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SHELDON L. GLOVER, Supervisor

Bulletin No. 43

EOCENE STRATIGRAPHY

OF THE

LOWER COWLITZ RIVER-EASTERN WILLAPA HILLS AREA, SOUTHWESTERN WASHINGTON

By

DONALD ANTON HENRIKSEN

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FOREWORD

This bulletin deals with a part of southwestern Washington for which only general information has been previously available. The details of structure and stratigraphy throughout much of the area have been unknown, and the igneous rocks of the area have heretofore received only perfunctory attention. The data here provided will be of interest to anyone concerned with the geology of this part of the state, not only for specific use in the area under discussion but also in studies of adjacent areas where similar rocks occur.

The field work upon which the report is based was done by the author during the summer seasons of 1951, 1952, and 1953. The report, when completed, was a dissertation submitted to the School of Mineral Sciences and the Committee on Graduate Study of Stanford University, in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Geology.

The Division of Mines and Geology is grateful to the author, Dr. Donald A. Henriksen, for his permission to publish the report as Bulletin No. 43 of its series of geologic studies of Washington, thus making the material more generally available than it might otherwise be.

SHELDON L. GLOVER, Supervisor,
Division of Mines and Geology

January 19, 1956

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EOCENE STRATIGRAPHY OF THE LOWER COWLITZ RIVER-EASTERN WILLAPA HILLS AREA, SOUTHWESTERN WASHINGTON

By Donald Anton Henriksen

ABSTRACT

The lower Cowlitz River-eastern Willapa Hills area is situated on the east side of the Coast Range in southwestern Lewis County, northwestern Cowlitz County, and northeastern Wahkiakum County, Washington. Predominantly Eocene rocks are exposed in the area, which is bounded by Oligocene rocks on the north and Miocene rocks on the south. The total area is approximately 250 square miles.

The purpose of the investigation is twofold: (1) to map the distribution and structure of the Eocene formations and to establish their stratigraphic sequence, correlation, and ages; and (2) to study the major volcanic rock units of southwestern Washington, in order to determine petrographic and lithologic criteria by which each may be distinguished.

The Eocene rocks of the area consist of the Metchosin volcanic series and the Cowlitz formation.

The Metchosin volcanic series is composed largely of basaltic flows, pillow lavas, flow breccia, and subordinate pyroclastic rocks, together with thin interbedded marine tuffaceous siltstones. The bulk of the series was deposited under shallow marine conditions. The minimum exposed thickness is 6,000-8,000 feet, and the total thickness probably exceeds 10,000 feet. The base of the series is not exposed in southwestern Washington. The lower part of the Metchosin is of unknown age, although volcanism may have been initiated in early Eocene time. The upper part of the formation is of upper middle Eocene age.

The Cowlitz formation consists of a varied series of marine, brackish-water, and nonmarine siltstones, mudstones, and sandstones, with subordinate interbedded volcanics. The total thickness ranges from 3,000 feet to more than 8,000 feet. The formation locally contains intercalated coal beds and is richly fossiliferous, especially in the upper part. It ranges in age from lower upper Eocene, or possibly upper middle Eocene, to the upper part of the upper Eocene. The type section of the Cowlitz formation along Olequa Creek is expanded to include 5,400 feet of Stillwater Creek strata overlying the Metchosin volcanics. The type Cowlitz represents the thickest predominantly marine Eocene section exposed in the Pacific Northwest.

The Cowlitz formation is subdivided into four mappable members, which in ascending stratigraphic order are: (1) the Stillwater Creek member, (2) the Pe Ell volcanics member, (3) the Olequa Creek member, and (4) the Goble volcanics member. The stratigraphic relations, ages, and correlation of the member units of the Cowlitz are discussed in detail. Partial faunal lists of foraminiferal assemblages are also presented.

The unconformity which apparently exists between middle and upper Eocene formations in many parts of southwestern Washington and northwestern Oregon is not present in this area. The Cowlitz sediments rest conformably upon the Metchosin volcanics. The Eocene rocks are unconformably overlain by Oligocene sediments on the north and Miocene sandstones and basalts on the south.

The major structural features trend northwest-southeast, transverse to the north-south structural axis of the Coast Range. The Eocene rocks comprise parts of two major folds—a complex anticline and a broad syncline. Numerous minor folds and a few small faults have been mapped. Faulting has played a minor role in the structural development of the area. Several stages of deformation are recognized.

Physiography and topographic features are discussed briefly. The region is largely in early maturity in the geomorphic cycle, although remnants of the uplifted pre-late Miocene surface are present along the southern edge of the mapped area. Topography is largely controlled by lithology and, to a lesser extent, structure.

The geologic history of the region is outlined, with particular emphasis on the geologic events of Eocene time.

The economic geology of the area is not promising, although the possibility of commercial accumulations of oil and gas in the Eocene rocks is not to be discounted. Further geologic exploration for petroleum is considered to be warranted. Large deposits of low-rank coal have been worked in the past, and industrial minerals—chiefly gravel, sand, and crushed basalt—are quarried.

The four major volcanic rock units of southwestern Washington—the Metchosin volcanic series, the Northcraft (Eocene) formation, the Goble volcanics, and the Astoria (Miocene) basalts—were studied in thin section. The distinctive petrographic and lithologic features of each unit have been determined, and are summarized here.

The Metchosin volcanic series is distinguished by the abundance and character of alteration products and secondary minerals. In the field, the pillow basalts and zeolitized flow breccia are lithologically distinctive.

The Northcraft formation is distinguished by its essentially andesitic, rather than basaltic, composition and by abundance of plagioclase. Trachytic texture and flow cleavage, together with platy jointing in many of the flows, are characteristic features.

The Goble volcanics show marked lithologic and petrographic similarity to some of the Astoria basalts. However, the Goble flows are more feldspathic, and the tabular form of the plagioclase in thin section is characteristic. The Goble rocks are also distinguished in part by platy jointing and the presence of associated flow breccia and pyroclastic rocks.

The Astoria flows are subdivided into two groups: (1) glassy, even-grained basalts which are characterized by abundance of black volcanic glass and which are pertrographically quite unlike any other lavas of the region; and (2) a largely crystalline group of porphyritic basalts, similar to the Goble volcanics but differentiated by lack of tabular plagioclase and platy jointing. They are also less feldspathic and typically more massive, although they show columar jointing locally.

INTRODUCTION

General Character of the Area

Location and accessibility.—The lower Cowlitz River-eastern Willapa Hills area is located in the Coast Range of southwestern Washington in southwestern Lewis County, northwestern Cowlitz County, and the northeastern corner of Wahkiakum County. It is irregularly triangular in shape, with the three corners of the triangle located as follows: (1) the northwest corner, along the Chehalis River 1½ miles north of the town of Pe Ell; (2) the southwest corner, approximately 2 miles northwest of the Incline Lookout, near the confluence of Elochoman (Elokomin) River and the East Fork of the Elochoman River; and (3) the east corner, in the Cowlitz River 2¼ miles southwest of Toledo, with the eastern border of the area extending southward along the Cowlitz River to the mouth of the Toutle River, 2½ miles north of the town of Castle Rock (fig. 1). Insofar as possible, natural geologic and topographic boundaries have been used in delimiting the area.

Figure 1. Index map of Washington, showing location of mapped area.

The lower Cowlitz River-eastern Willapa Hills area, as herein defined, lies west of the Pacific Highway (U. S. Highway 99) between Castle Rock and Chehalis, and largely south of the Ocean Beach Highway (State Highway 12) between Chehalis and Pe Ell. Access to the area may be gained via numerous side roads from these two main highways. State Highways 12E and 1P, the Wildwood-Vader road, the Boistfort-Winlock road, and the Pe Ell-Boistfort road, all traverse parts of the area. Most important for the purposes of field work, however, are the several networks of logging roads and fire trails built and maintained by the Weyerhaeuser Timber Company, the Long-Bell Lumber Company, the Abernathy Forest Association, and the Washington State Division of Forestry. These roads serve the timbered and logged-off areas away from the through highways, and give access to all parts of the mapped area.

Size of area.—The area mapped by the writer includes roughly the southern one-third of the Adna quadrangle and the northern one-half of the Ryderwood quadrangle, together with smaller portions of the Castle Rock, Pe Ell, and Skamokawa quadrangles (pl. 1). The above-named topographic maps are 15-minute quadrangles mapped at a scale of 1:62,500. The total area amounts to approximately 250 square miles.

Relief and drainage.—The area under discussion lies on the east side of the Coast Range in southwestern Washington. It is drained by the Chehalis River and its tributaries, by the Cowlitz River and its tributaries, and by the East Fork of the Elochoman River and Otter Creek in the Elochoman River drainage system. The rainfall is heavy, and, as a result, there are many streams. The countless tributaries have developed a complex drainage network which intricately dissects the area into a maze of forested hills. Most of the streams occupy steep-walled V-shaped valleys and have high gradients, especially in their upper portions. However, the major streams of the area are, at least in part, mature streams with relatively broad valleys and well-developed flood plains.

Elevations above sea level range from about 50 feet in the lower Cowlitz River Valley and 170 feet in the valley of the Chehalis River to 3,110 feet at the summit of Baw Faw Peak,[1] highest point in the Willapa Hills. The peaks of the Willapa Hills, many of which attain elevations in excess of 2,000 feet, rise abruptly from the neighboring stream valleys. Throughout the area, slopes are steep and the peaks and ridges are generally sharp.

Climate and vegetation.—The climate of the lower Cowlitz River-eastern Willapa Hills area is humid, with a relatively dry period in summer. Weather records compiled from readings taken at Centralia, Washington, during the past 33-year period give the following data for that station:

Annual rainfall, average	44.77	inches
Annual snowfall, average	11.2	inches
Temperatures:		
Mean annual maximum	61.8	degrees
Mean annual minimum	40.3	degrees
Record high	102	degrees
Record low	-16	degrees

[1]Shown as "Boistfort Peak" on the newer United States Geological Survey topographic map of the area. However, local usage favors "Baw Faw Peak," and the latter name is used throughout this report.

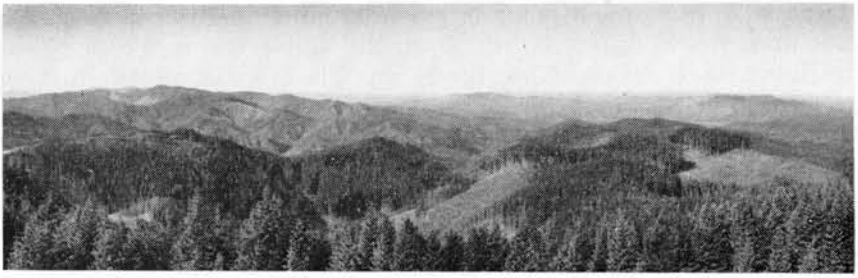

FIGURE 2. Panorama looking northwestward from Baw Faw Lookout.

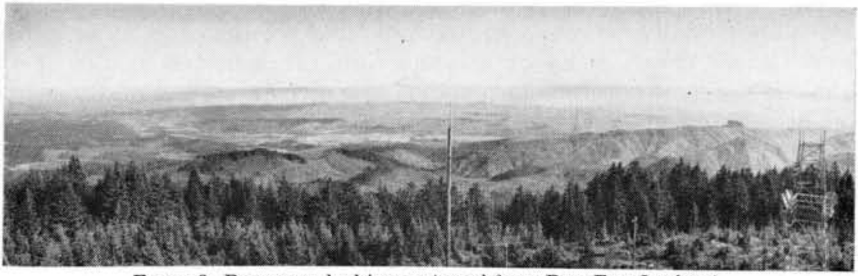

FIGURE 3. Panorama looking eastward from Baw Faw Lookout.

FIGURE 4. Panorama looking southward from Baw Faw Lookout.

Centralia is situated in the Chehalis River Valley 22 miles north of the northeastern corner of the mapped area. As average rainfall increases westward and northward, and maximum temperatures decrease in the same directions, rainfall and temperature figures for this area would differ slightly from the figures given for the Centralia weather station. The annual rainfall, including melted snow, ranges from about 40 inches to more than 85 inches, depending upon locality and year. Winter snow generally is not heavy and soon melts, except in the higher parts of the Willapa Hills. The long rainy season, from October to April, permits most of the abundant moisture to seep in, resulting in dense growth of vegetation.

A large portion of the area has been logged off, and is now covered with second-growth timber and a dense undergrowth of ferns, berry vines, and brush, along with slash and fallen timber, making geologic exploration difficult. There is considerable commercial timber in the area, and large-scale logging operations are being carried on at the present time. The most important forest trees are Douglas fir, western hemlock, and western red cedar, with Port Orford cedar, Sitka spruce, and Noble fir common locally. Red alder is the most common species in some stream valleys and logged-off areas, and in places is abundant to the virtual exclusion of all other forest trees.

Human Activities Within the Area

The population of the lower Cowlitz River-eastern Willapa Hills area is concentrated in the larger stream valleys, and the economy of the region is for the most part agricultural. There are a few small towns within the mapped area; the largest of these are Pe Ell (pop. 787), Vader (pop. 426), and Ryderwood (pop. 851 in 1950; now much less). Winlock, 1½ miles north of the northeastern boundary of the area, has a population of 878 and is a growing community at the present time. Most of the population of the area is widely distributed among the myriad small farms and ranches.

The most important industry is lumbering, with a production in recent years amounting to more than one hundred million board feet of timber annually. Plywood, wood pulp, and many other wood and pulp products in addition to finished lumber are produced from the timber cut in this area. Estimated reserves of standing commercial timber on the McDonald Tree Farm of Weyerhaeuser Timber Company are three billion board feet.[2] All other logging operations are now shut down, as most of the area has been logged off. There was perhaps fifteen billion board feet[3] of first-growth timber in the area at one time, but most of it has been cut during the past thirty years. Weyerhaeuser Timber Company operates the McDonald Tree

[2]Bickford, Richard, Forester, Lewis County, Washington: personal communication.
[3]Bickford, Richard, idem.

Farm on a sustained yield basis, and their logging operations will continue indefinitely.

Farming, especially poultry farming, is next in importance in the economy of the area. Other farming activities and products include dairying, livestock, hay and grain crops, peas, and fruit. Other industries are: tourist trade, the gathering of greens and herbs, and some quarrying and construction work.

The area abounds in fish and game, and its recreational facilities are widely enjoyed by sportsmen and travelers. Important game animals are deer (both blacktail and mule deer) and bears, and the game birds include pheasants, grouse, quail, pigeons, doves, ducks, and geese. Trout and salmon in the rivers and creeks are eagerly sought by fishermen. Other wild animals in this part of southwestern Washington include beavers, raccoons, squirrels, chipmunks, rabbits, coyotes, weasels, and mink.

Purpose, Method, and Scope of the Investigation

Plans for this work were originally made during the summer of 1951, although the scope of the investigation was widened after that time. The purpose of the investigation is twofold: (1) to map the distribution and structure of the Eocene formations of the area and to establish their stratigraphic sequence, correlation, and ages; and (2) to study the major volcanic rock units of southwestern Washington in order to determine petrographic and lithologic criteria by which each may be distinguished.

Field work was carried on during the summer seasons of 1951, 1952, and 1953. During those periods the writer spent a total of approximately 10 months in the field. Geologic field work in the region is difficult because of thick soil mantle and deep weathering, dense forest and undergrowth, steep slopes, and local landsliding and slumping. Thick brush and rugged topography impeded mapping in the Willapa Hills area. Geologic relationships are obscured by alluvium in the stream valleys and a few interstream areas. As a result, field work was limited largely to detailed examination of outcrops along rivers and smaller streams, highways and logging roads, and railroad grades. In localities lacking in outcrops, samples for lithologic and micropaleontologic study were obtained by means of a Mobile Auger mounted on the rear of a four-wheel drive Willys Jeep.

Most geologic data were plotted originally on vertical aerial photographs (scales 1:20,000 and 1:37,600) and later transferred to the topographic maps. In the parts of the area for which aerial photographs were not available, the data were placed directly on topographic maps (scale 1:62,500) in the field.

The accompanying areal geologic map (pl. 1) shows the distribution of the Tertiary rocks. Pleistocene and Recent alluvium and terrace deposits present along the larger streams are not shown.

Oligocene sediments overlying the Cowlitz formation along the northern boundary of the area, previously referred by Weaver (1937B) to the Lincoln formation and "undifferentiated Oligocene," are here assigned to Oligocene-undifferentiated.

Acknowledgments

The writer is deeply indebted to Professors J. J. Graham and Michael Wyatt of the School of Mineral Sciences, Stanford University, for many helpful suggestions and for critical reading of this dissertation. Advice and criticism offered by other members of the School of Mineral Sciences faculty are appreciated.

Phillips Petroleum Company generously extended financial assistance, office space, and the use of field equipment and laboratory facilities during the months spent in field work. Many thanks are due O. E. Childs, Exploration Projects Director, and S. P. O'Rourke, Project Geologist, Phillips Petroleum Company, for their suggestions and guidance. Appreciation is also expressed to R. W. Hickman and C. W. Betton, Jr., who assisted the writer in the field at various times.

Sincere thanks are extended to Richard Cifelli, Micropaleontologist, Phillips Petroleum Company, for examining microfaunal assemblages from the mapped area and preparing partial faunal lists giving age determinations and correlations.

The writer is grateful to G. S. Payne, Berkeley, California, who freely contributed his time and equipment for taking photomicrographs of thin sections of the volcanic rocks.

Appreciation is expressed to Weyerhaeuser Timber Company, Long-Bell Lumber Company, Abernathy Forest Association, and the Washington State Division of Forestry, for their cooperation and many courtesies extended during the course of the field work.

Finally, the writer wishes to express special thanks to his wife, Marilyn, for her constant encouragement and her assistance in the preparation of the manuscript and illustrations.

STRATIGRAPHY AND PETROGRAPHY

PART I. STRATIGRAPHIC GEOLOGY

Introduction

The rocks exposed in the lower Cowlitz River-eastern Willapa Hills area range in age from Eocene to Quaternary. They include marine, brackish-water, and terrestrial sediments, volcanic rocks, and minor igneous intrusives. Predominantly Eocene rocks are exposed in the area. The Eocene sediments and volcanics are overlain by Oligocene sandstone and siltstone on the north and northeast, and Miocene basalt and sandstone on the south.

The Eocene rocks are here assigned to two formational units. In ascending order of geologic age these are: (1) the Metchosin volcanic series, composed of pillow basalt, flow breccia, basaltic flows, subordinate pyroclastic rocks, and minor dikes, sills, and plug-like intrusives, together with relatively thin interbeds of tuffaceous sediments—the formation ranges in age from lower (?) Eocene to upper middle Eocene; and (2) the Cowlitz formation, which consists of marine, brackish-water, and nonmarine sediments with subordinate intercalated volcanic rocks—the Cowlitz ranges in age from upper middle (?) or lower upper Eocene to the upper part of the upper Eocene.

The subdivisions of the Cowlitz formation established by the writer are as follows, in order of their stratigraphic positions: (1) the Stillwater Creek member, of upper middle (?) to upper Eocene age, consisting of marine and near-shore tuffaceous siltstones, mudstones, and sandstones, with minor thin basalt flows and basaltic sediments; (2) the Pe Ell volcanics member, composed of lapilli tuff, agglomerate, breccia, and thin tuffaceous siltstones; this unit occurs only in the northwestern corner of the mapped area, and is probably lower upper Eocene in age; (3) the Olequa Creek member, of upper Eocene age, composed of brackish-water, marine, and terrestrial siltstones, sandstones, and mudstones, and intercalated coal beds; and (4) the Goble volcanics member, which consists of basalt flows, flow breccia, and subordinate pyroclastic rocks, and which interfingers with sediments of the Olequa Creek member; it is upper Eocene in age.

