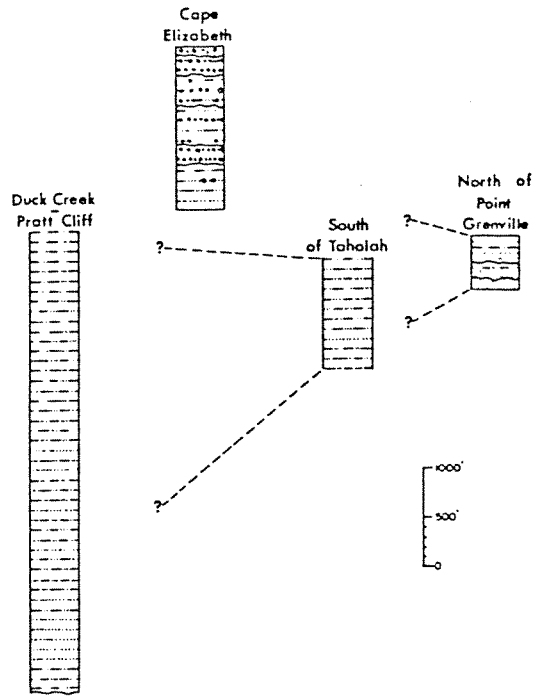


Figure 9. Suggested stratigraphic relations of four major coastal sections of the Pliocene Quinault Formation. Details of these sections are discussed in the original report (Rau, 1970).

Current geologic mapping by the U.S. Geological Survey in the northwest part of the Olympic Peninsula has provided foraminiferal data from a sequence of a deep, marginal basin facies (Rau, in Snavely and others, 1979). Although faunas are noticeably distinct from those of the adjacent northern Olympic Peninsula area to the east, West Coast foraminiferal stages have been recognized and local subdivisions are being developed as mapping progresses.

SUMMARY

Faunal differences in foraminiferal assemblages of the Pacific Northwest Tertiary sequence largely reflect variations in ecological conditions not only over a geographic area but through geologic time as well. The details of faunal characteristics for each zone are, therefore, most reliable for stratigraphic correlation within the provincial Tertiary sequence of southwest Washington where the zones were originally defined. Nevertheless, the general faunal characteristics of most of these biostratigraphic divisions are also recognizable over a larger area and are broadly applicable to correlations throughout western Washington and Oregon. Furthermore, a geographically widespread consistency of ecological evolution through time is obvious in foraminiferal assemblages of the entire Tertiary sequence of the West Coast, thus allowing broad stratigraphic correlations throughout this region at the stage level of magnitude.

The following is a brief synthesis of faunal characteristics for each zone or assemblage described and defined over the years and reviewed in the preceding section of this report (Fig. 11). Greater details of these faunal characteristics are presented in the original reports.

Pre-Ulatisian Assemblages

A few collections from scattered areas in western Washington that usually occur in association with the Crescent Formation have been referred to either the Penutian Stage of Mallory (1959) or a general early Eocene age. Such faunas are perhaps even more widespread in western Oregon. Thoms (1965) described some of these faunas from the Umpqua Group. Planktonic foraminifers are usually more prevalent in early Tertiary strata than in other parts of the Tertiary. Studies by Miles (1977), McKeel (1972), and McKeel and Lipps (1975) are important contributions to information on these foraminifers. Taxa listed below typically occur in, although are not necessarily restricted to, faunas that are assigned to a pre-Ulatisian age:

Anomalina dorri aragonensis Nuttall
Cibicides martinezensis Cushman and Barksdale
Globorotalia aragonensis Nuttall
Glomospira charoides (Jones and Parker)
Loxostomum applinae (Plummer)
Nodosaria velascoensis Cushman
Nonion micrum Cole
Silicosigmoilina californica Cushman and Church
Siphona cf. *S. wilcoxensis* Cushman
Spiroplectammina directa (Cushman and Siegfus)
Spiroplectammina richardi Martin
Tritaxilina colei Cushman and Siegfus
Vaginulinopsis asperuliformis Nuttall

Vaginulinopsis vacavillensis Assemblage

Although this group of species is not treated as characterizing a formal zone, its stratigraphic occurrence is consistent in Pacific Northwest Tertiary sequences. The faunal composition of the assemblage may be compared generally to that of the combined "B" zones of Laiming (1940), and its relative stratigraphic position in the Pacific Northwest sections is also comparable to that of the "B" zones in California, as well as a lower part of the Ulatisian Stage of Mallory (1959). The following listed species are among the most commonly occurring, and they typify the assemblage:

Amphistegina californica Cushman and M. A. Hanna
Asterigerina crassaformis Cushman and Siegfus
Bulimina lirata Cushman and Parker
Baggina teninoensis Rau
Cibicides coalingensis Cushman and G. D. Hanna
Cibicides martinezensis Cushman and Barksdale
Cibicides spiropunctatus Galloway and Morrey
Gaudryina coalingensis (Cushman and G. D. Hanna)
Marginulina subbullata Hantken
Nodosaria latejugata Gumbel
Pseudoglandulina nallpeensis Rau
Spiroplectammina mississippiensis (Cushman)
Tritaxilina colei Cushman and Siegfus
Vaginulinopsis asperuliformis (Nuttall)

Vaginulinopsis vacavillensis (G. D. Hanna) [*mexacana* var. A-D of Laiming]

Bulimina cf. *B. jacksonensis* Zone

This zone was defined from surface sections of southwest Washington (Rau, 1958) and has been broadly recognized throughout western Washington and parts of western Oregon. It is correlated with the upper part of the Ulatisian Stage of Mallory (1959). The following species occur typically in the zone:

Amphimorphina californica Cushman and McMasters
Asterigerina crassaformis Cushman and Siegfus
Bulimina cf. *B. jacksonensis* Cushman
Bulimina corrugata Cushman and Siegfus
Baggina teninoensis Rau
Cibicides warreni Cushman, Stewart, and Stewart
Gaudryina coalingensis (Cushman and G. D. Hanna)
Lenticulina sp. [robust, raised limbate sutures]
Nodosaria latejugata Gumbel

Uvigerina cf. *U. yazooensis* Zone

This zone was defined from surface sections and wells of southwest Washington (Rau, 1958), and it generally represents the lower part of the Narizian Stage of Mallory in the Pacific Northwest. Its faunal characteristics vary somewhat from area to area. However, the following taxa are common in the zone throughout western Washington and Oregon:

Asterigerina crassaformis Cushman and Siegfus
Bolivina basisenta Cushman and Stone
Bulimina corrugata Cushman and Siegfus
Cibicides warreni Cushman, Stewart, and Stewart
Eponides yeguaensis Weinzierl and Applin
Gyroidina simiensis Cushman and McMasters
Gyroidina soldanii octocamerata Cushman and G.D. Hanna
Lenticulina welchi (Church)
Plectofrondicularia searsi Cushman, Stewart, and Stewart
Pleurostomella acuta Hantken
Uvigerina cf. *U. yazooensis* Cushman
Uvigerina garzaensis Cushman and Siegfus
Valvulineria tumeyensis Cushman and Simonson
Valvulineria jacksonensis welcomensis Mallory
Vulvulina cf. *V. curta* Cushman and Siegfus

Bulimina schencki-Plectofrondicularia cf. *P. jenkinsi* Zone

Although the boundary between this zone and the subjacent *Uvigerina* cf. *U. yazooensis* Zone is gradational, the upper limit of the *Bulimina schencki-Plectofrondicularia* cf. *P. jenkinsi* Zone is relatively distinct, particularly in southwest Washington where the zone was originally defined (Rau, 1958). Many species ranging from below are not normally found above the top of this zone. The *Bulimina schencki-Plectofrondicularia* cf. *P. jenkinsi* Zone represents an upper part of the Narizian Stage of Mallory (1959) in the Pacific Northwest. A large number of species representing a wide range of depositional environments occur in this zone. The following are among the more commonly occurring species in the zone:

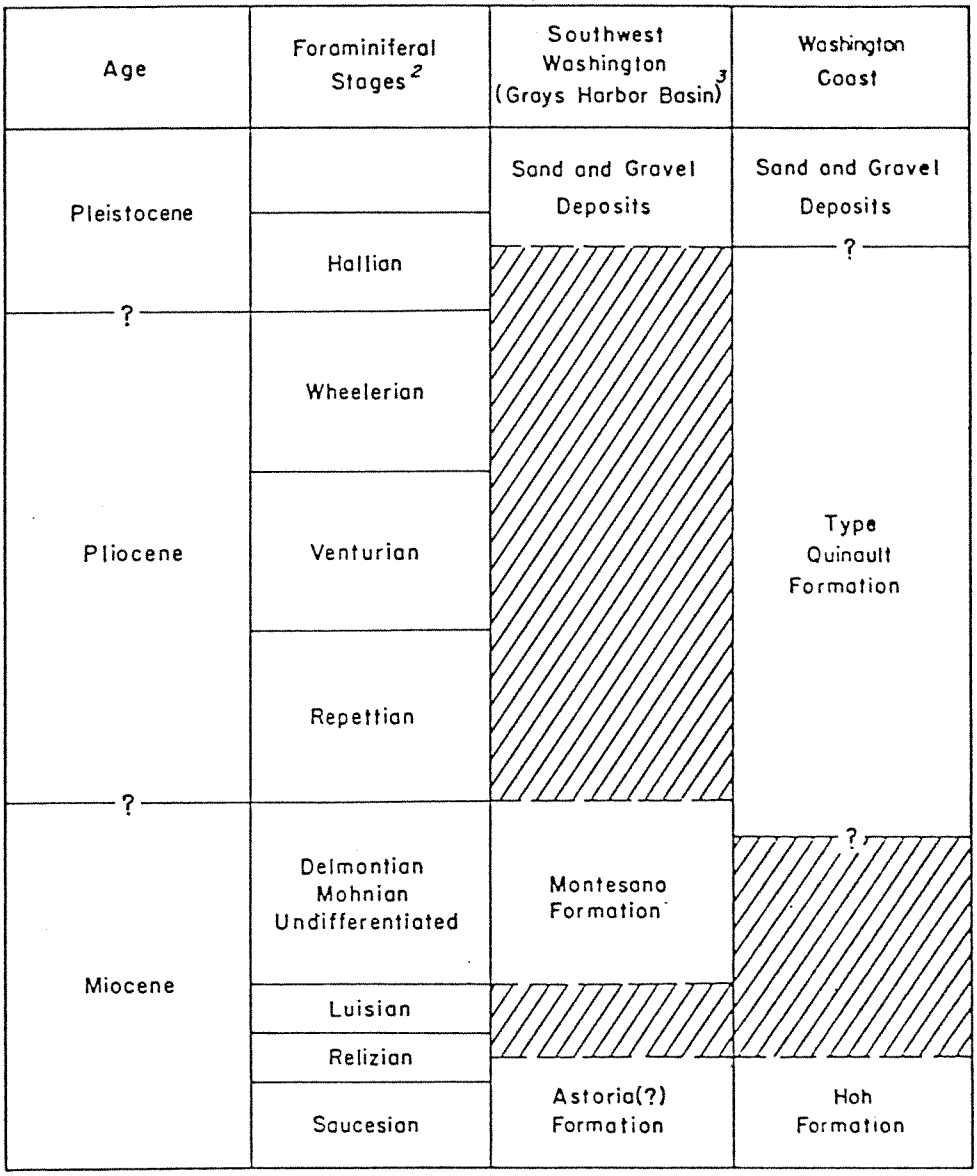
Alabamina kernensis Smith
Angulogerina hannai Beck
Bolivina basisenta Cushman and Stone
Bolivina kleinpelli Beck
Bulimina alazanensis Cushman
Bulimina schencki Beck
Cibicides haydoni (Cushman and Schenck)
Cibicides mcmastersi Beck
Cibicides natlandi Beck
Cibicides warreni Cushman, Stewart, and Stewart
Globocassidulina globosa (Hantken)
Gyroidina condoni (Cushman and Schenck)
Lenticulina welchi (Church)
Planularia cf. *P. markleyana* Church
Plectofrondicularia cf. *P. jenkinsi* Church
Plectofrondicularia cf. *P. searsi* Cushman, Stewart, and Stewart
Pseudoglandulina conica (Neugeboren)
Quinqueloculina goodspeedi Hanna and Hanna
Spiroloculina wilcoxensis Cushman and Garrett
Uvigerina garzaensis Cushman and Siegfus
Valvulineria aff. *V. willapaensis* Rau [a small form]
Valvulineria tumeyensis Cushman and Simonson
Virgulina hobsoni Beck