In addition to the thicker Tertiary stratigraphic units, Pleistocene deposits of sand, gravel, and clay mantle some lower portions of the area. Recent alluvium is present in the larger stream valleys and on terraces cut by the Cowlitz River.

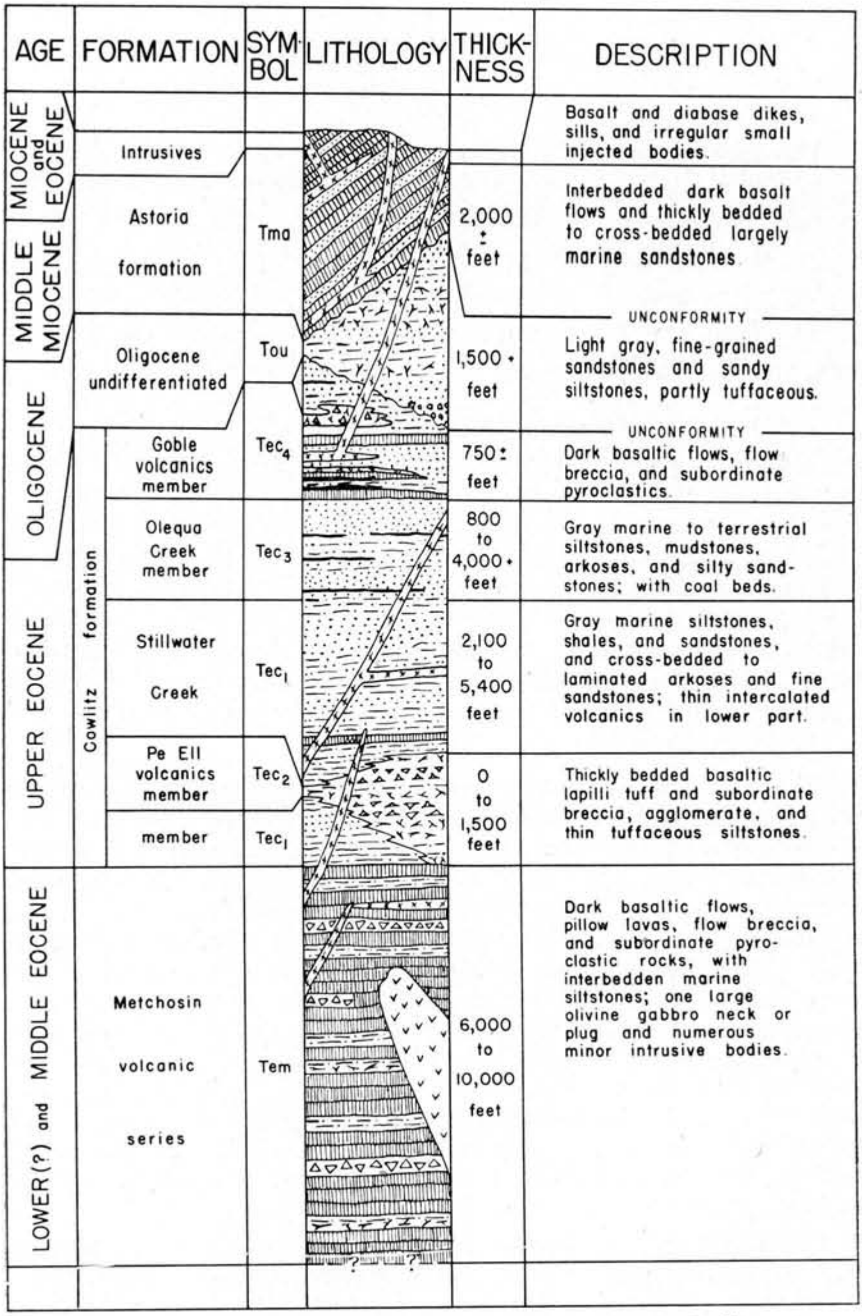

FIGURE 5. Columnar section of rocks exposed in the lower Cowlitz River-eastern Willapa Hills area.

Previous Geologic Work

Previous geologic exploration in the area mapped by the writer has consisted largely of regional reconnaissance investigations. Very little work on the petrographic and lithologic characteristics of the volcanic rock units of southwestern Washington has been published, and the basaltic rocks which underlie the Willapa Hills have never received more than a cursory examination. Much detailed geologic and paleontologic work remains to be done in most parts of the southwestern Washington region.

During the past several years geologists of many major oil companies and the United States Geological Survey have investigated portions of this and adjoining areas. Results of most of this work as yet have not been published. The files of oil companies and independent geologists undoubtedly contain a great deal more geologic and paleontologic data on the Tertiary rocks of southwestern Washington than the most complete library. However, this wealth of information is not available to the public, and geologists undertaking investigations in this region must overcome the handicap of a reference list which, in most instances, will be far from adequate.

The published results of previous geologic exploration in this part of southwestern Washington are summarized in the following brief historical review of the literature. All papers which have contributed information concerning the Eocene rocks of the lower Cowlitz River-eastern Willapa Hills area are cited in this list of references. For more complete bibliographies of the geology and paleontology of southwestern Washington, the reader is referred to Arnold (1902), Weaver (1916B, pp. 19-53; 1937B, pp. 208-224), and Bennett (1939).

The earliest records concerning the Tertiary formations of southwestern Washington are found in the report of James D. Dana (1849) on the geology of the Oregon Territory, which was investigated by the United States Exploring Expedition under Charles Wilkes. Dana and other members of the party examined the Tertiary rocks in the valleys of the streams entering the Columbia from the north, including the Cowlitz River. Dana reported that large deposits of lignite (probably those in the Castle Rock-Vader area) had been opened in the Cowlitz valley.

During the period from the publication of that report until 1912, when the first of Charles E. Weaver's papers on the Tertiary rocks of western Washington appeared, publications on the geology of southwestern Washington dealt largely with the coal deposits and coal-bearing strata of the region. The Eocene rocks of this area were not investigated. Important reports on the Eocene coal-bearing rocks of western Washington, and particularly the Puget group of the Puget Sound Basin and upper Cowlitz Valley, include those by Blake (1867), Willis (1880, 1897), White (1888, 1889), Kimball (1897), Lawson (1898), Landes (1902A), Landes and Ruddy (1903), and Diller (1905).

Certain other papers issued during the same period gave information on the general geology of southwestern Washington and

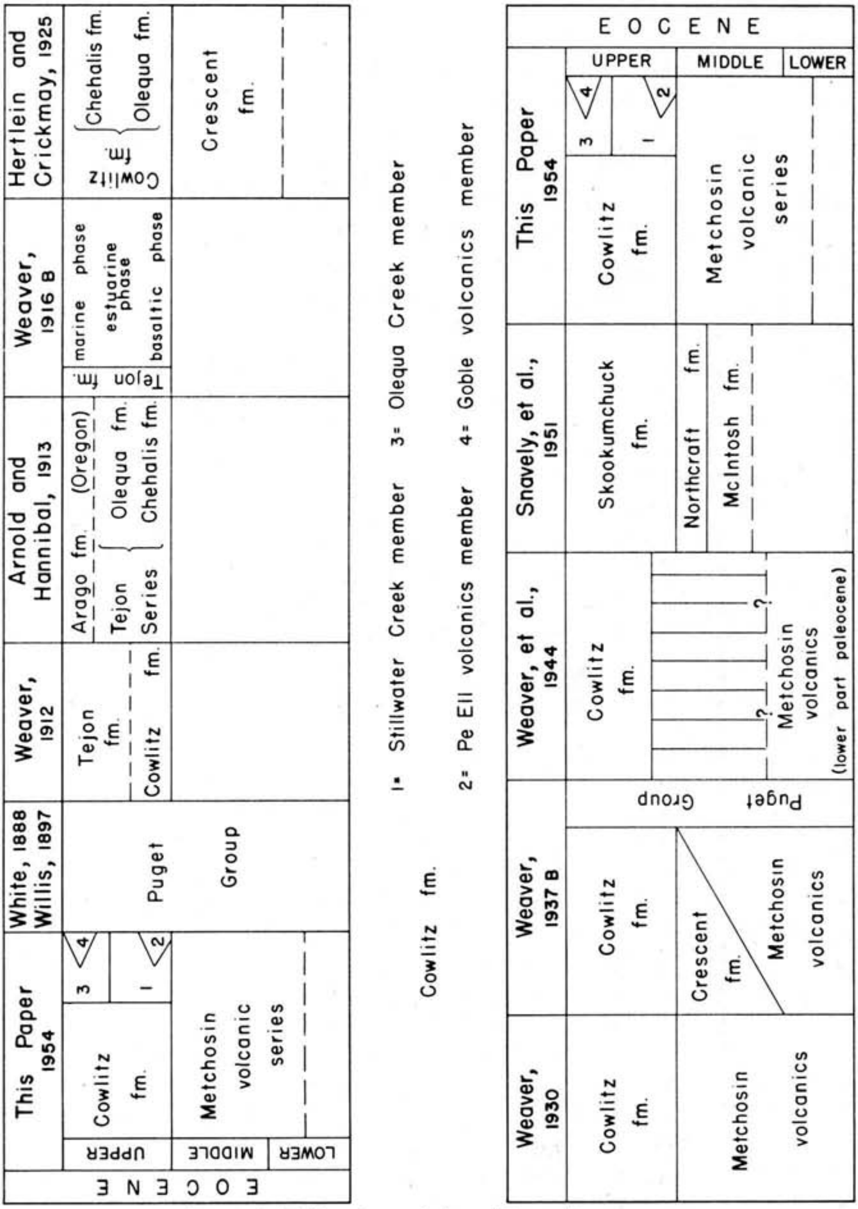

FIGURE 6. Table of correlation of formation names.

the correlation of Tertiary formations within the region, including a portion of the lower Cowlitz River-eastern Willapa Hills area. These include publications by the following: Clark (1891), Dall and Harris (1892), Dall (1898), Landes (1902B), and Arnold (1909).

Only one report published prior to 1912 contained specific information on the geology and paleontology of the area mapped by the writer. In that paper Arnold (1906B) listed and described important fossil localities near Little Falls (Vader), where Eocene strata are exposed along Olequa and Stillwater Creeks.

Results of the first large-scale investigation of the geology and paleontology of the region were published as a "Preliminary Report on the Tertiary Paleontology of Western Washington" by Weaver (1912). In this paper the name Cowlitz formation was proposed for the Eocene marine sediments exposed in the bluffs of the Cowlitz River east of Little Falls (Vader), and the Eocene sediments and volcanic rocks of part of the lower Cowlitz River-eastern Willapa Hills area were described for the first time. The Cowlitz formation was considered as slightly older than the typical marine upper Eocene Tejon formation of California.

In the following year Arnold and Hannibal (1913) presented the results of a study of the marine Tertiary stratigraphy of the Pacific Northwest, in which they correlated the marine Tertiary formations of Washington and Oregon and gave a faunal list for each formational unit. The Tejon "series" was subdivided into the Chehalis (lower) and Olequa (upper) formations, with the Arago formation of western Oregon overlying the Olequa formation.

Collier (1913) made a brief investigation of the geology and coal resources of the southern part of the Cowlitz River Valley in the same year. He correlated the coal-bearing Eocene strata in the Kelso-Castle Rock-Vader area with the Eocene coal measures in the Centralia-Chehalis district to the north, noting the relatively shallow dips of the Eocene rocks exposed south of Olequa and southwest of Winlock.

Dickerson (1915) reported on the similarity of the faunas of the type Tejon formation of California and the "Cowlitz Phase of the Tejon Group of Washington." The molluscan fauna from the Cowlitz River bluffs locality east of Vader was assigned to the *Rimella simplex* zone of the type Tejon.

In the following year Weaver (1916A) published lists of molluscan species known to occur in the Eocene, Oligocene, and Miocene formations of western Washington, describing several new species. The Eocene rocks were correlated with the Tejon of California.

Later in the same year Weaver (1916B) described the Tertiary formations of western Washington, setting forth the results of several years of geologic and paleontologic investigations. He presented the first large-scale geologic map of the southwestern Washington region and described the Eocene and younger Tertiary rocks, discussed their areal distribution, and presented complete faunal lists. The Eocene rocks of the region were referred to the Tejon formation, which was subdivided into three "phases": marine, estuarine, and basaltic.

Still later in the same year Weaver (1916C) published a short paper describing the Eocene strata of the lower Cowlitz River Valley, including Olequa Creek and lower Stillwater Creek. He measured the thickness of Eocene rocks exposed along the Cowlitz River and Olequa Creek and referred them to the upper Eocene Tejon formation. It was shown that the Chehalis formation, Arnold and Hannibal's (1913) lower division of the Tejon "series," rests upon their upper division or Olequa formation. A detailed geologic map, a list of collecting localities, and faunal lists were presented.

In a paper on the coal fields of southwestern Washington, Culver (1919) described the Eocene coal-bearing rocks and coal prospects of the Vader and Castle Rock areas.

Three years later Weaver and Palmer (1922) published a list of fossil localities and descriptions of all molluscan species from the Eocene of Washington. This paper represented the results of the continuation of Weaver's earlier work (Weaver, 1916A).

The first workers to record the presence of Foraminifera in the Eocene rocks of the area were G. D. Hanna and M. A. Hanna (1924). They described and illustrated a small foraminiferal faunule collected from the Cowlitz River bluffs locality east of Vader, noting its similarity to assemblages from various classical Eocene collecting localities in California.

A paper on the stratigraphy and correlation of the marine Tertiary formations of Oregon and Washington appeared in the following year (Hertlein and Crickmay, 1925). The writers divided the Cowlitz formation—upper Eocene of Washington in their charts—into the Olequa (lower) and Chehalis (upper) formations. They correlated the Olequa formation with the upper Tejon formation of California, and the Chehalis formation tentatively with the Jackson formation of the Gulf Coast of the United States.

At the Geological Society of America meeting in Washington, D. C., in December, 1929, Weaver (1930) presented a paper on Eocene lavas in western Washington. He stated that southwestern Washington is underlain by middle Eocene lavas, which in places are overlain in turn by upper Eocene, Oligocene, and Miocene rocks, and Pleistocene and Recent alluvial deposits.

The only official geologic map of the state of Washington thus far published was prepared by Culver (1936). This preliminary geologic map outlined the general features of Washington geology but gave little detail on the areal distribution of the Tertiary formations of the southwestern part of the state.

In a paper presented at the Pasadena meeting of the Cordilleran Section of the Geological Society of America, Weaver (1937A) expanded the type locality of the Cowlitz formation to include the 4,300 feet of upper Eocene sediments exposed along Olequa Creek between Winlock and the confluence with the Cowlitz River.

Weaver's (1937B) comprehensive report of the Tertiary stratigraphy of western Washington and northwestern Oregon was published later in 1937. He described in detail the Tertiary formations and stratigraphy of the region, presenting numerous maps, measured sections, and a complete list of Tertiary faunal localities. That paper remains the most complete reference on the Eocene rocks of the lower Cowlitz River-eastern Willapa Hills area. Weaver mapped parts of this area and described in considerable detail the Metchosin volcanics and the Cowlitz formation.

At the Berkeley meeting of the Geological Society of America two years later, Weaver (1939) presented a paper on the great volume of early (?) and middle Eocene Metchosin volcanics in western Washington and Oregon.

The results of many years' work by Weaver were set forth in a three-volume paper dealing with the paleontology of the marine Tertiary formations of Oregon and Washington (Weaver, 1943). All known species of megafossils from the Tertiary formations of Oregon and Washington were described and illustrated; faunal collecting localities were listed; and faunal lists were given for each formation. In addition, a correlation chart of the Tertiary formations of Oregon and Washington was presented.

The results of a detailed collection and study of the Foraminifera from the Cowlitz River bluffs locality were presented in a paper by Beck (1943). He confirmed the Eocene age of the Cowlitz River strata, correlating the Cowlitz formation in part with the Coaledo formation of Oregon and the Tejon and Poway formations of California.

The report by the Western Cenozoic Subcommittee of the Geological Society of America on the correlation of the marine Cenozoic formations of western North America (Weaver et al., 1944) included brief descriptions of the Eocene and younger formations of southwestern Washington and correlations with more complete and better known California formations, stages, and zones.

In the following year Weaver (1945) published a paper on the geology and oil and gas prospects of Oregon and Washington, in which he discussed the age, lithology, areal distribution, and petroleum potentialities of the Eocene and younger Tertiary rocks of southwestern Washington. He assigned the Metchosin formation to the Paleocene, and emphasized again the great volume and areal extent of these volcanic rocks.

In recent years two papers by geologists of the United States Geological Survey, Fuels Branch, have given much new information on the Eocene stratigraphy of southwestern Washington. These papers (Snavely, Rau, Hoover, and Roberts, 1951; Snavely, Roberts, Hoover, and Pease, 1951) did not deal directly with the lower Cowlitz River-eastern Willapa Hills area; however, their revisions of the Eocene stratigraphic sequence must be considered here, for new formational names were proposed for upper middle (?) and upper Eocene rocks in the district north and east of the area mapped by the writer. In their reports the McIntosh, Northcraft, and Skookumchuck formations occupy the same stratigraphic position as the Cowlitz formation toward the south and west.

In a short paper Campbell (1953) summarized Washington geology and resources, including in his summary a brief description of the Tertiary geology and mineral resources of the "Willapa Hills Province." This paper is the latest contribution on the geology and paleontology of this part of southwestern Washington.

Metchosin Volcanic Series

Distribution and Thickness

A thick series of basaltic flows, pillow lavas, flow breccias, subordinate pyroclastic rocks, and minor intrusive bodies, together with tuffaceous sedimentary interbeds, is exposed along the ridges and canyons of the Willapa Hills. The volcanic rocks are particularly well exposed in the valleys of the Chehalis River and its tributaries south of Pe Ell, the upper Elochoman River and its tributaries, the tributaries of the South Fork of the Chehalis River west of the Wildwood Valley and south of Halfway Creek, and the upper reaches of Stillwater Creek. This series has been referred by Weaver (1937B, pp. 26-40) to the Metchosin volcanics, a formation, originally named and described by Clapp (1910; 1912; 1913; 1917, pp. 255-292), in the southeastern part of Vancouver Island.

The Metchosin volcanic series comprises the central mass of the great Willapa Hills anticlinal uplift. The outcrop belt extends westward and northwestward for many miles, disappearing beneath the waters of Willapa Harbor west of Raymond. The anticline plunges eastward, the volcanic rocks dipping beneath upper Eocene sediments on the north and east. Toward the south the volcanics are overlapped and obscured by Miocene sandstones and intercalated basalt flows.

In the type area in southern Vancouver Island the Metchosin volcanics underlie an area approximately 37 miles in an east-west direction and 5 to 7 miles in a north-south direction, and reach a maximum thickness of probably 7,500 feet (Clapp, 1917, p. 277). The volcanics are all basic, chiefly basalts, and, according to Clapp (1917, p. 256), "they vary widely from coarsely porphyritic and ophitic basalts to pillow lavas and amygdaloids, from fine cherty tuffs to breccias and coarse agglomerates, and from flows and bedded fragmental rocks to dykes, pipes, and irregular injected masses."

Elsewhere in the Pacific Northwest, volcanic rocks which have been assigned by Weaver (1937B, pp. 26-40; 1939; 1945, p. 1406-1407) to the Metchosin underlie all of western Washington and Oregon between the Olympic Mountains and the Klamath Mountains. They also extend onto the south slope of the Olympic Mountains and around their eastern and northern margins. The volcanics reach a thickness of more than 4,000 feet (Weaver, 1945, p. 1405), and the total volume of Metchosin rocks in western Washington and Oregon has been estimated to be nearly 10,000 cubic miles (Weaver, 1939), and may be considerably greater than that figure.

The minimum exposed thickness of the Metchosin volcanic series in the section from the East Fork of the Elochoman River eastward to Stillwater Creek is 6,000 to 8,000 feet, and the minimum thickness exposed in the canyon of the Chehalis River south of Pe Ell is only slightly less; however, the base of the volcanics is not exposed in southwestern Washington. The thickness of the exposed volcanics is probably at least 8,000 feet in this part of the Willapa Hills area, and the total thickness of the series is undoubtedly much greater.

Locally, dips as high as 30° to 40° were measured in outcrops of the Metchosin volcanic series, but such steep dips are rare. Most dips are lower, ranging from 10° to 20°. Estimates of thickness were derived from average corrected dips of 10° to 18°.

There is no regular succession of different types of flows, breccias, and pyroclastics; all types occur interbedded with one another. The pillow lavas predominate in at least the lower part of the series in this area, and the pyroclastic rocks are largely restricted to the upper portion of the series. In general, however, any of the different rock types may occur at any horizon within the series.

Alteration of the lavas, weathering, and poor exposures make recognition of the upper and lower surfaces of individual flows difficult, and often impossible. Therefore, the thicknesses of most of the individual flows can only be estimated. Some flows and flow breccias are thin and irregular, with an average thickness of only a few feet. Other flows appear to attain a maximum thickness of as much as 100 feet.

Sedimentary interbeds, largely tuffaceous siltstones, occur in most sections, from the uppermost to the lowermost exposed portions of the Metchosin volcanic series in this area. The interbeds range in thickness from a few inches to nearly 100 feet, and are for the most part extremely lenticular in character.

The sedimentary interbeds yield microfossils which aid in determining the age of at least the upper part of the Metchosin and also serve in correlation with other formations. The thickest and best exposed interbeds of tuffaceous siltstones and shale are found in the canyon of the Chehalis River south of Pe Ell, in the Elochoman River-Stillwater Creek section west of Ryderwood, and in the lower canyon of the South Fork of the Chehalis River northwest of Ryderwood.

Lithology

The bulk of the Metchosin volcanic series is composed of pillow basalt, flow breccia, and basalt flows. A few pyroclastic members, chiefly tuffs and agglomerates, are present locally, especially in the upper part of the series. Well-defined flows, commonly exhibiting perfect to irregular columnar jointing (fig. 8), are also abundant in the upper part. Well-developed columnar jointing serves in determination of the attitudes of the flows where the tops and bottoms are not exposed and other indications of the bedding are absent.

The pillow basalt and flow breccia are commonly cut by numerous calcite veinlets and are typically zeolitized; quartz and other secondary minerals, notably chloritic minerals, may also be seen in hand specimens. Zeolites, chloritic minerals, and calcite occur in vesicles and fractures in many of the lavas. Interstitial spaces in the flow breccias and pyroclastic rocks are occupied by partly altered palagonite and the secondary minerals and alteration products mentioned above. Late magmatic alteration and mineralization of this type are common throughout the Metchosin.

One relatively large intrusive body and numerous minor basaltic and diabasic dikes, sills, and irregular injected masses occur in the volcanic series. In the area of Baw Faw Peak, in secs. 20, 28, 29, 32, and 33, T. 12 N., R. 4 W., there is an irregularly plug-shaped or stock-like body of fine-grained olivine gabbro which is exposed over a roughly circular area. Outcrops of this intrusive are restricted to the summit and upper slopes of Baw Faw Peak and the adjacent ridges to the east. It will be noted that the Baw Faw Peak intrusive body is not shown on the accompanying areal geologic map (pl. 1) although the probable outline of the intrusive is shown in structure section B-B′. This apparent omission is justified for two reasons: (1) the Baw Faw Peak gabbro body in places grades laterally into normal Metchosin basalt flows and is in part overlain and obscured by them, producing an irregular and somewhat confusing outcrop pattern; and (2) numerous dikes, sills, and other small intrusive bodies, several of which apparently are apophyses from the Baw Faw Peak intrusive, occur within the area of outcrop of the Metchosin volcanic series. None of these intrusives are shown distinct from the Metchosin extrusive rocks on the geologic map.

The basalt ranges in texture from coarsely porphyritic to very fine grained and hypocrystalline. Tabular to prismatic phenocrysts of plagioclase and equant phenocrysts of augite are visible in many hand specimens of the basalt. The color is typically dark greenish gray, in some specimens rendered darker by the presence of bluish- to brownish-black manganese and iron oxide stains. The interstitial material in the pillow lavas and breccias is dark-green to greenish-black palagonite, generally somewhat altered, together with fine particles and fragments of basalt.

Deep weathering causes the basalt to decompose and become reddish brown in color, whereas the palagonite weathers to a greenish-yellow clay.

All the basalts are altered to some extent, and locally chloritization has progressed so far that the rock may be classed as a greenstone. Chloritization is common throughout the Metchosin volcanic series; indeed, the abundance of chloritic alteration products is the chief criterion for distinguishing the Metchosin volcanic rocks from the younger Tertiary basalts.

Microscopically the Metchosin basalts are holocrystalline to hypocrystalline; porphyritic, diabasic, and vesicular textures are common. The groundmass of the porphyritic basalts is typically intergranular, or intersertal if volcanic glass is present. The minerals occurring as phenocrysts, in order of decreasing abundance, are: plagioclase, chiefly labradorite; augite; and olivine, which is greatly altered or completely replaced by secondary minerals. The groundmass consists of laths and plates of plagioclase (labradorite) and granules of augite, magnetite, and ilmenite, with dark volcanic glass present in about half of the thin sections examined. Chloritic alteration products are always present and usually constitute at least 15 percent of the section.

The Baw Faw Peak intrusive body is a relatively unaltered olivine gabbro containing large fresh anhedral crystals of olivine, labradorite, and augite. The texture of the rock is allotriomorphic to hypidiomorphic granular.

Detailed petrographic descriptions of the rocks of the Metchosin volcanic series are presented in Part II of this section of the report.

The pyroclastic rocks range from fine tuff to agglomerate; they constitute only a small part of the series. In their basaltic composition, color, and reaction to weathering, they are similar to the other volcanic rocks of the series.

The interbedded sedimentary rocks are predominantly tuffaceous siltstone and shale, with some basaltic grit and sandstone. Waterlaid tuff, tuffaceous sandstone, and conglomerate are present in minor amounts. The tuffaceous sedimentary rocks are generally hard and indurated but are only slightly baked along their contacts with the overlying flows. Typically they weather spheroidally, although the finer sediments often break down into thin chips parallel to the bedding. The sediments range in color from medium gray to dark greenish gray when fresh. The color of the weathered sedimentary interbeds varies from dark reddish or grayish brown to light brownish yellow.

Mode of Origin

The Metchosin volcanics are largely submarine in origin, as indicated by the abundance of pillow lavas and fossiliferous tuffaceous sediments interbedded with the volcanic rocks. Pillow lavas are considered generally to be of subaqueous origin (Anderson, 1910), although they may be subaerial in places (Lewis, 1914). The greater part of the exposed middle and lower portions of the volcanic series is composed of pillow lavas, which are present in the upper part as well. The pillow structure is usually well developed (fig. 7), individual pillows averaging 2 to 4 feet in diameter. Columnar joints radiating from the center of the ellipsoidal pillows can be seen in most exposures. The marine sedimentary interbeds, like the pillow lavas, are found in all parts of the Metchosin volcanic series in most sections.

FIGURE 7. Metchosin pillow lava.

FIGURE 8. Well-developed columnar jointing in Metchosin basalt flow.

Flow breccia is abundant throughout the Metchosin and is probably the result of autobrecciation of basalt flows by steam explosion which accompanies submarine extrusion. Breccias are interbedded with pillow lavas, and sporadic pillows are found in many of the breccias, giving further evidence of their submarine origin.

The pillow lavas are considerably altered, as are the other basaltic rocks of the series. In the pillow lavas the alteration is greatest in the interspheroidal material, which is fine grained and glassy, as noted previously. It has been replaced and cut by veinlets of calcite, zeolites, quartz, and other secondary minerals. The origin of the altered interspheroidal material of pillow lavas has been summarized by Lewis (1914, pp. 649-650) as follows:

The spalling off of glass fragments, which may be expected to occur in most cases—perhaps most actively in water—partially fills the inter-

> spheroidal spaces with breccia, when such openings persist, owing to the failure of the pillows to fit together perfectly. . . . Occasionally a growing pillow may crack during its expansion in such a manner as to spill a portion of its liquid contents into the spaces between underlying or adjacent pillows. . . .
>
> Where conditions suitable to their production exist, the spaces still remaining unfilled offer favorable places for the wonderful variety of beautifully crystallized minerals for which some of the pillow lavas are noted. These include quartz, calcite, the zeolites, datolite, prehnite, pectolite, epidote, and many other less abundant species. Secondary processes, especially in lavas that become deeply buried, have transformed the glassy crusts and interstitial fragments in many flows into green chloritic mixtures, and in many regions corresponding changes have taken place within the crystalline lava as well.

The suitable conditions necessary to produce the alteration have not yet been fully elucidated. These conditions have been discussed by many geologists, including Lewis (1915). The formation of zeolites and associated secondary minerals in basic volcanics has been summarized by Lindgren (1913, pp. 392-399; 1933, pp. 515-517), who embodies in his discussion the conclusions of Lewis (1915), Fenner (1908, 1910), and Dewey and Flett (1911). There are two principal theories of origin: (1) that they are deposited by percolating ground waters; and (2) that their formation follows closely upon eruption of the basaltic lavas and is distinctly connected with the cooling process, their deposition taking place in the still hot rocks by the aid of thermal solutions.

The first of these two theories is quickly disposed of by Lindgren (1933, p. 516), who states:

> That zeolitization is far from being simply an effect of the leaching by surface waters is shown by the absence of the zeolites from large areas of basic flows, many of them full of vacuoles or blow-holes.

Thus the formation of the zeolites and related secondary minerals can be attributed to thermal solutions, which are considered by most writers to be mixed magmatic and meteoric waters. Lindgren concludes that the "development [of zeolites] would be greatly furthered if the eruption of the effusive rock took place under water." The same conclusion was reached by Clapp (1917, p. 287) for the nature of the thermal solutions which promoted the formation of the zeolites and related secondary minerals in the Metchosin volcanics of southern Vancouver Island.

It should be noted that zeolitization of basalts is not necessarily indicative either of submarine extrusion or of penecontemporaneous alteration. Walker (1951) has shown that zeolites formed in the subaerial Tertiary plateau basalts of northeastern Ireland considerably later than the solidification and cooling of the lavas in which they occur.

The volcanics locally piled up above sea level from time to time, especially around centers of volcanic activity, with the result that subaerial flows and pyroclastics are included in the series. The lack of sedimentary interbeds and the presence of a plug-like intrusive mass in the Baw Faw Peak area indicate that a major volcanic center may have existed there in middle Eocene time. The fine-grained gabbro of the Baw Faw Peak intrusive appears to be gradational, at least in part, into normal basalt flows; similar relationships were noted by Clapp (1917, p. 259) in the type area of the Metchosin volcanics. The intrusive is probably an eroded volcanic neck.

The volcanic series contains many small diabasic dikes and irregular intrusive bodies which are thought by the writer to represent fissures and feeder channels through which the basalt flows, pillow lavas, and flow breccia were extruded. Most of the eruptions were quiet, although the presence of pyroclastic materials testifies to the partly explosive nature of the activity. The same conclusion was reached by other workers as to the origin of the Metchosin volcanics in southern Vancouver Island (Clapp, 1917, p. 281) and in other parts of western Washington (Weaver, 1937B, p. 27).

The clastic materials constituting the sedimentary interbeds in the Metchosin volcanic series were probably derived largely from a land mass east of this area, perhaps in the vicinity of the present Cascade Range. Some of the sediments are arkosic, indicating that the source area probably consisted of schistose rocks or acidic igneous rocks. The basaltic grits and sandstones locally present were apparently derived from the underlying flow rocks. Tuffaceous debris, which is found in most of the interbeds, was supplied by contemporaneous eruptions from the nearby centers of volcanic activity. In the Willapa Hills area there were apparently a large number of these volcanic vents and fissures pouring out basaltic lavas and associated extrusive rocks.

The sea in which most of the Metchosin rocks accumulated was of moderate to shallow depth in this area, as indicated by foraminiferal assemblages obtained from the sedimentary interbeds. These indicate depths ranging from upper bathyal to inner neritic or sublittoral. The greater part of the Metchosin was probably deposited well offshore on the continental shelf of a warm sea.

Age and Correlation

Samples were collected for micropaleontologic study from interbeds of tuffaceous siltstones and shale in the upper part of the Metchosin volcanics at several localities. These localities include the following: the canyon of the Chehalis River south of Pe Ell; along the upper portion of the South Fork of the Chehalis River northwest of Ryderwood; along the banks of Stillman Creek south of Camp McDonald; and in the main line rock quarry of Weyerhaeuser Timber Company southwest of Camp McDonald. In addition, one auger sample was collected from the middle part of the series at a locality on Long-Bell Lumber Company Road 604 southwest of Wildwood. The foraminiferal assemblage from the Chehalis River locality south of Pe Ell consisted entirely of arenaceous forms having long geologic ranges and, therefore, little value for age determination and correlation. Assemblages from the other microfaunal localities were submitted to Mr. Richard Cifelli, micropaleontologist in the Centralia, Washington, office of Phillips Petroleum Company; he identified the stratigraphically significant forms and prepared partial faunal lists and age determinations for each assemblage. Parts of his report[4] on the foraminiferal assemblages collected from the Metchosin volcanic series are quoted in succeeding paragraphs; all identifications are by Mr. Cifelli. Slides containing the foraminiferal asssemblages listed in this dissertation are deposited in the Stanford University Micropaleontological Collection.

In addition to Foraminifera, the sedimentary interbeds of the upper part of the volcanic series, as well as the lower beds of the overlying upper Eocene sediments, are characterized by an abundance of recrystallized radiolarian tests. The radiolarians are preserved as small white spheroids, apparently composed largely of siliceous material. They may be seen easily with the aid of a hand lens.

Samples Wd-Ch-8 and Wd-Ch-9A, both from beds which lie 1,000 to 1,400 feet stratigraphically below the top of the Metchosin volcanic series, were collected from LSJU Micropaleontological Locality No. M-575, in the lower canyon of the South Fork of the Chehalis River. These samples yielded the following diagnostic and important species:

Sample Wd-Ch-8

Virgulina cf. V. zetina Cole
Virgulina cf. V. dibollensis Cushman and Applin
Uvigerina elongata Cole
Bulimina pyrula d'Orbigny
Bulimina ovata cowlitzensis Beck
Globobulimina pacifica Cushman
Dentalina cf. D. communis d'Orbigny

Sample Wd-Ch-9A

Nonion cf. N. applini Howe and Wallace
Virgulina cf. V. zetina Cole
Bulimina ovata cowlitzensis Beck
Uvigerina elongata Cole
Cassidulina sp.
Bulimina cf. B. stalacta Cushman and Parker
Globigerina sp.

[4]Cifelli, Richard, personal communication.

In assigning an upper middle Eocene age to the above assemblages, Mr. Cifelli makes the following comment:

> The Foraminifera in this group are poorly preserved, and identified with great difficulty. They are peculiar assemblages and show greater affinity with Gulf Coast faunas than with anything from the West Coast. The species, therefore, are only tentatively identified. To me they indicate upper middle Eocene age, but the evidence is weak. *Virgulina zetina* and *Nonion* cf. *N. applini* have been recorded by Cushman and McMasters (1936) from the B-1A zone (Laiming, 1943) of the California Eocene. (Cifelli, MS.)

The foraminiferal assemblages from the upper part of the Metchosin volcanics exposed along the banks of Stillman Creek, like those from the Chehalis River locality south of Pe Ell, consist largely of arenaceous forms which have long stratigraphic ranges. Since these assemblages have little value in age determination and correlation, they are not listed here.

Sample DH-15A was collected from thin siltstone interbeds exposed between basalt flows in the McDonald Tree Farm main line rock quarry, in sec. 16, T. 12 N., R. 4 W. (LSJU Micropaleontological Locality No. M-574). These interbeds lie within 250 feet of the top of the Metchosin volcanic series. They yielded, in addition to many arenaceous forms, the following significant species:

Sample DH-15A

Bulimina corrugata Cushman and Siegfus
Robulus weaveri Beck
Eponides umbonatus Reuss
Bulimina ovata cowlitzensis Beck

> Age upper (?) Eocene; probably equivalent to the stratigraphically lower part of the Stillwater Creek section, older than the A-1 zone Laiming, (1943). (Cifelli, MS.)

A sample from a siltstone interbed in the upper middle part of the Metchosin volcanic series exposed along Long-Bell Lumber Company Road 604 is particularly significant in that it represents the oldest Eocene foraminiferal assemblage yet reported from southwestern Washington. This sample was obtained by means of a Mobile Auger at LSJU Micropaleontological Locality No. M-573, southwest of Wildwood, from a depth of approximately 45 feet. The interbed is 2,000 to 2,500 feet stratigraphically below the top of the Metchosin volcanics in this area. The assemblage consists of more than thirty species, including the following diagnostic and important forms:

Sample Wd-59

Vaginulinopsis mexicanus var. nudicostatus (Cushman and G. D. Hanna)
Amphimorphina californica Cushman and McMasters
Eponides mexicana (Cushman)
Robulus inornatus (d'Orbigny)

Nodosaria latejugata Gümbel

Robulus pseudovortex Cole

The above list is not complete. Age middle Eocene; probably equivalent to the B-1 zone (Laiming, 1943) of the middle Eocene of California. (Cifelli, MS.)

The foraminiferal assemblages listed above from the upper one-third of the exposed section of the Metchosin volcanic series in the lower Cowlitz River-eastern Willapa Hills area indicate a middle Eocene age for that part of the series, ranging as high as uppermost middle Eocene. No fossils have been found anywhere in sedimentary interbeds in the lower part of the Metchosin volcanics, so that the age of the earliest Metchosin flows is unknown. However, it seems likely that Metchosin volcanism began early in Eocene time in this part of southwestern Washington.

The age of the Metchosin volcanic series in western Washington and Oregon has never been satisfactorily established, even though the upper part of the unit is relatively well exposed in many places. Many contradictory statements are found in the literature, and it would seem advisable to summarize here the age assignments given by previous workers.

The Metchosin volcanics in the type area in southern Vancouver Island were considered by Clapp (1917, p. 290) to be of the upper Eocene age, although he had originally assigned a doubtful Jurassic or Triassic age (Clapp, 1912, pp. 94-95) to the formation. The determination of upper Eocene age for the volcanics was based on a molluscan assemblage collected from a thin interbed of basaltic sandstone in the normal basalts on the south shore of Albert Head, west of Victoria. The specimens were examined independently by Weaver and Dall, both of whom reported that the species were characteristic of the Tejon upper Eocene of California.

It was also noted by Clapp (1917, pp. 291-292) that the fossils from the Metchosin volcanics were identical with fossils in the basalts and tuffs at Port Crecent, on the northern coast of the Olympic Peninsula. These latter volcanics were called the Crescent formation by Arnold (1906A, pp. 460-461), who correlated them with the Tejon. The Crescent formation of the northern Olympic Peninsula and the Metchosin volcanics of southern Vancouver Island were considered by Clapp to be the same formation.

Weaver originally considered all basaltic lavas and tuffs occurring within the Eocene of western Washington and northwestern Oregon to be of Tejon age (Weaver, 1912, p. 13 and Plate A). Thus he correlated the Crescent formation with the Eocene basalts which are exposed in the Coast Range of western Washington and Oregon.