Sigmomorphina schencki Zone

This zone was originally defined from surface sections and wells of southwest Washington where it occurs in the lower part of the Lincoln Creek Formation (Rau, 1958). Its base is well defined by the lowest occurrence of many of the taxa listed below. The upper limits of the zone are less well defined and are based largely on the absence of species that are known to occur in the superjacent *Cassidulina galvinensis* Zone. Locally, at least, as indicated on the checklist, a few species make their highest appearance at or near the top of the zone. Many of the taxa that first appear at the base of the *Sigmomorphina schencki* Zone continue to occur throughout this and the overlying *Cassidulina galvinensis* Zone, thus suggesting very little or at least gradational change in environmental conditions through time. Although some variations in faunal character occur with increased distance away from its type area, generally the *Sigmomorphina schencki* Zone is recognizable throughout western Washington and at least as far south as the Alsea Bay area of western Oregon.

The following species are significant to the recognition of the *Sigmomorphina schencki* Zone (- indicates species is particularly common and first to appear at base; + indicates highest appearance at or near top of zone):

\+ *Angulogerina* cf. *A. occidentalis* (Cushman)
Cancris joaquinensis Smith
\+ *Cassidulina* cf. *C. kernensis* Smith
\+ *Ceratobulimina washburni* Cushman and Schenck



/ Berggren (1969), based on radiometric data, suggests that the Mio-Pliocene boundary may fall somewhere within the Wheelerian stage. Various workers place the Plio-Pleistocene boundary either in or at the base of the Hallian stage.

2 Miocene stages of Kleinpell (1938); Plio-Pleistocene stages of Natland (1952).

3 After Rau (1967).

Figure 10. Suggested stratigraphic relations of the Washington coast Quinault Formation, formations of the Grays Harbor basin, and West Coast foraminiferal stages (Rau, 1970).

- *Cibicides elemaensis* Rau
  Cibicides haydoni (Cushman and Schenck)
  Cibicides hodgei Cushman and Schenck
  Dentalina dusenburyi Beck
  Eponides yeguaensis Weinzierl and Applin
- *Gaudryina alazanensis* Cushman
- *Karreriella washingtonensis* Rau
+ *Lenticulina becki* (Rau)
+ *Lenticulina texanus* (Cushman and Applin)
  Listerella nodulosa (Cushman)
+ *Marginulina alazanensis* Nuttall
+ *Melonis halkyardi* (Cushman)
  Plectofrondicularia packardi Cushman and Schenck *sensu lato*
  Pseudoglandulina inflata (Bornemann)
  Quinqueloculina imperialis Hanna and Hanna
  Quinqueloculina weaveri Rau
- *Sigmomorphina* sp. A [similar to *S. schencki* but with edges less acute]
+ *Sigmomorphina schencki* Cushman and Ozawa
  Spiroloculina texanus Cushman and Ellisor
- *Uvigerina atwilli* Cushman and Simonson
+ *Uvigerina cocoaensis* Cushman
  Uvigerina cf. *U. garzaensis* Cushman and Siegfus

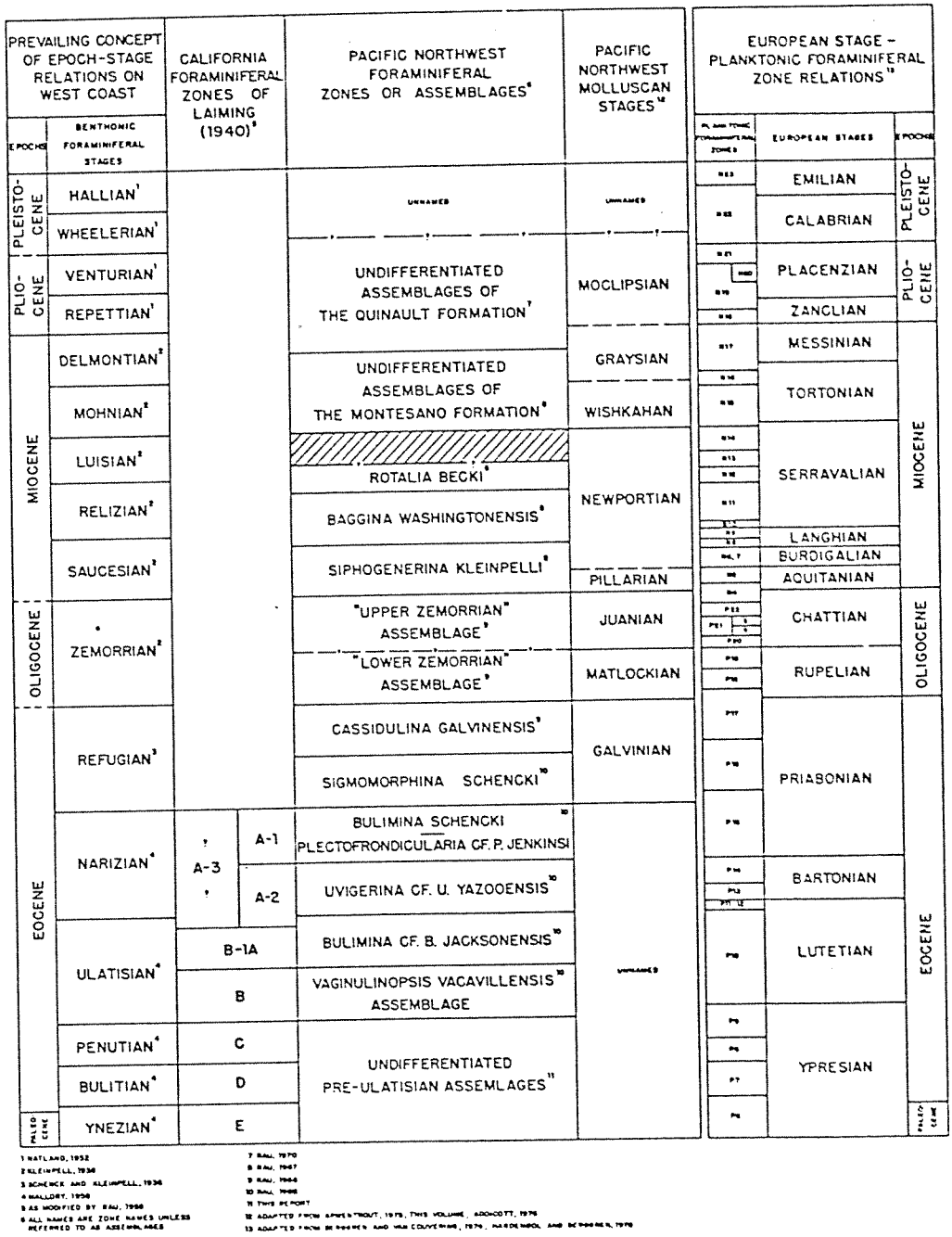


Figure 11. Pacific Northwest foraminiferal biostratigraphic units with correlations to other West Coast standards and a suggested correlation of European stages with planktonic foraminiferal zones.

+ *Vaginulinopsis saundersi* (Hanna and Hanna)
- *Valvulineria willapaensis* Rau

Cassidulina galvinensis Zone

This zone locally represents an upper part of the Refugian Stage. It was first defined from surface sections and wells of southwest Washington and named the *Eponides kleinpelli* Zone (Rau, 1958). It was later redefined from additional surface sections of southwest Washington and renamed the *Cassidulina galvinensis* Zone (Rau, 1966). It is represented in southwest Washington in a middle part of the Lincoln Creek Formation. The *Cassidulina galvinensis* Zone lacks clear definition both at the base and at the top because faunal changes through both Refugian and the superjacent Zemorrian time were not only few but gradational. Thus, locally, the upper Refugian foraminiferal faunas are transitional in character between that of the lower Refugian *Sigmomorphina schencki* Zone and the overlying faunas of the Zemorrian Stage. The faunal character of the upper Refugian *Cassidulina galvinensis* Zone is broadly recognizable

throughout western Washington and at least as far south as the Alsea Bay area of Oregon. The following species are locally common in the *Cassidulina galvinensis* Zone; the occurrence together of those making either their highest or lowest appearance characterizes this zone (+ indicates first appearance at base of zone; + indicates highest appearance at top of zone):