In the later paper Weaver (1916B, Plate 3) referred specifically to the Eocene basalts of western Washington as "the basaltic phase of the Tejon." He showed the balsaltic phase as the lowermost of his three divisions of the Tejon, which was considered to be of upper Eocene age.

It should be noted that, in these early age determinations, the term "Tejon" had been used in an unrestricted sense. That is, all Eocene rocks which were considered to be younger than the Martinez of California were correlated with the Tejon or "Tejon upper Eocene" of California. The early unrestricted use of these names has led to some confusion in the light of subsequent stratigraphic refinements.

Later work by Weaver and others unearthed new evidence concerning the age of the Eocene volcanic units, and the earlier age assignments were revised. Regarding the age of the Metchosin volcanics, Weaver (1937B, p. 29) made the following statement: "The discovery of specimens of *Turritella andersoni* in stratified tuffs intercalated within the basaltic flows at Albert Head near Victoria indicates a middle Eocene age for the upper portion of the Metchosin volcanics." In the same paper Weaver (1937B, p. 28) applied the name Metchosin volcanics to the "eruptive rocks around the margin of the Olympic Peninsula, in the Wildcat Hills of Kitsap County, the Black Mountains of Thurston County, the hills between the Chehalis and Columbia Rivers, and the low hills between Willapa and Grays Harbors." He also noted that the lower age limit of the Metchosin volcanics is unknown, but may extend down to the middle of the early Eocene.

At about the same time the Crescent formation was assigned a middle Eocene age by Berthiaume (1938). On the basis of Foraminifera he dated the marine tuffs overlying the Metchosin volcanics "as lower middle Eocene and equivalent in part to the deposits of the Capay stage of California and Oregon."

Later Weaver (1939) extended the geographical distribution of the Metchosin volcanics by applying that name to Eocene lavas in parts of western Washington and "in the Coast Range of Oregon as far south as the Klamath Mountains. These lavas are of middle and possibly early Eocene age and range from 1,000 to 3,000 feet thick."

However, in his latest paper Weaver (1945, p. 1405) assigned the Metchosin volcanics in the Coast Range of Washington and Oregon to the Paleocene, without giving any reason for this new age assignment. There is no direct evidence that any part of the Metchosin volcanic series is older than middle Eocene, and it seems advisable to consider the age of the Metchosin as middle and possibly lower Eocene.

In recent years several new names have been proposed for middle and lower (?) Eocene volcanic units in various parts of northwestern Oregon. These new names include the Tillamook volcanic series (Warren, Norbisrath, and Grivetti, 1945); the Siletz River volcanic series (Baldwin, 1947, pp. 6-14; Snavely and Baldwin, 1948); and the Coffin Butte volcanics (Allison, 1953, pp. 3-5). These volcanic units are correlative at least in part with each other, and all three may be correlated with the Metchosin volcanic series. It is the writer's opinion that these new formational names are unnecessary, and that the name Metchosin volcanic series should be used for the lower (?) and middle Eocene volcanics which constitute the Tertiary "basement rocks" of western Oregon and Washington.

The upper part of the Metchosin volcanic series in the lower Cowlitz River-eastern Willapa Hills area is correlated on the basis of its foraminiferal fauna with the Domengine stage (middle Eocene) of California; the lower exposed part is probably equivalent to the Capay stage of the California Eocene. The Metchosin is correlated largely on the basis of stratigraphic position with the Siletz River and Tillamook volcanic series and the Coffin Butte volcanics of western Oregon and, in part, with at least the lower portion of the Crescent formation of the northern Olympic Peninsula. The tuffs and sediments of the upper part of the Crescent formation are not present in this area; the basalt flows and sedimentary interbeds of the upper part of the Metchosin probably represent their time-equivalent.

Although the lower (?) and middle Eocene volcanic units of southwestern Washington and northwestern Oregon are considered by the writer to be correlative, it is recognized that their upper age limits vary from one area to another. However, the exact age equivalence of volcanic units like these is not to be expected. The widespread volcanism which prevailed during this time probably did not begin at the same time in all parts of western Washington and Oregon, and it certainly continued later in some areas than in others. The Willapa Hills area, as noted previously, was one of the longest lived of the volcanic centers. In spite of this relatively slight variation in the age of the lavas and associated rocks, all may be assigned to the Metchosin volcanic series.

The microfauna from the lower part of the marine sedimentary formation overlying the Metchosin volcanic series in this area indicates a probable lower upper Eocene age for those sediments. Metchosin volcanism had largely ceased by the end of middle Eocene time, although locally sporadic volcanic activity seems to have continued into the early part of the late Eocene time.

Contact Relations

The base of the Metchosin volcanic series is not exposed in southwestern Washington, and the nature of the basal contact in the lower Cowlitz River-eastern Willapa Hills area is not known. Around the northern, eastern, and southern borders of the Olympic Peninsula, the Metchosin volcanics rest upon the basal Tertiary or pre-Tertiary complex of closely folded sedimentary and metamorphic rocks which constitute the central mass of the Olympic Mountains. This basal contact is either apparently conformable (Park, 1946, p. 307) or markedly unconformable (Weaver, 1937B, pp. 17, 30, 31, 33, 36; 1945, p. 1401). In the Solduc River area the volcanics overlie with angular unconformity the Solduc (Soleduck) formation (Weaver, 1937B, p. 30), which is of questionable Cretaceous age (Reagan, 1909, p. 161) or which ranges in age from early Paleocene (?) to Jurassic (?) (Weaver, 1945, p. 1401). In the type area on Vancouver Island the Metchosin volcanics lie in fault contact on the Carboniferous Leech River formation (Clapp, 1917, pp. 277-279). The contact between the volcanics and the upper Cretaceous rocks of southern Vancouver Island is not exposed.

The upper flows of the Metchosin volcanic series are overlain conformably by siltstones and shales of the lower part of the Cowlitz formation (Stillwater Creek member) along the northern and eastern borders of the Willapa Hills in the area mapped by the writer. Deposition of the marine tuffaceous sediments which comprise interbeds in the upper part of the volcanic series apparently continued as volcanism ceased, so that the contact is essentially a gradational one.

Elsewhere the contact of the Metchosin volcanics with overlying Eocene and younger Tertiary rocks has been considered as unconformable. Along the southern coast of Vancouver Island the Metchosin volcanics are unconformably overlain by relatively small basins of clastic sediments constituting the lower Miocene (?) Sooke formation, which has a coarse basal conglomerate of basalt detritus (Clapp, 1917, p. 279). Eocene sediments younger than the Metchosin volcanics are not present on Vancouver Island.

Previous workers in the Coast Range of western Washington and Oregon have considered that the volcanics and associated sedimentary rocks of middle Eocene age are separated from the sediments and intercalated volcanics of upper Eocene age by an unconformity (Weaver et al., 1944; Allen and Baldwin, 1944, p. 21 and pls. 5 and 6; Weaver, 1945, p. 1405; Warren, Norbisrath, and Grivetti, 1945; Baldwin, 1947, p. 25; Snavely and Baldwin, 1948, p. 812; Rau, 1951, p. 420; Snavely, Rau, Hoover, and Roberts, 1951, p. 1060; Snavely, Roberts, Hoover, and Pease, 1951). However, there is no widespread unconformity within the Eocene rock sequence of the area mapped by the writer; the upper Eocene Cowlitz formation rests conformably upon the middle Eocene Metchosin volcanic series. Thus, while there may be an unconformity between middle and upper Eocene rocks in other parts of western Washington and Oregon, there is no such stratigraphic break in this area. Indeed, in many places it is difficult to draw the line between middle and upper Eocene rocks in this part of southwestern Washington.

In the Willapa Hills southwest of Ryderwood, along the southern boundary of the mapped area, the Metchosin volcanic series is overlain with marked angular unconformity by basalt flows and sandstones of the middle Miocene Astoria formation.

COWLITZ FORMATION

General Statement

After the end of Metchosin volcanism in the lower Cowlitz River-eastern Willapa Hills area, deposition apparently persisted until very late Eocene time with only local, minor interruptions. Marine sedimentation continued as the volcanic activity waned, and a few thin basalt interbeds and intrusions are found in the lower part of the predominantly marine sedimentary sequence of post-Metchosin Eocene rocks.

A thick series of marine, brackish-water, and terrestrial sediments with relatively minor intercalated basaltic rocks, accumulated during late Eocene deposition. This rock sequence is a mappable formation unit in this part of southwestern Washington, and, since it includes the original and emended type sections of the Cowlitz formation (Weaver, 1912, p. 13; 1937A), it is here referred to the Cowlitz formation. This thick formation includes more than 5,000 feet of marine siltstones and sandstones which are stratigraphically lower than the rocks exposed along Olequa Creek, and it therefore becomes necessary to expand Weaver's (1937A) type section of the Cowlitz formation to include the strata exposed along Stillwater Creek from its confluence with Olequa Creek westward to the contact with the uppermost basalt flows of the Metchosin volcanic series 3 miles west of Ryderwood. The type Cowlitz formation, as redefined herein, consists of more than 8,000 feet of upper Eocene sediments and subordinate volcanic rocks exposed along Stillwater and Olequa Creeks as far south as the Cowlitz River (pl. 2). The beds exposed along the Cowlitz River from the bend 1½ miles east of Vader southward to the mouth of Olequa Creek are approximately equivalent to the middle part of the above section.

The Cowlitz formation as originally defined by Weaver (1912, p. 13) in southwestern Lewis County consisted of the 200 feet of upper Eocene sediments exposed in the bluffs along the west bank of the Cowlitz River and 1¼ miles east of Vader. Later the type Cowlitz formation was expanded (Weaver 1937A) to include the 4,300 feet of upper Eocene strata exposed along Olequa Creek from its confluence with the Cowlitz River northward to the contact with the overlying Oligocene sediments south of Winlock. Weaver stated that the extreme lower portion of the Cowlitz formation was not exposed in this section. Later Weaver (1937B, p. 90) noted the Eocene sediments in the valley of Stillwater Creek, which has cut its channel in Metchosin volcanic rocks and the overlying sediments, and he stated (idem, p. 91): "There may be several thousand feet of shales between the base of the [Olequa Creek] measured section and the top of the Metchosin volcanics." The foregoing statement indicates to the writer that Weaver considered the sediments of at least the upper part of the Stillwater Creek section as part of the Cowlitz formation. He certainly left room for the expansion of the type Cowlitz formation, if subsequent work should show (as it has shown) that the emendation is desirable, to include the Eocene sediments and subordinate volcanic rocks exposed along Stillwater Creek above the Metchosin.

Aside from the type locality, sections of the Cowlitz formation are best exposed along the South Fork of the Chehalis River from the mouth of its canyon about 2 miles south of Wildwood to the contact with overlying Oligocene sediments 1 mile southwest of Curtis; along the streams and logging roads in the hills east of the Wildwood-Vader road, in Tps. 11 and 12 N., R. 3 W., W. M.; in road cuts along R-101 and other logging roads, the Lost Valley road, and the Wendling road, northwest of Camp McDonald; and along the Chehalis River from a point 1 mile south of Pe Ell northward to the mouth of the tributary stream in the SE¼ sec. 22, T. 13 N., R. 5 W. In this area the Cowlitz formation includes all Eocene sediments and intercalated volcanics from the top of the Metchosin volcanic series to the top of the upper Eocene sedimentary section. In the opinion of the writer, predominantly marine sediments and intercalated volcanic rocks of upper Eocene and questionable upper middle Eocene age in all parts of southwestern Washington may be referred to the Cowlitz formation.

The Cowlitz formation in the lower Cowlitz River-eastern Willapa Hills area has been subdivided by the writer into four members, each of which is a mappable unit in part of the area under investigation. The members are closely related, in some instances interfingering with one another and in other instances grading one into the other, so that they represent simply different lithologic facies of the Cowlitz formation. The formation may be traced over wide areas, whereas its member units are only locally well developed. It is not advisable to split the Cowlitz formation in this area into several new formations, thereby introducing new formational names which would be useless, or even confusing, in other areas.

A more-or-less continuous section of 5,400 feet of marine and brackish-water siltstones, sandstones, and shales is exposed along Stillwater Creek from the contact with the Metchosin volcanic series about 3 miles west of Ryderwood eastward to the mouth of Brim Creek, 3½ miles northeast of Ryderwood (pl. 2). Excellent exposures of part of this section are found along the railroad grade which follows the ridge south of Stillwater Creek for a distance of some 2½ miles, west of Ryderwood. The sediments are in part tuffaceous, micaceous, carbonaceous, limy, or clayey, and they locally contain abundant Foraminifera. The name "Stillwater Creek member" is here proposed for these sediments. This member includes near its base a few thin basalt flows, sills, and dikes. It is characterized by the absence of coal beds and the virtual absence of megafossils, which are abundant in the upper part of the Cowlitz formation in this area.

Overlying the Stillwater Creek member of the Cowlitz formation are more than 2,500 feet of brackish-water, marine, and nonmarine sandstones, siltstones, and mudstones, with numerous local intercalated coal beds. These overlying sediments are in part carbonaceous, micaceous, glauconitic, or limy, and they contain abundant well-preserved megafossils and foraminifers in many places. These strata are exposed in the lower course of Stillwater Creek from its confluence with Olequa Creek upstream to the mouth of Brim Creek, and along Olequa Creek from its confluence with the Cowlitz River northward to the contact with the overlying Oligocene sediments south of Winlock (pl. 2). It is here proposed to name this coal-bearing, highly fossiliferous upper portion of the Cowlitz formation, the "Olequa Creek member." This member includes, in the southeast corner of the area under investigation, basalt flows and flow breccia intercalated with the marine and brackish-water sediments.

The "Goble volcanics member" is the name here applied to the relatively thin basalt flows and flow breccia interbedded with upper Eocene marine and coal-bearing sediments in the vicinity of the town of Olequa and southward along Olequa Creek and the Cowlitz River at least as far as the mouth of the Toutle River. The Goble volcanic series was named and described by Lowry and Baldwin (Wilkinson, Lowry, and Baldwin, 1946, pp. 4-15) and was thought to be upper Eocene in age and possibly in part lower Oligocene. In its type area in the vicinity of Goble, Oregon, and along both sides of the Columbia River as far north as Kelso, Washington, the Goble volcanic series consists of more than 5,000 feet of basaltic flows, pyroclastics, and minor amounts of sediments. The Goble volcanics member in the lower Cowlitz River-eastern Willapa Hills area consists of numerous basalt flows, flow breccia, and thin pyroclastic rocks, which are interbedded with sediments of the Cowlitz formation exposed along the Cowlitz River and the lower course of Olequa Creek. No thickness has been measured for the volcanics in this area, although the total thickness of the intercalated basalt flows, flow breccia, and pyroclastics may be as great as 1,000 feet.

The fourth member of the Cowlitz formation appears to be more restricted in its areal distribution than any of the other three. It is a sequence of 1,200 to 1,500 feet of massive and bedded lapilli tuff, agglomerate, breccia, and thin tuffaceous siltstones exposed in a wedge-shaped area of outcrop in the vicinity of Pe Ell, where it is interfingered with the lower beds of the Stillwater Creek member. This volcanic unit is best exposed along the Chehalis River southward from Pe Ell for a distance of 1.4 miles. The name "Pe Ell volcanics member" is here proposed for this volcanic unit in the lower part of the Cowlitz formation.

On succeeding pages the members of the Cowlitz formation are described in stratigraphic sequence, from older to younger: (1) the Stillwater Creek member, (2) the Pe Ell volcanics member, (3) the Olequa Creek member, and (4) the Goble volcanics member. Following the descriptions of the member units, a brief discussion of the age and correlation of the Cowlitz formation is presented.

Stillwater Creek Member

Distribution and Thickness

The type section of the Stillwater Creek member, as described previously, is a sectioin across the widest part of the roughly arc-shaped belt of outcrop of this unit around the northern and eastern margins of the Willapa Hills (pl. 1). This member can be traced from the hills west of Pe Ell eastward through Camp McDonald and Boistfort, thence southward through the type section to the contact with Miocene rocks south of Ryderwood. A thick sequence of marine and brackish-water siltstones, shales, arkoses, and basaltic sandstones, with subordinate intercalated volcanic rocks, is exposed along the streams, roads, and railroad grades which cross this outcrop belt. The predominantly sedimentary unit includes a thick volcanic member near its base in the vicinity of Pe Ell, and relatively minor basalt flows and intrusives in other parts of the mapped area.

Within the lower Cowlitz River-eastern Willapa Hills area the minimum thickness of the Stillwater Creek member is exposed in the northwest corner near Pe Ell, where 2,100-2,600 feet of marine sediments and volcanic rocks crop out along the Chehalis River between the top of the Metchosin volcanic series and the base of the Olequa Creek member. This thickness is fairly constant in sections between Pe Ell and Boistfort, increasing slightly from west to east. The member thickens markedly toward the south from Boistfort, reaching its maximum thickness of 5,400 feet along Stillwater Creek.

Dips in the Stillwater Creek member are locally as high as 30°-35°, but many of these are probably due to faulting or slumping. Most dips are lower, generally between 10° and 20°. Estimates of thickness are based in part on measured sections in river traverses and in part on an average dip of 15°.

The direction of the regional dip of the Stillwater Creek member is northerly to northeasterly between Pe Ell and Boistfort; between Boistfort and Ryderwood it changes gradually from northeasterly to southeasterly along Sillwater Creek. The sediments and intercalated volcanic rocks of this member constitute part of the north limb and eastward-plunging nose of the Willapa Hills anticline.

Lithology

The Stillwater Creek member consists largely of soft to indurated, laminated to massive marine shales, siltstones, silty sandstones, and mudstones, together with massive to crossbedded or laminated, friable to compact, fine-grained arkoses, feldspathic sandstones, and sandy siltstones. Locally it includes thin interbedded basalt flows and pyroclastic material, and tuffaceous and basaltic sandstones. A series of lapilli tuff, agglomerate, breccia, and thin tuffaceous siltstones interfingered with the lower part of this predominantly sedimentary unit in the Pe Ell area is described under the heading "Pe Ell volcanics member."

The finer grained sediments of the Stillwater Creek member are thin bedded to massive; they are commonly tuffaceous and micaceous and may be either carbonaceous, limy, glauconitic, or pyritized. Sporadic calcareous concretions and limy layers are present in some exposures. Locally the shales and siltstones contain pieces and fragments of white to light-gray silicified wood. Abundant recrystallized Radiolaria are found in some beds, and most sections of the member yield well-preserved Foraminifera.

The arkoses of the Stillwater Creek member typically constitute beds 100 feet or more in thickness, although they also occur rhythmically bedded with siltstones and sandy siltstones. The arkoses are usually massive to crossbedded, well sorted, and friable. Mineralogically, the sand grains consist of feldspar, quartz, micas, and rock fragments, in order of decreasing abundance. The matrix and cementing material are calcite, clay minerals, and iron oxides, in varying proportions. Under the attack of weathering processes, these sandstones either break down to a fine sand or form a fine brownish-gray impure clay. The tuffaceous and basaltic sandstones are generally thin, hard, and massive. They weather spheroidally and are more resistant to physical and chemical breakdown than are the arkoses.

The colors of the Stillwater Creek sediments vary widely. The marine shales, siltstones, and mudstones range from bluish gray and greenish gray to dark brownish gray, with medium gray the most common color. Weathering causes these rocks to disintegrate into chips and fragments which are typically pale yellowish brown in color. The arkoses and sandy siltstones are generally bluish gray in fresh exposures, and weathering produces a variety of colors ranging from dark reddish brown to pale brownish yellow and yellowish white. Where the sandstones contain abundant ferruginous material, weathered outcrops are streaked and banded in various shades of red, brown, and yellow. The tuffaceous and basaltic sandstones are typically greenish gray to brownish gray, weathering to a pale brownish color.