+ *Angulogerina* cf. *A. occidentalis* (Cushman)
+ *Cassidulina galvinensis* Cushman and Frizzell
+ *Cassidulina* cf. *C. kernensis* Smith
- *Cassidulina* cf. *C. oblonga* Reuss
Cibicides elmaensis Rau
Epistomina eocenica (Cushman and Hanna)
Eponides kleinpelli Cushman and Frizzell
+ *Guttulina hantkeni* Cushman and Ozawa
Gyroidina orbicularis planata Cushman
+ *Karreriella chilostoma* (Reuss)
- *Plectofrondicularia* cf. *P. packardi multilineata* Cushman and Simonson
Pseudoglandulina inflata (Bornemann)
Quinqueloculina imperialis Hanna and Hanna
- *Virgulina bramlettei* Galloway and Morrey

Faunas of the Zemorrian Stage

The Zemorrian Stage is well represented in rocks of western Washington and Oregon. In southwest Washington the stage is contained in some 2,000 m of section within the Lincoln Creek Formation. It therefore would be desirable to be able to recognize local subdivisions of the stage. Unfortunately, as previously pointed out, depositional conditions were relatively uniform and faunal changes are minimal throughout the thick section in which the stage is represented. Although formal names have not been assigned, the terms "lower" and "upper" Zemorrian have been employed in both southwest Washington and the northern Olympic Peninsula (Rau, 1964, 1966, 1967). The recognition of these informal subdivisions is based largely on combinations of species ranging from above and below, and the reader is referred to the original reports for a more complete discussion. The boundary between the lower and upper parts of the Zemorrian Stage is not defined, even though in a general way the lower and upper parts of the stage can be distinguished faunally. The Zemorrian Stage is also well represented in the Newport-Alsea Bay area of west-central Oregon where the lower and upper parts of the stage are also generally distinguishable on many of the same faunal criteria as are presented for western Washington. In addition, the stage is well represented in a thick sequence exposed on the southern part of Bainbridge Island and nearby areas of Puget Sound. Fulmer (1975) has made detailed studies of the foraminifers of these strata.

A typical congregation of foraminifers occurring in the lower part of Zemorrian Stage in the Pacific Northwest is listed below (- indicates range from below the Zemorrian Stage; + indicates range from above the "lower" Zemorrian):

+ *Anomalina californiensis* Cushman and Hobson
+ *Buccella mansfieldi oregonensis* (Cushman, Stewart, and Stewart)
+ *Bulimina alsatica* Cushman and Parker
+ *Cassidulina crassipunctata* Cushman and Hobson
+ *Cassidulinoides* sp.
- *Cassidulina* cf. *C. oblonga* Reuss
- *Cornuspira byramensis* Cushman
- *Eggerella bradyi* (Cushman)
+ *Entosolenia* sp.
- *Guttulina problema* d'Orbigny
Lagena hexagona (Williamson)
Marginulina cf. *M. alazanensis* Nuttall
+ *Plectofrondicularia* cf. *P. californica* Cushman and Stewart
- *Plectofrondicularia packardi multilineata* Cushman and Simonson
Pseudopolymorphina cf. *P. ligua* (Roemer)
- *Quinqueloculina weaveri* Rau
Sigmoilina tenuis (Czjzek)
+ *Sphaeroidina variabilis* Reuss

Although many species range throughout the Zemorrian Stage, others are far more common to, or are not found at all below, the upper part of the stage. Furthermore, species ranging from below the Zemorrian Stage are fewer in the upper part than they are in the lower part of the stage. The following congregation of species is typical of upper Zemorrian strata (- indicates range from below the "upper" Zemorrian; + indicates range from above the Zemorrian Stage; 0 indicates occurrence is most common in the "upper" Zemorrian):

+ *Anomalina californiensis* Cushman and Hobson
+ *Buccella mansfieldi oregonensis* (Cushman, Stewart, and Stewart)
+ *Bolivina marginata adelaidana* Cushman and Kleinpell
0+ *Buliminella subfusiformis* Cushman
+ *Bulimina alsatica* Cushman and Parker
+ *Cassidulina crassipunctata* Cushman and Hobson
+ *Cassidulinoides* sp.
0- *Cibicides elmaensis* Rau var. A [highly convexed ventrally]
0 *Dentalina quadrulata* Cushman and Laiming
0+ *Elphidium* cf. *E. minutum* (Reuss)
+ *Entosolenia* sp.
0+ *Florilus incisum* (Cushman)
0 *Lenticulina* cf. *L.* calcar (Linne)
- *Plectofrondicularia packardi multilineata* Cushman and Simonson
- *Quinqueloculina weaveri* Rau
0 *Siphogenerina nodifera* Cushman and Kleinpell
0 *Sphaeroidina variabilis* Reuss
+ *Uvigerinella obesa impolita* Cushman and Laiming