Two rock types not previously mentioned occur locally in this lower member of the Cowlitz formation. One is basaltic pebble and cobble conglomerate, thin beds of which crop out at several localities, notably along Stillwater Creek and in road cuts along logging roads in the hills east of the Wildwood-Vader road. The other rock type is an intraformational breccia which occurs in siltstones in the bed of the South Fork of the Chehalis River south of Wildwood. The presence of these rocks is significant in that they reflect at least local orogenic movements during the deposition of the Stillwater Creek member.

Mode of Origin

The finer sediments of the Stillwater Creek member are marine in origin, as is indicated by the lithology and bedding of the sediments and by their well-preserved foraminiferal assemblages. The species of Foraminifera in the Stillwater Creek sediments indicate a depth of water ranging from inner neritic to upper bathyal. The environment of deposition in the type section becomes progressively shallower in the upper part of the member, and the Foraminifera also indicate progressively deeper water conditions of deposition to the north and west along the belt of outcrop. A general decrease in grain size of the sediments toward the northwest gives further evidence of deepening of the sea in that direction.

The arkoses, feldspathic sandstones, and sandy siltstones are commonly crossbedded, apparently having been deposited in shallow marine or brackish water under near-shore or deltaic conditions. In some exposures, deltaic bedding is readily observed, with topset, foreset, and bottomset beds clearly visible. Locally the deltaic sediments may have piled up above sea level, so that the coarser sediments possibly were deposited under subaerial conditions. The sediments of the Stillwater Creek member are largely marine, however, and most of them were deposited in water as much as 200 meters in depth.

The thin basalt flows, dikes, and sills in the lower part of the member represent the final stage of the volcanic activity which produced the Metchosin volcanic series. At various places in western Washington and Oregon Metchosin volcanism persisted longer than in most places, and these thin basalt flows and minor intrusives are the products of the last feeble eruptions from the volcanic vents and fissures in the Willapa Hills area.

The embayment or trough in which the sediments of the Cowlitz formation were deposited apparently accumulated clastic materials from two or more source areas. The abundant quartz and mica in the arkose and siltstones of the Stillwater Creek member could not have been derived from basalt but must have come from an area of schistose rocks or acidic igneous rocks. Such a source area may have existed in the vicinity of the Cascade Range, east of the Cowlitz Basin, during late Eocene time. Some of the sediment deposited during this time was probably carried by the same westward-flowing rivers which were supplying material to the Puget Basin, where the thick coal-bearing Puget group was deposited during Eocene time. The basaltic sandstones and conglomerates were apparently derived from Metchosin volcanic rocks which rose above sea level in the Willapa Hills area during Cowlitz time and which remained above sea level as a source of sediments through late Eocene and Oligocene time.

Age and Correlation

The Stillwater Creek member of the Cowlitz formation contains in most sections a well-preserved microfauna, by means of which the age of this unit can be determined. The foraminiferal fauna indicates an upper Eocene age, with the lowest beds possibly of upper middle Eocene age locally; the upper part of the member is equivalent in part to the A-1 foraminiferal zone (Laiming, 1943) of the upper Eocene of California. However, the Californian Eocene foraminiferal zones are not strictly valid in western Washington, although they are used in correlation. The A-3 and A-2 zones of the upper Eocene are apparently not represented in the Cowlitz foraminiferal assemblages.

Megafossils are rare in the lower part of the Cowlitz formation in this area and are poorly preserved where present. However, microfossiliferous samples were collected from many localities within the outcrop belt of the Stillwater Creek member, and the foraminiferal assemblages obtained from these samples were used in dating and correlating the unit. The following partial faunal lists and age determinations were prepared by Mr. Richard Cifelli, who examined the foraminiferal assemblages and identified the forms useful for dating and correlation. The assemblages submitted to Mr. Cifelli were selected by the writer from groups of samples collected from several sections of the Stillwater Creek member.

The following diagnostic and important species are from strata exposed along Stillwater Creek west and northwest of Ryderwood (LSJU Micropaleontological Locality No. M-580). The beds from which sample DH-260A was taken lies approximately 1,600 feet stratigraphically above the base of the Stillwater Creek member; sample DH-257 was collected from siltstones 3,000 feet stratigraphically above the base of the member.

Sample DH-260A

Plectofrondicularia jenkinsi Church
Plectofrondicularia packardi var. multilineata Cushman and Simonson
Cibicides hodgei Cushman and Schenck

Cibicides aff. C. natlandi Beck
Robulus weaveri Beck
Eponides ellisorae Garrett
Dentalina colei Cushman and Dusenbury
Bulimina sp.

Sample DH-257

Uvigerina yazooensis Cushman
Uvigerina garzaensis Cushman and Siegfus
Eponides pygmea (Hantken)
Plectofrondicularia jenkinsi Church
Marginulina sp.
Robulus sp.

Age upper Eocene; correlative with the A-1 zone (Laiming, 1943) of upper Tejon age of California. (Cifelli, MS.)

The following species are from the lower part of the Stillwater Creek member along the South Fork of the Chehalis River south of Wildwood (LSJU Micropaleontological Locality No. M-576). The beds from which this sample was collected lie 400 feet stratigraphically above the base of the member.

Sample Wd-Ch-17L

Robulus welchi Church
Bulimina jacksonensis Cushman
Ellipsonodosaria sp.
Haplophragmoides sp.
Cyclammina pacifica Beck
Textularia?

Age upper (?) Eocene; probably equivalent to the stratigraphically lower part of the Stillwater Creek section, below DH-260A (see above). Probably older than A-1 (Laiming, 1943). Upper Eocene age is indicated by the presence of *Robulus welchi* and *Bulimina jacksonensis,* however the evidence is not very strong. (Cifelli, MS.)

Foraminiferal assemblages from the middle part of the Stillwater Creek member along the South Fork of the Chehalis River are similar to those previously recorded from the type section in Stillwater Creek, and therefore are not listed. They are characterized by the presence of the same diagnostic species, namely *Plectofrondicularia jenkinsi, Eponides pygmea, Robulus welchi,* and *Plectofrondicularia packardi* var. *multilineata.* All but the last of the above-named species are considered by Laiming (1943) as characteristic of the A-1 zone of the upper Eocene in California.

The species listed below were identified in a sample from the upper part of the Stillwater Creek member along the South Fork of the Chehalis River downstream from its confluence with Stillman Creek, southwest of Klaber (LSJU Micropaleontological Locality No. M-577), from beds approximately 300 feet stratigraphically below the top of the member. This assemblage has not been recognized elsewhere in the area. However, an equivalent faunule occurs in a core sample from the Selburn-Washington Oil Corporation Wulz No. 1 well from a depth of about 5,900 feet. The core was taken approximately 500 feet below the base of the coal-bearing rocks, in strata equivalent to the upper part of the Stillwater Creek member in its type section. The Wulz well was drilled in 1952 on the Forest structure, 7 miles southeast of Chehalis and about 8 miles northeast of Winlock.

Sample Wd-Ch-55C

Robulus inornatus (d'Orbigny)
Bulimina schencki Beck
Plectofrondicularia packardi var. multilineata Cushman and Simonson
Bolivina basisenta Cushman and Stone
Bolivina jacksonensis Cushman and Applin
Valvulineria? cf. V. willapaensis Rau

Age upper Eocene, A-1 (Laiming, 1943); the exact equivalent of this faunule was not found along Stillwater Creek. However, it does occur in the Wulz well at about 5,900 feet, 500 feet below the Skookumchuck-McIntosh contact. It is probably represented by a barren interval in Stillwater Creek. (Cifelli, MS.)

A group of samples from the lowermost part of the Cowlitz formation along Stillman Creek south of Camp McDonald (LSJU Micropaleontological Locality No. M-579) were collected from strata less than 500 feet above the top of the Metchosin volcanics. The following species were identified from one foraminiferal assemblage in this group.

Sample MK-S-6H

Bulimina jacksonensis Cushman
Bulimina corrugata Cushman and Siegfus
Valvulineria thomasi Cushman and Simonson
Robulus sp.
Robulus weaveri Beck
Eponides sp.
Cibicides cf. C. pseudowuellerstorfi Cole

This assemblage may be the equivalent of the McIntosh Lake fauna (Snavely, Rau, Hoover, and Roberts, 1951). It has the general appearance of an upper Eocene faunule, but does not correlate well with any of Laiming's zones. It is probably older than A-1. Upper Eocene age is indicated by the presence of *Bulimina jacksonensis*, *B. corrugata*, and *Cibicides* cf. *C. pseudowuellerstorfi*. (Cifelli, MS.)

Siltstones immediately overlying the Metchosin volcanic series are exposed in a large road cut near the junction of road R-1 and the Main Line Truck Road west of Camp McDonald. The foraminiferal assemblage from this locality (Sample DH-291) closely resembles the Stillman Creek assemblage listed above, and the two are considered to be correlative. They represent the oldest faunules yet found in the lower part of the Cowlitz formation in this area.

Other samples collected along Stillman Creek yielded foraminiferal assemblages similar to those already noted from the Stillwater Creek member in its type section and along the South Fork of the Chehalis River. An assemblage from beds in Stillman Creek approximately 1,200 feet stratigraphically above the base of the member was assigned an upper Eocene age, older than Laiming's (1943) A-1 zone. Other faunules from beds higher in the section indicate upper Eocene age and are correlative with the A-1 zone.

Samples were also collected from the upper part of the Stillwater Creek member along the Chehalis River north of Pe Ell (LSJU Micropaleontological Locality No. M-581). This section is about 20 miles (along the strike) distant from the Stillwater Creek section, and the faunules apparently represent deeper water equivalents of the fauna of the type section. The following species were identified in two assemblages from the Chehalis River locality. These two assemblages are from strata respectively 220 feet and 50 feet below the top of the member.

Sample DH-210

Uvigerina garzaensis Cushman and Siegfus
Plectofrondicularia packardi var. multilineata Cushman and Simonson
Cibicides natlandi Beck
Eponides pygmea (Hantken)
Gyroidina orbicularis var. planata Cushman
Allomorphina cf. A. macrostomata Karrer
Robulus sp.

Sample DH-212

Uvigerina garzaenis Cushman and Siegfus
Eponides pygmea (Hantken)
Plectofrondicularia jenkinsi Church
Robulus sp.

Age upper Eocene; correlated with the A-1 zone of Laiming (1943) on the basis of the presence of *Plectofrondicularia jenkinsi*. (Cifelli, MS.)

The foraminiferal assemblages listed above indicate an upper Eocene age for the Stillwater Creek member. The upper one-third to two-thirds of the member is correlative in part with the A-1 zone (Laiming, 1943) of upper Tejon age of California. The lower part cannot be correlated with any of the Californian Eocene zones, since the A-2 and A-3 zones do not seem to be present in this region. This lower part is probably upper Eocene in age, but may range as low as uppermost middle Eocene. There is no direct evidence for this possibility, but lithologically similar sediments which have been assigned an upper middle Eocene age (Snavely, Rau, Hoover, and Roberts, 1951) are found in the Centralia-Chehalis coal districts and in western Oregon.

The Stillwater Creek member of the Cowlitz formation is correlated with at least the upper part of the McIntosh formation

(Snavely, Rau, Hoover, and Roberts, 1951) in its type area in southern Thurston County. The McIntosh formation was assigned a middle Eocene age and correlated with the B-1A zone (Laiming, 1943) of California on the basis of a microfauna collected from less than 100 feet of beds in the lower part of the exposed section. The upper part of the McIntosh formation in its type area has yielded no fossils, but the foraminiferal faunule from the upper part of the McIntosh formation in the Wulz well is correlative with the A-1 zone (Laiming, 1943) of the upper Eocene of California.[5] Thus the Stillwater Creek member is to be correlated at least in part with the McIntosh formation and perhaps with the Mill Creek beds and Sacchi Beach beds of local usage (Snavely, Rau, Hoover, and Roberts, 1951, p. 1059) in western Oregon. The upper part of the member may also be correlative with the lower Coaledo formation of Oregon,[6] as described by Allen and Baldwin (1944, pp. 21-23).

Contact Relations

The basal contact of the Stillwater Creek member, as discussed previously, is essentially gradational upward from the Metchosin volcanic series. The two units are conformable in all sections, and there is no evidence for a stratigraphic break between Metchosin and Cowlitz deposition in this region. A marked hiatus would seem to be indicated by the absence of Laiming's A-2 and A-3 foraminiferal zones in this area. However, this apparent gap in the stratigraphic record is probably due to facies differences which cause some of the Californian zones to be absent here.

The contact with the overlying sediments of the Olequa Creek member is also conformable and gradational. It represents the change from predominantly marine conditions of deposition to the brackish-water, shallow marine, and terrestrial conditions under which the coal-bearing sediments, marine mudstones and siltstones, and intercalated volcanics of the Olequa Creek member were deposited.

The Stillwater Creek member is unconformably overlain by basalt flows and intercalated sandstones of the middle Miocene Astoria formation in the vicinity of Ryderwood. The contact exhibits marked angular unconformity in places. It is apparent that the Miocene sediments and volcanics were laid down on the upturned and eroded edges of the Eocene strata, probably in a transgressing sea.

[5] Cifelli, Richard, personal communication.
[6] Idem.

Pe Ell Volcanics Member

Distribution and Thickness

The name "Pe Ell volcanics member" of the Cowlitz formation is here proposed for a series of lapilli tuffs, agglomerates, breccia, and thin interbedded tuffaceous siltstones in the vicinity of Pe Ell, western Lewis County, Washington. The volcanics are best exposed in the banks of the Chehalis River in sec. 4, T. 12 N., R. 5 W., and secs. 33 and 34, T. 13 N., R. 5 W., W. M., where 1,200-1,500 feet of pyroclastic rocks are intercalated with the lower part of the Stillwater Creek member. This locality is designated as the type section of the Pe Ell volcanics member.

In the area mapped by the writer the volcanic member attains a maximum thickness of 1,200-1,500 feet in its type section along the Chehalis River. It thins rapidly eastward, wedging out at the surface in the southern part of sec. 6, T. 12 N., R. 4 W., about 4 miles southeast of Pe Ell. The Pe Ell member is not exposed elsewhere in the area. Investigation by the writer in the hills west of Pe Ell indicates that the volcanics thin rapidly along strike toward the west as well.

Dips in the Pe Ell volcanics vary from 8° to 18°, averaging between 12° and 15°. The beds trend in a general east-west direction, and all dips measured are, with one exception, northerly. The exception is a southwesterly dip in a siltstone exposure in the upper part of the member; this anomalous dip is probably due to faulting. The siltstone is part of a small block which was rotated and faulted down into the upper part of the volcanics.

Lithology

The Pe Ell volcanics member consists chiefly of massive to thickly bedded water-laid basaltic lapilli tuff, with subordinate basaltic agglomerate and breccia and thin hard tuffaceous siltstone interbeds. Fragments of basalt in the lapilli tuff are generally angular and less than 1 inch in average diameter, and are set in a matrix of sandy to silty lithic tuff. The agglomerate and breccia, similar to the lapilli tuff in appearance, are considerably coarser, their component basalt fragments averaging from 1 to 3 inches in diameter.

The thin tuffaceous siltstone interbeds are hard and indurated, consisting almost entirely of very fine basaltic grains and tuffaceous material. They rarely exceed a foot or two in thickness, and no fossils have yet been found in them. They are, however, significant because they provide the only reliable dips in much of the member.

Outcrops typically appear massive and rounded, as weathering produces smoothly rounded forms in these pyroclastic rocks. The Pe Ell volcanics show rectangular jointing locally, and numerous small faults cut many exposures. Locally the volcanics are cut by veins and thin seams of calcite and other secondary minerals, which stand out as miniature ridges in fresh outcrops. Calcite, zeolites, chlorite, and other secondary minerals occur in the interstices and matrix of the coarse pyroclastic rocks.

The volcanic rocks are typically greenish gray to dark gray in color in fresh exposures, ranging from dull green to nearly black. Weathering initially causes rounding of the outcrops and joint blocks, followed by the development of spheroidal fracturing with continued deep weathering. The rocks tend to break down into their component basaltic grains, and the matrix weathers to yellowish-brown clayey material. The colors change to shades of dark brown and yellowish brown. Weathered outcrops of the volcanics are commonly streaked with reddish-brown iron oxide stain.

Mode of Origin

The rocks of the Pe Ell volcanics member were apparently deposited under marine conditions and well offshore. The unit is conformably underlain and overlain by well-bedded microfossiliferous marine siltstones. Foraminiferal assemblages from the beds above and below the volcanics indicate deposition largely in the outer neritic depth zone. Although no fossils have been found within the volcanic member, the uniform, thick bedding and thin siltstone interbeds indicate marine deposition in quiet waters.

The source of the basaltic and tuffaceous material which constitutes the Pe Ell volcanics was probably a volcanic center, or several centers, in the Doty Hills area about 8 miles north of Pe Ell. There a thicker and considerably more extensive sequence of lapilli tuff, agglomerate, tuff, and basaltic sandstone is exposed.[7] In the area mapped by the writer the volcanic member attains its maximum thickness in the vicinity of Pe Ell, thinning rapidly both eastward and westward.

Age and Correlation

Foraminiferal assemblages from the 100-foot section of siltstones immediately underlying the Pe Ell volcanics member unfortunately consist of arenaceous forms which have not as yet proved useful in age determination and correlation. However, it is interesting to note that the lower beds of the Stillwater Creek member in its type section yielded a similar arenaceous microfauna. The siltstones in the Chehalis River section are lithologically similar to the lowermost siltstones along Stillwater Creek, the South Fork of the Chehalis River, and Stillman Creek. The latter contain foraminiferal assemblages which indicate lower upper (?) Eocene age. The siltstones underlying the Pe Ell volcanics along the Chehalis River are to be correlated with the lowermost beds of the Stillwater

[7] Pease, Michael H., Jr., personal communication.

Creek member in its type section and are of lower upper (?) Eocene age.

The foraminiferal fauna in the part of the Stillwater Creek member overlying the volcanic member north of Pe Ell has been discussed previously. It indicates upper Eocene age and is correlative with the A-1 foraminiferal zone (Laiming, 1943) of the Californian Eocene. The fauna was collected from beds 800-1,000 feet stratigraphically higher than the top of the volcanics. Therefore, it does not date precisely the upper limit of the volcanics. However, the upper part of the Pe Ell volcanics member is considered to be of upper Eocene age, perhaps older than the A-1 zone (Laiming, 1943). Thus the age of the Pe Ell volcanics member ranges from lower upper (?) Eocene to upper Eocene. As mentioned previously, the volcanics are intercalated with the lower half of the Stillwater Creek member of the Cowlitz formation.

The Pe Ell volcanics are lithologically similar to the Crescent formation of the northern Olympic Peninsula (Arnold, 1906A, pp. 460-461; Weaver, 1937, pp. 40-45), and, like the Crescent formation, they closely overlie the Metchosin volcanic series. However, the age of the Crescent formation has been established as middle Eocene, equivalent to the Capay stage of California (Weaver, 1937, p. 42; Berthiaume, 1938). The Pe Ell volcanics are distinctly younger, and cannot be correlated with the Crescent formation.

The Pe Ell member occupies approximately the same stratigraphic position as the Northcraft formation (Snavely, Roberts, Hoover, and Pease, 1951) of the Centralia-Chehalis coal district. The Northcraft formation consists of 700-1,000 feet of lava flows (largely calcic andesite, with some basalt), pyroclastic rocks, and tuffaceous and basaltic sedimentary rocks. The formation was thought to be of upper middle Eocene age, but later studies indicate that it is of probable lower upper Eocene age. The Pe Ell volcanics show little lithologic similarity to the Northcraft formation, but the two units may be correlative. The Pe Ell volcanics are older than the Goble volcanics (Wilkinson, Lowry, and Baldwin, 1946, pp. 4-15), which interfinger with the upper part of the Cowlitz formation in the southeastern part of the area.