Siphogenerina kleinpelli Zone

This is the lowest of three zones that were defined from the early and middle Miocene Astoria(?) Formation of southwest Washington (Rau, 1967). The faunal composition of each of the three zones reflects changing ecological

conditions through time in a gradually filling depositional basin. Deepest conditions apparently existed during earliest Miocene time and are represented by the faunas of the *Siphogenerina kleinpelli* Zone. The following species are commonly found in this zone:

Bolivina advena Cushman
Buccella mansfieldi oregonensis (Cushman, Stewart, and Stewart)
Cassidulina pulchella d'Orbigny
Epistominella parva (Cushman and Laiming)
Florilus costiferum (Cushman)
Planulina astoriensis Cushman, Stewart, and Stewart
Plectofrondicularia californica Cushman and Stewart
Siphogenerina kleinpelli Cushman
Sphaeroidina variabilis Reuss
Uvigerinella obesa impolita Cushman and Laiming
Valvulineria araucana (d'Orbigny)

Baggina washingtonensis Zone

Intermediate depths are believed to have dominated during the deposition of the overlying strata of the *Baggina washingtonensis* Zone. The following species are common in this zone:

Baggina washingtonensis Rau
Bolivina chehalisensis Rau
Buccella mansfieldi oregonensis (Cushman, Stewart, and Stewart)
Cassidulina pulchella d'Orbigny
Cibicides elmaensis Rau var. A
Epistominella parva (Cushman and Laiming)
Florilus costiferum Cushman
Uvigerinella californica Cushman

Rotalia becki Zone

Shallow-water conditions are believed to have prevailed during the deposition of the uppermost part of the lower to middle Miocene Astoria(?) Formation. During this time faunas of the *Rotalia becki* Zone dominated. Listed below is a typical congregation of commonly occurring species for this zone:

Bolivina chehalisensis Rau
Buccella cf. *B. frigida* (Cushman)
Buliminella elegantissima (d'Orbigny)
Cassidulina pulchella d'Orbigny
Elphidium cf. *E. minutum* Cushman
Rotalia becki Bandy and Arnal
Uvigerina auberiana d'Orbigny
Valvulineria menloensis Rau

The three preceding zones, although applicable in southwest Washington, have not been recognized in the Miocene Clallam Formation of the northern Olympic Peninsula of Washington, nor the Astoria Formation and Nye Mudstone of Oregon, particularly the Newport area of west-central Oregon. In the latter area the faunas of the Nye Mudstone and the Astoria Formation have been listed by Rau (in Snavely and others, 1964, 1969); their characteristics have been discussed, and they have been referred to the Saucesian Stage. Species characteristically common to the Nye Mudstone of Newport embayment are listed below:

Bolivina advena Cushman
Bolivina marginata adelaidana Cushman and Kleinpell
Buccella mansfieldi oregonensis (Cushman, Stewart, and Stewart)
Buliminella subfusiformis Cushman
Bulimina inflata alligata Cushman and Laiming
Cassidulina laevigata carinata Cushman
Epistominella parva (Cushman and Laiming)
Gyroidina soldanii d'Orbigny
Florilus costiferum (Cushman)
Florilus incisum (Cushman)
Plectofrondicularia californica Cushman and Stewart
Uvigerina auberiana d'Orbigny
Uvigerinella obesa impolita Cushman and Laiming
Virgulina californiensis Cushman

Species characteristically common to the Astoria Formation of Newport embayment are listed below:

Bolivina advena Cushman
Buccella mansfieldi oregonensis (Cushman, Stewart, and Stewart)
Buliminella elegantissima (d'Orbigny)
Buliminella subfusiformis Cushman
Epistominella parva (Cushman and Laiming)
Florilus costiferum (Cushman)
Nonionella miocenica Cushman
Lenticulina mayi Cushman and Parker
Uvigerinella californica ornata Cushman

Although many of the same species occur in both the Astoria Formation and the Nye Mudstone, the assemblage of the Nye Mudstone is more diverse and therefore easier to recognize. A few Astoria species, particularly *Buliminella elegantissima* and *Lenticulina mayi*, are not known to occur in the Nye Mudstone and are useful for distinguishing the faunas of the Astoria Formation from those of the Nye Mudstone.