Contact Relations

The Pe Ell volcanics member is underlain and overlain conformably by marine siltstones of the lower part of the Stillwater Creek member, with which it is interfingered.

Olequa Creek Member

Distribution and Thickness

A thick series of brackish-water, marine, and terrestrial arkoses, feldspathic sandstones, and siltstones with intercalated coal beds, together with fossiliferous siltstones and mudstones, constitutes the Olequa Creek member of the Cowlitz formation. These rocks are exposed in an irregular belt of outcrop trending southeast across the lower Cowlitz River-eastern Willapa Hills area from the Chehalis River to the Cowlitz River (pl. 1). The type section, as described previously, is the well-exposed and abundantly fossiliferous section along Olequa Creek from its confluence with the Cowlitz River northward to the Oligocene contact south of Winlock, and along the lower course of Stillwater Creek from Brim Creek to Olequa Creek (pl. 2.).

The outcrop belt of the Olequa Creek member is narrowest in the northwest corner of the area, where it is only ½ mile wide along the Chehalis River. It widens gradually and irregularly eastward to Klaber, where the section across the member is a little more than 1 mile long. The Olequa Creek member thickens rapidly southeastward from Klaber, attaining its maximum width of outcrop—nearly 5 miles—in the section between Olequa Creek and the Cowlitz River. Exposures of the sediments and intercalated volcanics of this part of the Cowlitz formation extend southward along the banks of the Cowlitz River to and beyond the mouth of the Toutle River.

Within the mapped area the minimum thickness of the Olequa Creek member is exposed in the Chehalis River north of Pe Ell, where the member consists of 800 feet of carbonaceous siltstones and sandstones. The thickness of the type section in Olequa and Stillwater Creeks is approximately 2,500 feet, and the unit continues to increase in thickness toward the southeast. Although exposures are not continuous, and calculation of total thickness is difficult, the thickness of the Olequa Creek member along the banks of the Cowlitz River is apparently not less than 4,000 feet and may be as great as 5,000 feet or more.

Dips within the Olequa Creek member are locally as high as 45°, although the average dip is less than 20°. Dips greater than 20° have been measured more commonly in the sediments of this member than in any of the other Eocene rocks in the area under investigation. These high dips may be due to one or more of several factors: faulting; structural incompetence of the sandstones and sandy siltstones; slumping and rotation of slump blocks; and irregular cross-bedding, which may give rise to both abnormally high and abnormally low dips. However, dips ranging from 10° to 20° predominate, and estimated thickness of the Olequa Creek member in most sections is based on an average dip of 12° to 15°.

The direction of regional dip of this upper part of the Cowlitz formation varies in much the same manner as that of the underlying Stillwater Creek member. Dips are generally northerly to northeasterly in sections across the narrow outcrop from Klaber to the Chehalis River north of Pe Ell. From Klaber southeastward to the Cowlitz River the regional dip is northeasterly to easterly, with minor reversals of dip and anomalous attitudes locally. Along the banks of the Cowlitz River southward from the mouth of Olequa Creek the sediments and intercalated volcanics have a northerly regional dip.

Lithology

The sediments of the Olequa Creek member comprise two distinct lithologic facies: (1) brackish-water, shallow marine, and nonmarine facies consisting of massive to crossbedded, fine-grained arkoses, feldspathic sandstones, and thin-bedded sandy siltstones, with intercalated beds of coal, bone, and carbonaceous siltstone and claystone; and (2) a near-shore marine facies composed of massive to well-bedded mudstones, siltstones, and silty sandstones, in part carbonaceous, micaceous, glauconitic, and limy, and containing abundant well-preserved megafossils and microfossils. In addition, pyroclastic rocks and basaltic sediments are interbedded with the upper part of the member southwest of Toledo, and basalt flows and flow breccia of the Goble volcanics member are interfingered with the Olequa Creek sediments south of Vader.

The sandstones of the coal-bearing facies of the Olequa Creek member are typically fine grained, well sorted, crossbedded to massive, and friable to compact. They are arkoses and feldspathic sandstones, which may be tuffaceous or basaltic in part. The constituent sand grains are angular to subangular grains of feldspar, quartz, mica, and rock fragments, in order of decreasing abundance. The matrix of the rock is composed of calcite, clay materials, glass shards, and iron oxides, in varying proportions. In most exposures the sandstone is friable; however, it is cemented in places with calcite, iron oxide, or clay.

The color of the sandstone is typically medium bluish gray on fresh surfaces, but the appearance changes rapidly on exposure to the air. The rock weathers to a light-gray or brownish-gray clay where water is abundant, or breaks down into its component sand grains where the exposures are relatively dry. Weathered exposures vary in color from mottled white, yellowish white, and light gray to various shades of orange yellow, brown, or reddish brown. Many weathered outcrops are streaked with seams and stains of bright to dark reddish-brown iron oxide minerals.

The siltstones of the coal-bearing facies are finely micaceous, carbonaceous, and tuffaceous in part, and they are generally sandy. Thin-bedded siltstone and fine silty sandstone are interbedded in places, producing finely laminated rocks which show "poker-chip" structure on weathering. The fresh rocks are medium gray to bluish gray in color. They disintegrate into thin chips, fragments, and fine sand on weathering, or form a massive impure clay, sandy in part, if the outcrop is wet. Weathered exposures are usually light yellowish brown in color.

Relatively thin beds of highly carbonaceous claystone, siltstone, and bone are interbedded with the coal-bearing rocks of the Olequa Creek member. Locally the carbonaceous beds grade laterally or vertically into coal beds. Bone ranges in color from brown to nearly black, and typically has a platy parting and a waxy luster. Silicified bone and silicified wood occur in the coal-bearing rocks in a few localities.

The coal beds of this upper member of the Cowlitz formation are variable and irregular in thickness and lateral extent, and the seams generally cannot be traced for long distances. The coal beds rarely exceed 5 feet in thickness, and are usually only 1 or 2 feet thick. In addition, seams and "pockets" of coal and carbonaceous material, generally just a few inches in thickness, are present in many exposures.

The rank of the coal in this area ranges from subbituminous to lignite. Most of the coal examined by the writer appeared to be of subbituminous rank, although Culver (1919, p. 36) states:

> Those coals found in the Vader area . . . are the nearest to the true lignites. These are uniformly black in color, with brown streak, but are of distinctly woody texture and have a relatively high moisture content which causes them to air-slack to a considerable degree.

The coals exposed along Olequa Creek and in the hills southeast of Klaber have the following general properties: (1) grayish- or brownish-black to black color; (2) black or brownish-black streak; (3) high moisture content, which is given off on exposure to air, producing the irregular weathering known as "air-slacking"; and (4) tendency to separate on weathering into thin irregular plates and chips roughly parallel to the bedding.

Coal beds and thin seams of carbonaceous material are found in all parts of the outcrop belt of the Olequa Creek member except for the section along the Chehalis River north of Pe Ell. The coal beds are most abundant and best exposed in the section along Olequa Creek.

The mudstones and siltstones of the marine facies are partly glauconitic, limy, sandy, carbonaceous, micaceous, or tuffaceous; glauconite is abundant in some layers. They are generally massive, though locally well bedded. Thin limy layers and sporadic calcareous concretions, usually containing megafossils, are present in most sections. These marine sediments are abundantly fossiliferous in places, and the rich molluscan faunas from this upper part of the Cowlitz formation have been well known for many years. Rich foraminiferal assemblages have been recorded from the Cowlitz River (Beck, 1943) and are present in other sections as well.

The pyroclastic rocks and basaltic sediments interbedded with the upper part of the Olequa Creek member along the banks of the Cowlitz River approximately 2½ miles southwest of Toledo are apparently restricted to that section. They consist of alternating and intergradational beds of the following rock types: basaltic tuff-breccia, lapilli tuff, crystal tuff, and thin basalt flows; basaltic conglomerates and sandstones, and tuffaceous sandstones and siltstones; and one thin volcanic breccia containing boulders as much as 3 feet in maximum diameter. These rocks are hard, indurated, and generally massive, although bedding is exposed in most parts of the section. They range in color from dark gray or greenish gray to nearly black in fresh exposures and weather to shades of yellowish brown to reddish brown. The total exposed thickness of this largely pyroclastic sequence is less than 200 feet. The volcanic rocks are interbedded with marine sandstones and siltstones which contain shells of gastropods and pelecypods.

The basalt flows and flow breccia interbedded with coal-bearing sandstones and siltstones of the Olequa Creek member along Olequa Creek south of Vader, and with marine mudstones and siltstones of the same member farther south along the Cowlitz River, are described under the heading "Goble volcanics member."

Mode of Origin

Just as the sediments of the Olequa Creek member are represented by two contrasting lithologic facies, so their environments of deposition were characterized by two contrasting sets of conditions. The lithologic facies interfinger and are intercalated with each other in most sectiions; hence the corresponding depositional environments must have been laterally and vertically gradational during late Eocene time.

The sediments and organic matter of the coal-bearing facies were deposited in a variable shallow marine, estuarine, and terrestrial environment. Deposition was rhythmic, the shallow sea advancing and retreating at irregular intervals. Several coal beds are generally present in any one section, and successive coal seams may be separated by as little as a few feet or as much as several hundred feet of sediments. There is no evidence to indicate that there was regular, cyclic deposition. The lenticularity and irregularity of the sediments and coal beds indicate that tectonic conditions were unstable at the time of deposition, and local angular discordances within the Olequa Creek member give further evidence of tectonic instability.

The environment of deposition of this sandstone-siltstone-coal facies was complex. Sedimentation occurred simultaneously on broad river flood plains and in fresh-water swamps and lakes, in brackish-water estuaries and lagoons, and offshore in the shallow ocean. Apparently slight tectonic movements were sufficient to cause marked transgressions and regressions of the sea, so that the land mass must have had low relief.

The main land mass from which the sediments were derived lay east and southeast of the mapped area, and the rivers transporting rock detritus flowed westward into a sea which deepened toward the west and northwest. The shoreline fluctuated back and forth across the area now crossed by Olequa Creek and the Cowlitz River. The source of sediments must have been an area of schistose rocks or acidic igneous rocks, in order to account for the abundance of feldspar, quartz, and micas in the arkoses, feldspathic sandstones, and siltstones.

The mudstones and siltstones of the marine facies of the Olequa Creek member were deposited in an environment which ranged probably from the inner neritic zone to the upper bathyal zone. The presence of carbonaceous material in the mudstone and siltstone, and of course clastics locally interbedded with the fine sediments, suggests relatively shallow water. Along Olequa Creek the marine strata equivalent to the beds exposed at the Cowlitz River bluffs locality are overlain and underlain by coal-bearing estaurine deposits, suggesting that the shoreline was not far distant during their deposition. Cifelli[8] reached the same conclusion on the basis of foraminiferal assemblages from the marine facies in the southeastern part of the area. However, in reporting on the foraminiferal faunule from the Cowlitz River bluffs locality east of Vader, Beck (1943, p. 587) expressed the opinion that the foraminifers suggest deeper water deposition of the Cowlitz River beds. He stated:

> The absence of lagoonal and littoral species and the scarcity of bathyal forms suggest that . . . the Cowlitz River faunule lived off a tropical coast in warm to cool marine waters at the outer margin of the neritic zone, down to and perhaps into the upper bathyal zone.

The climate of the area during deposition of the Olequa Creek member was tropical or subtropical. The Foraminifera indicate warm to cool marine waters and tropical climate. Likewise, the presence of coal beds and abundant carbonaceous material in the Olequa Creek member are indicative of a wet, tropical or subtropical climate, which favored vegetation and coal swamps.

The pyroclastic rocks interbedded with the sediments of the Olequa Creek member southwest of Toledo, and the basalt flows and flow breccia which are interfingered with the Cowlitz sediments south of Vader, are the products of widespread late Eocene volcanic activity. The source of these rocks was a volcanic center south of the mapped area. The late Eocene volcanism is discussed under the heading "Goble volcanics member."

[8]Cifelli, Richard, personal communication.

Age and Correlation

Megafossils are abundant in many exposures of the Olequa Creek member, notably in its type section and along the Cowlitz River. The Cowlitz molluscan fauna has been well known for many years, since it was first described by Weaver (1912, pp. 11-15). Since 1912 Weaver and others have described additional species from many localities in western Washington, so that the molluscan fauna of the Cowlitz formation is probably the best known megafauna of the Pacific Northwest. On the basis of these molluscan assemblages, the upper part of the Cowlitz formation of this report has been assigned an upper Eocene age, correlative with the upper part of the Tejon formation of California (Weaver, 1937B, p. 94).

No megafossils were collected by the writer from the Cowlitz formation; however, numerous microfossiliferous samples were collected, and the foraminiferal assemblages were studied by Richard Cifelli. The partial faunal lists and age determinations presented on succeeding pages were prepared by him.

Samples were collected for micropaleontologic study from exposures of the Olequa Creek member along the Cowlitz River, Olequa Creek, the South Fork of the Chehalis River, and the Chehalis River north of Pe Ell. In many localities Foraminifera are beautifully preserved, and diagnostic species are usually readily identifiable. They establish the age of the Olequa Creek member of the Cowlitz formation as upper Eocene, correlative with the A-1 zone (Laiming, 1943) of upper Tejon age of California.

The foraminiferal faunule from the Cowlitz River bluffs locality 1½ miles east of Vader has been adequately described by Beck (1943); hence assemblages collected by the writer from that locality are not listed here. The species reported by Beck (1943) include most of the forms present in assemblages collected by the writer and others and identified by Mr. Cifelli.

The following significant species occur in mustones of the Olequa Creek member exposed along Olequa Creek approximately 3 miles south of Winlock (LSJU Micropaleontological Locality No. M-583). The exposure from which this sample was collected is 1,400 feet stratigraphically below the top of the member.

Sample DH-O-22A

Vaginulinopsis saundersi (Hanna and Hanna)
Cibicides natlandi Beck
Eponides yeguaensis Weinzierl and Applin
Robulus inornatus (d'Orbigny)
Triloculina gilboei Beck
Globulina landesi (Hanna and Hanna)

Age upper Eocene; equivalent to the type Cowlitz beds at the Cowlitz River bluffs locality east of Vader. This assemblage, like the type Cowlitz faunule from the Cowlitz River locality, represents the shallow water faunal facies of the A-1 foraminiferal zone (Laiming, 1943) in this area. (Cifelli, MS.)

A meager microfaunal assemblage was obtained from siltstone collected along Olequa Creek approximately 200 yards downstream (east) from its confluence with Stillwater Creek (LSJU Micropaleontological Locality No. M-584). The beds at this locality are approximately 1,700 feet stratigraphically below the top of the member. In addition to several well-preserved ostracode shells, this assemblage contained the following species:

Sample OS-3

Nonion planatum Cushman and Thomas
Elphidium smithi Cushman and Dusenbury
Robulus inornatus (d'Orbigny)

Age upper Eocene, A-1 zone; based largely on stratigraphic position. Shallow water faunal facies of the A-1 zone. (Cifelli, MS.)

Equivalent faunules were found at several localities; they are characterized by an abundance of *Elphidium smithi*,[9] giving further evidence for the shallow marine deposition of at least this part of the Olequa Creek member. The above assemblage indicates an environment of deposition ranging from sublittoral to lagoonal.

Foraminiferal assemblages which appear to be identical to the type Cowlitz faunule of Beck (1943) were collected from siltstones and mudstones along the south bank of the Cowlitz River 2.4 miles south of the mouth of Olequa Creek (LSJU Micropaleontological Locality No. M-585). The sediments at this locality are lithologically similar to the strata at the Cowlitz River bluffs locality 5 miles to the north but are underlain here by a thick basalt flow. If meager structural data from the discontinuous exposures along the river between the two localities are reliable, the beds at this locality are at least 3,000 feet stratigraphically below the Cowlitz bluffs strata. If this is true, then the type Cowlitz faunule is certainly a facies faunule which may recur higher or lower in the section, depending upon variations in the depositional environment.

The following species were identified in a sample from the Cowlitz River locality 2.4 miles south of the mouth of Olequa Creek. The strata from which this assemblage was collected are 4,400 (?) feet stratigraphically below the top of the member.

Sample DH-CR-17C

Cibicides natlandi Beck
Eponides yeguaensis Weinzierl and Applin
Robulus weaveri Beck
Triloculina gilboei Beck

[9] Cifelli, Richard, personal communication.

Vaginulinopsis saundersi (Hanna and Hanna)
Nonion inflatum Cushman and Ellisor
Quinqueloculina goodspeedi Hanna and Hanna

Equivalent to type Cowlitz faunule; age upper Eocene, near-shore faunal facies of A-1 zone. (Cifelli, MS.)

Northwestward from the type section, foraminiferal assemblages from the Olequa Creek member indicate progressively deeper water deposition of the sediments. In addition, the coal-bearing facies thins and wedges out in that direction. It is apparent that the Cowlitz sea deepened toward the northwest in this area.

The foraminiferal faunule from strata exposed along the South Fork of the Chehalis River in the vicinity of Boistfort (LSJU Micropaleontological Locality No. M-578) reflects the deepening of the sea in that section. The Olequa Creek member along the South Fork of the Chehalis River is only about half as thick as the type section. The foraminiferal assemblages listed here were obtained from beds 1,200 feet stratigraphically below the top of the member and less than 100 feet above its base. The following forms occur in samples collected near Boistfort.

Sample Wd-Ch-39A

Plectofrondicularia jenkinsi Church
Plectofrondicularia packardi var. multilineata Cushman and Simonson
Gyroidina cf. G. planulata Cushman and Renz
Cassidulina globosa Hantken

Sample Wd-Ch-49

Robulus inornatus (d'Orbigny)
Robulus weaveri Beck
Robulus welchi Church
Eponides yeguaensis Weinzierl and Applin
Cibicides hodgei Cushman and Schenck
Plectofrondicularia jenkinsi Church
Plectofrondicularia packardi var. multilineata Cushman and Simonson
Gyroidina cf. G. planulata Cushman and Renz
Cassidulina globosa Hantken

It is difficult to determine how this section ties in with the Olequa Creek section because of lithologic and faunal facies changes. This faunule is similar to the type Cowlitz faunule but appears to represent a deeper water facies. Age upper Eocene, A-1 zone. (Cifelli, MS.)

In the northwest corner of the lower Cowlitz River-eastern Willapa Hills area the Olequa Creek member is less than 800 feet thick and is represented wholly by the marine lithologic facies. The following species were identified from siltstones exposed along the Chehalis River about 1 mile north of Pe Ell (LSJU Micropaleontological Locality No. M-582). The strata at this locality are 600 feet stratigraphically below the top of the member and about 150 feet above the base.

Sample DH-213

Plectofrondicularia jenkinsi Church
Robulus inornatus (d'Orbigny)
Bolivina basisenta Cushman and Stone
Cassidulina globosa Hantken
Robulus sp.

Age upper Eocene, A-1 zone. This Pe Ell section is apparently the offshore equivalent of the Stillwater-Olequa Creek section. The upper part of this section is approximately equivalent to the Olequa Creek section. (Cifelli, MS.)

All foraminiferal assemblages from the Olequa Creek member of the Cowlitz formation are correlative with Laiming's (1943) A-1 zone of upper Tejon age of California. Inasmuch as this part of the Cowlitz formation has already been correlated with the Tejon of California by Arnold and Hannibal (1913), Dickerson (1915), Weaver (1916A, 1937B, 1942) and others on the basis of mollusks, the age of these beds seems established beyond doubt.