The subjacent Yaquina Formation, on the basis of a limited number of significant species, has been generally regarded as representing an upper part of the Zemorrian Stage. However, the reported occurrence of *Florilus costiferum* (R. G. Gonsalves, 1963, personal communs.) in the upper part of the formation suggests that at least a part of the formation may be as young as Saucesian.

Assemblages of the Upper Miocene Montesano Formation

Onshore outcrops of upper Miocene strata in Washington are largely confined to the Montesano Formation of southwest Washington. Although our studies of foraminifers were limited to use as an aid to geologic mapping, other workers have presented more comprehensive observations of these foraminifers. Fowler (1965) discussed foraminiferal biostratigraphy of the Montesano Formation in considerable detail and presented extensive lists of foraminifers. Bergen and Bird (1972), in their discussion of the biostratigraphy of the Ocean City area, presented addi-

tional data on late Miocene foraminiferal biostratigraphy. The following species are common to or characteristic of the Montesano Formation:

Bolivina brevior Cushman
Bolivina rankini Kleinpell
Buccella frigida (Cushman)
Buliminella curta Cushman
Cibicides mckannai Galloway and Wissler
Epistominella pacifica (Cushman)
Epistominella smithi (Stewart and Stewart)
Nonionella cf. *N. basispinata* (Cushman and Moyer)
Nonionella miocenica Cushman
Pullenia salisburyi Stewart and Stewart
Rotalia cf. *R. garveyensis* Natland
Uvigerina hootsi Rankin
Uvigerina modeloensis Cushman and Kleinpell
Uvigerina subperegrina Cushman and Kleinpell
Virgulina californiensis ticensis (Cushman and Kleinpell)
Virgulina subplana Barbat and Johnson

Assemblages of the Pliocene Quinault Formation

Marine rocks of Pliocene age in western Washington are confined to the Olympic coastal area and constitute a major part of the Quinault Formation. Outcrops of the lowermost part of the formation are generally regarded as late Miocene in age, largely on the basis of the rare occurrence of *Rotalia garveyensis*. Furthermore, offshore data indicate that strata of late Miocene age are extensive beneath rocks of Pliocene age (Rau, 1970).

Biostratigraphic subdivisions of the Quinault Pliocene have not been defined largely because stratigraphic control between isolated surface sections is insufficient. The following listed foraminifers are either among those characteristically common in the Quinault Formation or are particularly useful for general correlation of the formation:

Angulogerina semitrigona (Galloway and Wissler)
Anomalinoides quinaultensis Rau
Bolivina acuminata Natland
Bolivina advena Cushman
Buccella inusitata Andersen
Bulimina subacuminata Cushman and Todd
Buliminella elegantissima (d'Orbigny)
Cassidulina islandica Norvang
Cassidulina limbata Cushman and Hughes
Cassidulina reflexa Galloway and Wissler
Cassidulina translucens Cushman and Hughes
Cibicides conoideus Galloway and Wissler
Cibicides fletcheri Galloway and Wissler
Cibicides mckannai Galloway and Wissler
Elphidiella hannai (Cushman and Grant)
Elphidium hughesi foraminosum Cushman
Elphidium hughesi hughesi Cushman and Grant
Elphidium microgranulosum (Galloway and Wissler)
Epistominella pacifica (Cushman)
Florilus basispinatum (Cushman and Moyer)
Globigerina bulloides d'Orbigny
Globigerina pachyderma (Ehrenberg)
Globobulimina auriculata (Bailey)
Globorotalia crassaformis (Galloway and Wissler)
Lagena pliocenica timmsana Cushman and Gray
Nonionella miocenica Cushman
Oolina borealis Loeblich and Tappan
Pullenia cf. *P. salisburyi* Stewart and Stewart
Rotalia cf. *R. garveyensis* Natland
Uvigerina juncea Cushman and Todd
Uvigerina cf. *U. Hootsi* Rankin
Uvigerina senticosa Cushman
Uvigerina subperegrina Cushman and Kleinpell
Virgulina californiensis ticensis Cushman and Kleinpell

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