Beck (1943, pp. 590-591) concluded that the foraminifers of the Cowlitz River bluffs locality probably lived during a portion of the time represented by the upper 900 feet of the type Tejon formation. He stated that the Cowlitz River beds are in part correlative with the Coaledo formation of Oregon and the Poway conglomerate of California, as well as the Tejon. It was also noted that the Eocene Cook Mountain formation (Claiborne) of the Gulf Coast contains several species in common with the Cowlitz.

Turner (1938) correlated the Coaledo formation of Oregon with the Cowlitz formation of Washington and Tejon of California on the basis of mollusks. The subdivisions of the Coaledo formation have been described by Allen and Baldwin (1944, pp. 21-27). The marine mudstone-siltstone facies of the Olequa Creek member is lithologically similar to the middle Coaledo, and the foraminiferal faunas (Detling, 1946; Cushman, Stewart, and Stewart, 1947) are correlative.[10] The sandstone-siltstone-coal facies is lithologically similar to the lower Coaledo and in part to the upper Coaledo.

The coal-bearing facies of the Olequa Creek member also shows marked lithologic similarity to the Skookumchuck formation (Snavely, Roberts, Hoover, and Pease, 1951) of the Centralia-Chehalis coal district. The Skookumchuck formation is the upper Eocene coal-bearing formation of that district. Megafossils from the Skookumchuck correlate with the molluscan fauna from the type Cowlitz locality, and the meager foraminiferal fauna from well and surface samples of the Skookumchuck sediments was reported (idem) to be identical with one from beds exposed along Olequa Creek south of Winlock.

Cifelli[11] reported that the foraminiferal fauna of the Olequa

[10] Cifelli, Richard, personal communication.
[11] Personal communication.

Creek member correlates well with the fauna of the Sidney shale of California.

The foraminiferal faunule of Hanna and Hanna (1924) from the Cowlitz River bluffs locality was assigned by Laiming (1943, p 195) to his upper Eocene A-3 (*Planulina pseudowuellerstorfi*) zone. Later work has shown that the Cowlitz bluffs faunule, like others from the Olequa Creek member, should be assigned to Laiming's upper Eocene A-1 (*Plectofrondicularia jenkinsi*) zone.

To summarize: the Olequa Creek member of the Cowlitz formation is correlative with the upper Tejon, the Poway conglomerate, and the Sidney shale of California; with the Coaledo formation (particularly the middle Coaledo) of Oregon; and with the Skookumchuck formation of Washington. Its age is upper Eocene, and it is assigned to Laiming's A-1 foraminiferal zone.

Contact Relations

In the lower Cowlitz River-eastern Willapa Hills area the lower beds of the Olequa Creek member rest conformably on the Stillwater Creek member, as discussed previously. In the type section the contact is gradational, the predominantly marine siltstone and sandstone of the lower member grading upward into the predominantly brackish-water sandstone-siltstone-coal facies of the upper member. The contact is drawn arbitrarily at the base of the sandstone immediately underlying the stratigraphically lowest coal bed.

In the northwestern part of the area, where the Olequa Creek member is entirely marine and contains no coal beds, it is lithologically similar to the Stillwater Creek member. However, the sediments of the Olequa Creek member are generally a little coarser and more carbonaceous than those of the lower member, and the foraminiferal faunas are sufficiently distinctive to permit differentiation between the two members. The contact in that part of the mapped area is graduational.

The Olequa Creek member is overlain unconformably by Oligocene sediments along a contact line which trends northwestward from the Cowlitz River southwest of Toledo to the Chehalis River north of Pe Ell. This line marks the northern and northeastern boundary of the mapped area. The contact represents overlap of the Eocene rocks by Oligocene sediments deposited in a transgressing sea. It is locally a disconformity rather than an angular unconformity.

In the southeastern part of the area the Olequa Creek member is overlain with marked angular unconformity by basalt flows and interbedded sediments of the Astoria formation, of middle Miocene age. The contact between the Eocene and Miocene rocks is traced with difficulty along the west side of the Cowlitz River Valley south of Olequa, because exposures are principally restricted to the basalt flows of both units. However, the Eocene rocks in that area have a prevailing northerly dip, whereas the Miocene basalts and sediments generally dip toward the south and east.

In the hills southwest of Winlock several of the highest peaks and ridges underlain by sediments of the Olequa Creek member are capped by thin Miocene lava flows. These basalt flows are horizontal or nearly so, whereas the underlying Eocene sediments have dips of 10° to 15° to the northeast. The contacts, in all cases where attitudes can be determined, exhibit marked angular unconformity.

Goble Volcanics Member

Distribution and Thickness

The name "Goble volcanics series" was originally proposed by Lowry and Baldwin (Wilkinson, Lowry, and Baldwin, 1946, p 4) for a thick section of basaltic flows, pyroclastics, and minor amounts of sediments exposed in the vicinity of Goble, Oregon, and elsewhere along the Oregon and Washington sides of the Columbia River from Deer Island, Oregon, northward to Kelso, Washington. The total thickness of the volcanic series in the type area is more than 5,000 feet.

In the lower Cowlitz River-eastern Willapa Hills area the Goble volcanics are represented by basaltic flows and flow breccia interbedded with both marine and coal-bearing Cowlitz sediments. These intercalated volcanics are largely restricted to the area south of Vader, although the pyroclastic rocks exposed along the Cowlitz River southwest of Toledo are probably equivalent to the upper part of the Goble volcanic series. The basalt flows and flow breccia are well exposed along the lower course of Olequa Creek south of Vader and along the Cowlitz River and the roads and railroads paralleling the river southward to the mouth of the Toutle River.

The thickness of the Goble volcanic rocks in the mapped area cannot be precisely determined because of the irregularly interbedded nature of the basalts and the lack of continuous exposures. The aggregate thickness of intercalated volcanic rocks in the upper part of the Cowlitz formation is probably less than 1,000 feet. Since the Goble volcanics are relatively thin here and are interfingered with sediments of the Cowlitz formation, it is considered justifiable to lower the rank of the Goble volcanics to a member in this area. Thus the name "Goble volcanics member" is used here for rocks which constitute a much thicker unit of formational rank in another area.

Dips in the Goble volcanics member generally range from 7° to 15° although a few as high as 35° were observed. The basalt flows and flow breccia along lower Olequa Creek and the Cowlitz River dip northeatsward to northward, following the regional dip of the Cowlitz formation in that part of the area.

Lithology

The Goble volcanics member consists largely of basalt flows and flow breccia, together with minor amounts of pyroclastic rocks and tuffaceous sediments. The thickness of individual flows ranges from 40 to 100 feet, averaging perhaps 60 feet; the pyroclastic rocks are generally thinner.

The Goble flows typically show either platy jointing or crude columnar jointing, or both. The flows generally are hard, dense, and fine grained, and locally appear to be massive. They are resistant to weathering, and the outcrops are usually bold.

The flows of the Goble member are vesicular in part, especially near the tops of the flows. Flow breccia is common, and the basaltic fragments in the breccia are usually highly vesicular. The vesicles are commonly filled with secondary calcite and zeolites. In a few exposures, the flows and breccias are highly zeolitized.

In the hand specimen the Goble basalts are typically porphyritic, with rectangular feldspar phenocrysts set in a dense, fine-grained, aphanitic groundmass. They range from bluish gray and greenish gray to dark gray in color when fresh. On weathering, the color of the rock changes to shades ranging from brownish gray to dark reddish brown. The vesicular rocks become soft and clayey on deep weathering and appear pitted or moth eaten; the breccias weather in much the same manner. The dense basalt flows, on the other hand, are much more resistant to weathering; outcrops of the flows become rounded and change in color as noted above.

The Goble flow rocks and breccia examined in thin section are basaltic. They range in composition from andesitic basalt to olivine basalt, and there is considerable textural variation. All the thin sections are highly feldspathic and weakly to markedly porphyritic. The basalts are partly glassy and generally exhibit some alteration.

Detailed petrographic descriptions of the Goble volcanic rocks are presented under the heading "Petrographic Study of the Volcanic Rock Units."

Mode of Origin

The basalts of the Goble volcanics member are interbedded with sediments of shallow marine to terrestrial origin, and it seems likely that the volcanic rocks are partly submarine and partly subaerial in origin. Probably most of the sediments and volcanics were laid down under marine or estuarine conditions, so that only a few of the Goble flows solidified under subaerial conditions. Deposition of sediments apparently continued without interruption between successive eruptions.

Additional evidence for subaqueous extrusion of the Goble volcanics is provided by the flow breccias, which are probably the result of autobrecciation by steam explosion which accompanied subaqueous volcanism. Flow breccias occur throughout the Goble volcanics member in this area, either alone or associated with basalt flows.

A coal bed overlies with apparent conformity a weathered basalt flow in the south bank of Olequa Creek approximately 1.1 miles northwest of its confluence with the Cowlitz River (pl. 2). The coal bed is a little more than 1 foot thick and is in turn overlain by sandy siltstone. The upper 5 or 6 feet of the basalt flow is highly vesicular and deeply weathered, grading downward into hard, dense Goble basalt. In this locality the basalt flow must have formed the floor of the swamp or estuary in which the coal-forming organic material accumulated.

The source of the basaltic lavas, flow breccia, and pyroclastic rocks was probably a volcanic center (or group of volcanic fissures or cones) many miles southeast of the lower Cowlitz River-eastern Willapa Hills area. The northern end of the type section of the Goble volcanic series is 16 miles south of the confluence of Olequa Creek and the Cowlitz River. The upper Eocene volcanics thicken rapidly southward and eastward from that point, attaining their maximum thickness farther south along the Columbia River.

Age and Correlation

The Goble volcanics member is overlain and underlain by sediments of the Olequa Creek member, with which it is interfingered in this area. Hence, the Goble volcanics are equivalent in age to the Olequa Creek member, which is upper Eocene, correlative with the A-1 foraminiferal zone (Laiming, 1943) of upper Tejon age of California. The same age assignment was given by Lowry and Baldwin (Wilkinson, Lowry, and Baldwin, 1946, p. 4) for the Goble volcanic series in the type area, where "the series is interfingered with the marine Cowlitz formation of upper Eocene age and is unconformably overlain by beds tentatively correlated with the Gries Ranch stage of the lower Oligocene."

Most of the Goble volcanic rocks are interbedded with the lower part of the Olequa Creek member in this area. Approximately 2,500 feet of Cowlitz sediments overlie the uppermost Goble flow along Olequa Creek. However, the pyroclastic rocks exposed along the Cowlitz River southwest of Toledo are probably equivalent to similar rocks described by Wilkinson, Lowry, and Baldwin (1946, p. 5) in the type area of the Goble volcanic series, the upper part of which is "comprised of basaltic lavas with associated pyroclastic rocks in significant, if not predominant, amounts." The pyroclastics occur near the top of the Cowlitz formation in the Cowlitz River section and may be correlative with the uppermost part of the Goble volcanic series; they are considerably younger than the flows and flow breccia along Olequa Creek and the Cowlitz River south of Vader.

The Goble volcanics member is equivalent in age to most or all of the Olequa Creek member.

The Goble member of the Cowlitz formation in the mapped area is equivalent to the Goble volcanic series of the St. Helens quadrangle, Oregon-Washington, and the adjoining area northward to Kelso, Washington. It is probably correlative with the basaltic flows encountered in the Selburn-Washington Oil Corporation well Wulz No. 1 near Forest, Washington, in the depth interval from 2,200 to 2,850 feet. The volcanic rocks in that well overlie coal-bearing sediments containing a foraminiferal faunule which is equivalent to the type Cowlitz faunule. The Goble volcanics may also be correlative in part with the Eocene volcanics which overlie and are interbedded with Cowlitz sediments along the highway between Renton and Seattle, Washington (Warren, Norbisrath, Grivetti, and Brown, 1945). The lower part of the Goble volcanics member occupies the same relative stratigraphic position as the Northcraft formation (Snavely, Roberts, Hoover, and Pease, 1951) of the Centralia-Chehalis coal district. The two units are petrographically distinct from each other, but they may be correlative.

The Goble volcanics are probably to be correlated with all basaltic rocks which may be found to be interbedded with sediments of at least the upper part of the Cowlitz formation in southwestern Washington and northwestern Oregon.

Contact Relations

The Goble volcanics member is interfingered with sediments of the Olequa Creek member; the contacts are conformable in all sections. The Goble volcanic rocks are restricted to the southeastern part of the mapped area, thinning and wedging out toward the northwest.

Summary

The type section of the Cowlitz formation as described by Weaver (1937A) has been expanded in this report to include the Eocene sediments exposed along Stillwater Creek (pl. 2). Addition of these strata to the Cowlitz formation fills the previously existing gap in the southwestern Washington stratigraphic column between the top of the Metchosin volcanics and the base of the Cowlitz (Weaver, 1937B, pp. 90-94; Weaver et al., 1944). This addition is considered necessary because the Stillwater Creek beds do not represent a formation distinct from the strata exposed along Olequa Creek and the Cowlitz River; they are an integral part of the thick lithogenetic unit which has been named the Cowlitz formation.

The original type section of the Cowlitz formation (Weaver, 1912, p. 13) consisted of the 200 feet of beds exposed along the Cowlitz River bluffs 1½ miles east of Vader. Later, Weaver (1937A) expanded the type section to include the upper Eocene strata exposed along Olequa Creek from its confluence with the Cowlitz River northward to Winlock.

This emendation was considered undesirable by Beck (1943, p. 584), "because the Olequa Creek section was not included in the original definition and the addition would necessitate two type localities for the Cowlitz formation." He limited the type Cowlitz to the Cowlitz River bluffs locality.

In 1944 Weaver repeated his earlier assertion (1937A) that the Olequa Creek section was the type section of the Cowlitz formation. He made the following statement (Weaver et al., 1944, p. 593):

> The Cowlitz formation is composed of about 8000 feet of marine grayish-brown sandstone and sandy shale containing well-preserved molluscan fossils in many layers from the base to the top of the section. The type section is in the banks of Olequah Creek and not in the banks of Cowlitz River. The best known fauna of the formation does occur in about 200 feet of strata exposed in the bluffs of Cowlitz River, 1½ miles east of Vader, and corresponds to strata in the middle of the type section on Olequah Creek.

Beck's view in this controversy is incomprehensible to the writer. It seems absurd to continue to regard some 200 feet of strata as the type section of a formation which attains a thickness of more than 8,000 feet in the type area. Weaver's emendation of the type section of the Cowlitz formation was justifiable, just as the addition of the Stillwater Creek section is justifiable. The type section of a formation should, if possible, be representative of the entire formation throughout the area in which it is exposed. In addition, the definition of the formation in its type section should include, wherever possible, the upper and lower limits of the formation. The Stillwater Creek-Olequa Creek section satisfies these requirements and should become the accepted type section of the Cowlitz formation (pl. 2).

The Cowlitz formation in the lower Cowlitz River-eastern Willapa Hills area is the thickest and best exposed predominantly marine Eocene sedimentary section in the Pacific Northwest. The great thickness of the Cowlitz formation and the presence of several fairly continuous sections across the formation are two of the many reasons for the writer's selection of this area as the subject of the report. If the maximum exposed thicknesses of the Cowlitz formation and the Metchosin volcanic series are added, the total thickness of the Eocene section in the mapped area is at least 18,000 feet.

Correlation of the Cowlitz formation and its several members in this area is rendered difficult by facies changes, which are reflected in variations both in lithology and in foraminiferal assemblages. The faunal facies changes are marked and give rise to correlation problems even within the limited area involved in this study. In a general way, the difficulties in correlation may be said to result from two factors: (1) interfingering of a marine sedimentary facies with an essentially estuarine and nonmarine facies in the eastern part of the area; and (2) apparent westward and northward deepening of the Cowlitz basin of deposition, so that beds which contain a near-shore foraminiferal faunule along Olequa Creek are equivalent in age to strata which contain a distinct offshore faunule along the Chehalis River.

These facies changes make precise correlations difficult and impractical without complete and continuous foraminiferal sequences. Complete foraminiferal sequences from the Cowlitz formation have not yet been found in the southwestern Washington region. A great deal of work remains to be done in determining the precise stratigraphic relations of the Cowlitz formation and its member units.

The problem of correlation is further complicated by the complete absence of rock exposures in some areas and the lack of continuous sections in all areas. The type section of the Cowlitz formation, as redefined herein, is the most complete section of upper Eocene sediments exposed in Washington, but there are large gaps even in that section. Deep weathering, thick soil cover, abundant vegetation, and a mantle of Pleistocene and Recent alluvium conceal the Eocene rocks in many places. This difficulty can be alleviated to some extent by the use of a Mobile Auger or other instrument to obtain fresh samples of the Tertiary sediments. However, such mechanical aids are necessarily restricted in their use by purely physical limitations.

The subdivisions of the Cowlitz formation in the lower Cowlitz River-eastern Willapa Hills area are not expected to be valid elsewhere. The four members established by the writer can be mapped in most parts of this area and are extremely useful in working out the details of the Eocene stratigraphic sequence. However, it should be clearly understood that these member units are intended to apply only to the mapped area. In many areas the Cowlitz formation cannot be subdivided; for example, along the Willapa River south of Holcomb, 17 miles west of Pe Ell, the formation consists of about 700 feet of relatively homogeneous massive marine siltstones. The Willapa River Eocene beds contain a foraminiferal fauna correlative, at least in part, with the type Cowlitz fauna (Rau, 1951, p. 423).

The upper Eocene age of the Cowlitz formation, and its correlation with equivalent units in the California and Oregon Eocene sections, has been demonstrated. The Cowlitz formation has not been definitely correlated with European stages, and its precise position in the Eocene time-stratigraphic scale is not known. However, the upper part of the formation is certainly high in the Eocene section, and it may represent the uppermost division of the Eocene of the Pacific Coast (Weaver, 1937B, p. 94).

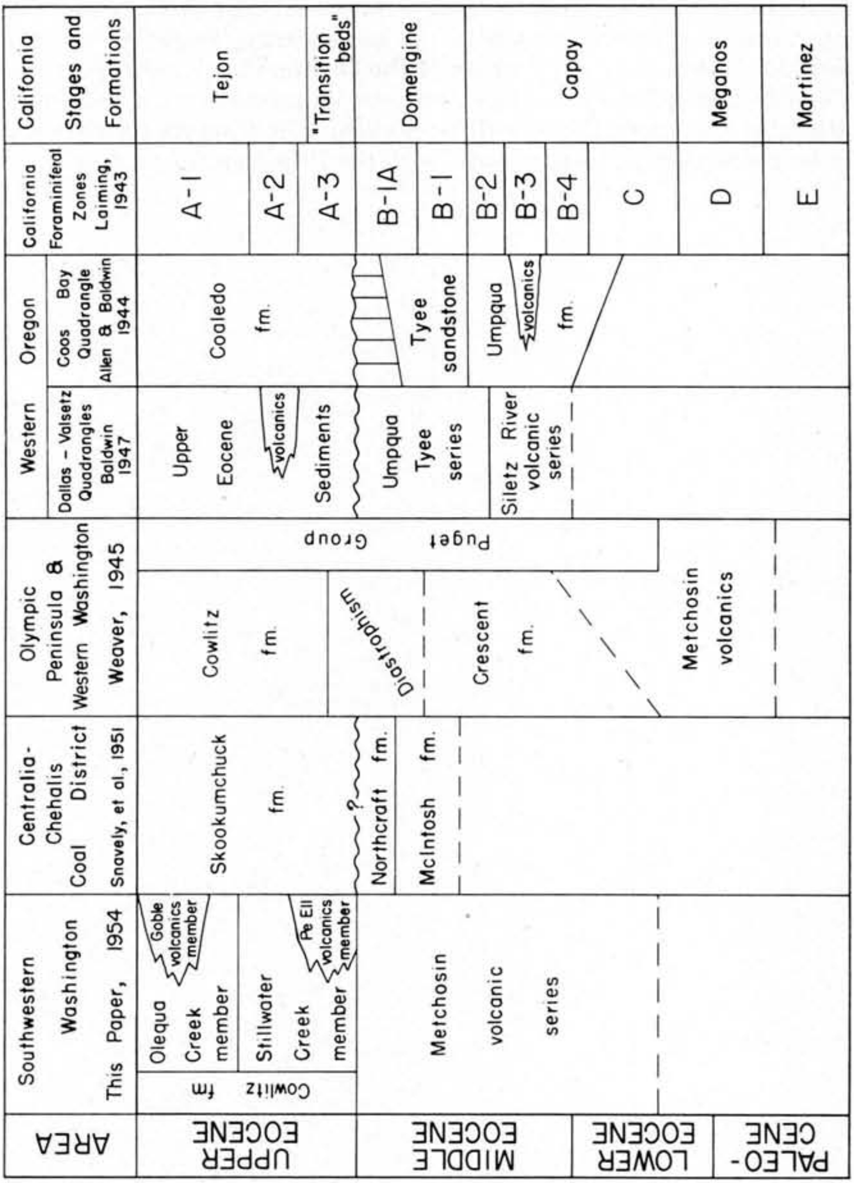

FIGURE 9. Stratigraphic correlation chart.

In addition to the correlations noted previously, the Cowlitz formation may be correlated with the Arago formation of Oregon (Weaver, 1945, p. 1408), which includes the Coaledo and Pulaski formations. Weaver (1945, p. 1408) also noted that the marine Cowlitz formation interfingers with the coal-bearing Puget group near Seattle. The coal-bearing strata of the Olequa Creek member of the Cowlitz formation in this area may be continuous with the Puget group in the upper Cowlitz River Valley. The Cowlitz formation is to be correlated, at least in part, with the Puget group.

STRATIGRAPHY AND PETROGRAPHY

PART II. PETROGRAPHIC STUDY OF THE VOLCANIC ROCK UNITS

Introduction

In many parts of southwestern Washington the folded Tertiary rocks are poorly exposed. Since late Eocene time the Tertiary sediments and volcanics have been intermittently eroded and, in places, covered by deposits of Pleistocene and Recent alluvium. The climate of the region favors rapid physical and chemical weathering, which leads to the development of a thick soil mantle and heavy plant cover. Hence, surface exposures of the Tertiary rocks are absent in some localities and rare in others.

In many places the only rocks exposed at the surface are volcanics, which are much more resistant to weathering and erosion than the sedimentary rocks. These volcanic rocks then provide the only readily available information concerning the concealed Tertiary rocks. If the volcanic rock units can be differentiated, then the scattered igneous rock outcrops can be used in mapping and interpreting the geology of the region. Hence, the volcanic rocks of southwestern Washington should be studied in as much detail as the sedimentary rocks with which they are interbedded.

Plans for geologic investigation of the lower Cowlitz River-eastern Willapa Hills area, as originally outlined in 1951, included a petrographic study of the volcanic rocks. The scope of the study was later expanded to cover all major volcanic rock units of the southwestern Washington region. The purpose of the study has been the determination of lithologic and petrographic criteria for the differentiation of the volcanic units wherever they are encountered in this region.

Considerable time was devoted to the examination of volcanic rock exposures in the field, and hundreds of hand specimens were collected for additional study. Fifty thin sections were prepared from selected hand specimens, and all of them were studied by the writer. Volcanic rocks of all four major volcanic units in the southwestern Washington Coast Range were examined in thin section.

The Pe Ell volcanics member of the Cowlitz formation has a limited areal distribution and very distinctive lithologic characteristics, and exposures are easily recognizable in the field, even where the rock is deeply weathered; therefore, it was not considered necessary to study the Pe Ell volcanic rocks in thin section.

Rocks of the four major volcanic units commonly resemble each other in the field, and further petrographic study of these rocks proved essential. The four volcanic rock units which were studied microscopically are the following: (1) the Metchosin volcanic series; (2) the Northcraft formation, which is not exposed in the lower Cowlitz River-eastern Willapa Hills area but underlies part of the adjacent district to the northeast; (3) the Goble volcanics, which constitute a thin member of the Cowlitz formation in this area but are thick and widely distributed a few miles to the south; and (4) the middle Miocene basalts which are locally interbedded with sediments of the Astoria formation.

The number of thin sections of each volcanic unit examined is as follows:

Metchosin volcanic series	22 thin sections
Northcraft formation	1 thin section
Goble volcanics	8 thin sections
Astoria (Miocene) basalts	12 thin sections
Unknown	7 thin sections

It will be noted that only one thin section from the Northcraft formation was studied. The Northcraft formation is the thinnest and least extensive of the major volcanic units of southwestern Washington. Furthermore, the Northcraft lavas are essentially andesitic, whereas the other volcanics of the region are basaltic. The petrographic characteristics of the thin section examined are similar to those of the type Northcraft (Snavely, Roberts, Hoover, and Pease, 1951), and further petrographic study was not deemed necessary.

The seven thin sections classified as "unknown" were collected from areas in which exposures are rare and consist entirely of volcanic rocks. It was found that each of these "unknown" rocks could be assigned to one of the volcanic units on the basis of its petrographic characteristics. These assignments were made with a fair degree of confidence, based on the writer's study of thin sections of igneous rock samples previously collected from locatities in which the areal geology is better known. Four of the "unknown" samples were assigned to the Metchosin volcanic series and three to the Astoria basalts. Subsequent field work has yielded stratigraphic and structural evidence supporting these original determinations.

Petrographic study of individual thin sections, taken together with even fragmentary lithologic and stratigraphic evidence, generally permits definite assignment to one of the known volcanic formations, although petrographic data alone are not always sufficient for differentiation of the volcanic rock units.

Notes on Procedure

Petrographic descriptions of the volcanic rock units are based upon determinations of the typical minerals present and percentages of each, textures, and special features, as shown in the thin sections examined. The nature and extent of the variations within each group are discussed. Following each petrographic description a summary of the distinctive petrographic features of the unit is presented.

Rock specimens were collected from a number of localities in western Washington and northwestern Oregon and sent to Alexander Tihonravov, Stanford University, for preparation of thin sections. The collecting localities are generally noted only in the descriptions of photomicrographs which show characteristic features of particular thin sections.

The composition of plagioclase is given as percentage of the anorthite (An) molecule. Compositions were determined by measuring maximum extinction angles in albite-twin lamellae in the symmetrical zone, following the procedure described by Chudoba (1933, pp. 24-26). In many instances the results obtained by the above method were checked by determination of refractive indices of the plagioclase by oil immersion (Larsen and Berman, 1934, pp. 8-10). The composition of the plagioclase, as indicated by the refractive indices measured on cleavage flakes, was determined by use of the chart and information given by Winchell (1933, pp. 338-339 and fig. 268). The An-percentages obtained by oil immersion are generally a little higher than those indicated by the extinction angles; however, the difference is not greater than 5 percent of anorthite in the thin sections examined.

The term "chloritic alteration products," as used in this report, includes a variety of secondary minerals, predominantly green in color and having the general optical properties of the chlorite group. Most of these minerals are poorly crystallized and fine grained. They fill cavities and replace the primary constituents of the rocks. They range in color from yellow and brown to many shades of green, and in birefringence from very weak to moderate. This group probably includes, in addition to the chlorites, some of the ill-defined, poorly crystallized sheet-structure silicates such as bowlingite, xylotile, and saponite.

The term "clay minerals" is used for the fine-grained, typically dusty- or flaky-appearing alteration products of plagioclase and, rarely, other primary minerals. They range in color from brownish or grayish to colorless and are poorly crystallized. This secondary material probably includes such minerals as sericite and gibbsite, as well as the true clay minerals.

Magnetite and/or ilmenite are primary constituents of most of the rocks sectioned. Ilmenite is recorded as present only if the skeletal crystals typical of that mineral occur in significant amount in the thin section. Otherwise, the opaque metallic constituent of the rock is recorded as magnetite.

Zeolites are present as alteration products and vesicle fillings in several thin sections. No attempt was made to identify individual mineral species; they are recorded simply as zeolites.

In general, the presence and amount of alteration products and other secondary minerals in a thin section are significant. Precise identification of the mineral varieties present, however, is not necessary for the purposes of this report. Therefore, it has been considered advisable to use only the general group names mentioned previously.

The photomicrographs on succeeding pages were taken by the writer and G. S. Payne, using the latter's camera and attachments mounted directly on the petrographic microscope. The camera used is a Zeiss-Ikon Contax III-A (35 mm.) with an f/2 lens. The microscope used in this work is a Spencer No. 42 student model polarizing microscope.

Petrographic descriptions of the volcanic rock units are presented under separate headings on succeeding pages. In conclusion, the distinguishing lithologic and petrographic features of each unit are summarized.

Metchosin Volcanic Series

Rock Types

The Metchosin volcanics comprise various lithologic types. Thin sections were prepared from basaltic flows, pillow lavas, flow breccia, dike rocks, and a fine-grained olivine gabbro. Most of the normal basalt flows of the Metchosin are similar to the younger Tertiary flow rocks, whereas the other Metchosin rocks are lithologically distinctive. The pillow lavas and flow breccia are chloritized and zeolitized, and the gabbro intrusive exposed in the vicinity of Baw Faw Peak is quite unlike other igneous rocks in the region.

Most of the rocks sectioned are normal basalt flows, which exhibit considerable lithologic variation; they are fine to coarse grained, dense to vesicular and amygdaloidal, and massive to strongly jointed. The other Metchosin rocks are generally recognizable without difficulty in the field. Hence, the following petrographic description of the Metchosin volcanic series is based largely upon the rocks which are lithologically most like the younger volcanics of southwestern Washington.

Twenty-two thin sections were prepared from rock specimens collected from exposures of known Metchosin volcanics. Four additional thin sections of basaltic rocks whose stratigraphic position could not be determined on the basis of field evidence have been assigned to the Metchosin on the basis of marked petrographic similarity.

Most of the rocks sectioned were collected within the mapped area. However, others represent exposures of the Metchosin volcanics in places as far distant as the sea cliffs west of Port Crescent, on the southern shore of the Strait of Juan de Fuca; the Black Hills north of Oakville and east of Porter, in Grays Harbor County; and the hills between Willapa Harbor and Grays Harbor, north of Raymond.

Petrographic Description

All Metchosin volcanic rocks examined in thin section are basalts, with the exception of the fine-grained olivine gabbro instrusive which is described in a subsequent paragraph. The basalts show considerable alteration. They consist essentially of plagioclase and augite, with accessory magnetite and/or ilmenite; olivine is present in only one thin section, although it may have been a primary constitutent of many of the basalts. Slightly more than half of the basalts are holocrystalline, and the others are partly glassy. The shape and texture of patches of secondary minerals, especially the chloritic alteration products, in some thin sections suggest that olivine or volcanic glass, or both, were among the primary constituents of several of the rocks in which they are not found now.

The Metchosin basalts are holocrystalline to hypocrystalline with varied textures. Most of them are at least slightly porphyritic, and nearly half are strongly porphyritic, with prismatic and lath-shaped phenocrysts as much as 4 mm. long. The phenocrysts are set in a fine-grained groundmass ranging in texture from intergranular to intersertal. Almost half of the thin sections examined exhibit poorly developed to conspicuous diabasic texture, which is poikilitic in part. The lath-shaped crystals of plagioclase have an irregular to subradial arrangement; augite grains are interstitial to the plagioclase laths and enclose them in places. Most of the diabasic basalts are weakly porphyritic; a few are even grained.

Phenocrysts constitute 3 to 30 percent of the basalts, averaging about 15 percent. They include plagioclase, augite, and, in one thin section, olivine. In a few of the sections the phenocrysts of plagioclase and augite are arranged in clusters, giving rise to cumulophyric texture (fig. 10). This texture is not common in the Metchosin basalts.

Plagioclase, chiefly labradorite, is the most abundant mineral, constituting 30 to 60 percent of the fresh basalts and averaging about 45 percent. Phenocrysts and the large crystals in the diabasic rocks are 0.3 to 4.0 mm. long, with an average length of about 0.5 mm. These crystals are generally euhedral to subhedral in outline and may be considerably corroded and altered (fig. 14). Most of the plagioclase shows albite twinning, and combined Carlsbad-albite twinning is common. Other types of twinning are present as well (fig. 19). Many of the phenocrysts show poor to well-developed zoning (figs. 15 and 20).

The composition of the plagioclase in the Metchosin basalts ranges from slightly less basic than An_{60} to slightly more basic than An_{75}. The phenocrysts of the porphyritic basalts are generally more basic than the average, with a composition of An_{70} (labradorite-bytownite). More calcic plagioclase is found in the coarse diabasic basalts, in some of which the plagioclase is An_{75} (bytownite). The plagioclase laths in the groundmass of the porphyritic basalts are much less basic, averaging about An_{62} (labradorite). Some phenocrysts are markedly zoned, with cores which are considerably more calcic than the rims of the crystals.

Augite occurs in all thin sections, in amounts ranging from 2 to 40 percent of the rock. In the relatively unaltered basalts the minimum content of augite is 15 percent, and the average augite content of these rocks is a little greater than 25 percent. In the porphyritic varieties, phenocrysts of augite are usually present but are not as large or as abundant as the plagioclase phenocrysts. They are generally subhedral in outline, ranging from anhedral to euhedral. The largest augite crystals are 1.5 mm. long, and the average length is about 0.3 mm. Anhedral to subhedral augite grains are present in the groundmass of the porphyritic basalts. In the diabasic varieties, augite is intergrown with and interstitial to the plagioclase laths (fig. 11), which are generally larger, more numerous, and better crystallized.

The augite of the Metchosin basalts is generally pinkish in color in thin section; weak to strong dispersion, producing anomalous interference colors, is seen in many of the larger crystals. Most of the thin sections contain twinned augite. Slight zoning is also common in some of the phenocrysts. The pyroxene of the Metchosin basalts is normal augite, with an optic angle of 45°-60°.

Plagioclase and augite phenocrysts in some of the porphyritic basalts are in part distorted, fractured, and sheared (fig. 16). The movement which caused these effects took place prior to crystallization of the groundmass, as the cracks and lines of distortion do not extend into the groundmass.

As previously noted, olivine occurs as phenocrysts in one thin section—a porphyritic basalt exposed in the sea cliff west of Port Crescent, Washington, on the northern shore of the Olympic Peninsula. Olivine phenocrysts constitute about 5 percent of the rock; they are subhedral to euhedral in outline and are considerably altered to serpentine and chloritic minerals (fig. 13). Some of the phenocrysts are altered around their edges and along thin seams, and others are almost wholly altered, with small remnants of olivine surrounded by alteration products. In other thin sections the arrangement of the alteration products suggests that olivine phenocrysts present originally have been completely replaced.

Magnetite and/or ilmenite are present as accessory minerals in all Metchosin basalts examined in thin section, in amounts ranging from 2 to 10 percent and averaging about 5 percent. Magnetite occurs as euhedral to subhedral crystals, some more than 1 mm. long, and as grains in the groundmass. Ilmenite is present in nine of the thin sections (fig. 17). The larger magnetite and ilmenite crystals are corroded and pitted in some sections. Magnetite also occurs as small, fine-grained to dust-size inclusions in plagioclase crystals and in the volcanic glass of some basalts.

Volcanic glass is present in slightly less than half of the sections, in amounts ranging from less than 5 percent to 30 percent. It generally constitutes 5 to 10 percent of the basalts in which it occurs. It is light brown to black in color, usually contains grains and particles of magnetite, and may be considerably devitrified and altered (fig. 18). It is a rather basic glass; a refractive index of 1.56 was measured. Chloritic alteration products have replaced most of the devitrified glass in some sections, and in other basalts which now appear holocrystalline the chloritic minerals occur in interstitial spaces which were probably occupied originally by volcanic glass.

Secondary minerals and alteration products, chiefly green chloritic minerals, comprise at least 10 percent of all Metchosin basalts. They constitute 10 to 90 percent of the rocks examined in thin section, averaging about 20 percent. In order of decreasing abundance these minerals are: (1) green to brown or yellow chloritic alteration products and serpentine; (2) zeolites, probably including several varieties of this group of minerals; (3) clay minerals, which are usually dusty, patchy, or minutely flaky in appearance; and (4) calcite, and perhaps other carbonates as well. The processes which caused the formation of these minerals have already been discussed. Zeolitization and chloritization, together with the associated alteration, are thought to be due to the work of late magmatic solutions aided by the heated and activated sea water into which these basalts were extruded.

Chloritic alteration products are found in all thin sections, in amounts ranging from less than 10 percent to nearly 80 percent, averaging 10 to 15 percent. The chloritic minerals replace any or all of the primary constituents of the rock, with the possible exception of magnetite and ilmenite, and also fill vesicles and fractures in the rock. In some thin sections they replace the cores of zoned plagioclase phenocrysts, leaving the rims relatively unaltered (fig. 21). This type of selective replacement of certain minerals or parts of crystals is seen in several thin sections; in other sections the chloritic minerals replace all constituents of the rock indiscriminately. Devitrified volcanic glass and the fine-grained groundmass of porphyritic basalts appear to be particularly susceptible to replacement by these minerals. Where the chloritic minerals occupy vesicles they commonly exhibit concentric banding or radiating structure (fig. 18).

Chloritic alteration products constitute nearly 80 percent of a rock which occurs in the Metchosin volcanic series along the northern edge of the Willapa Hills south of Holcomb, 17 miles west of

Pe Ell. The rock is a basaltic flow breccia which has been so thoroughly altered that only about 10 percent of the original constituents remain. This rock, like others in various parts of the Metchosin, may be classified as a greenstone.

Zeolites are present in about half of the thin sections examined, and the percentage would be considerably greater if more pillow basalts and flow breccias had been sectioned. The zeolites in these thin sections constitute 2 to 35 percent of the basalts in which they occur, averaging about 10 percent. They occur as vesicle and fracture fillings, as complete or partial pseudomorphs after plagioclase phenocrysts and laths which they have replaced (figs. 23-A and 23-B), and as irregular patches in the groundmass of some rocks. The zeolites commonly show well-developed radiating structure (fig. 22).

Clay minerals and calcite are present in most of the thin sections, usually in small amounts. Clay materials occur chiefly as dusty-, patchy-, or flaky-appearing alteration products of plagioclase (fig. 25). They constitute 1 to 25 percent of some thin sections, averaging 5 to 10 percent of most of those in which they are present in significant amounts. Calcite is present in amounts ranging from 2 to 20 percent of the thin sections in which it occurs, usually as fillings of vesicles and fractures (fig. 24); it also replaces primary minerals in a few rocks.

The intrusive mass in the vicinity of Baw Faw Peak is a fine-

FIGURE 10. Glassy Metchosin basalt, showing cumulophyric texture (photomicrograph). ×41. Plain light.

grained olivine gabbro; it is sufficiently distinctive to warrant separate petrographic description. The texture is allotriomorphic to hypidiomorphic granular (fig. 25). The primary mineral constituents and percentages of each are: labradorite (An_{68}), 40 to 45 percent; augite, 30 percent; olivine, 10 percent; and magnetite, about 3 percent. Grain size ranges from 0.5 to 1.5 mm., although some of the olivine crystals are smaller. Serpentine and chloritic minerals constitute about 5 percent of the rock, chiefly as alteration seams and rims in and around olivine crystals. Clay minerals are common, largely as alteration patches and dusty streaks in plagioclase; they constitute about 10 percent of the rock.

It may be noted that the foregoing descriptions of the Metchosin volcanic rocks conform in general to the petrographic descriptions given by Clapp (1917, pp. 256-264) for the Metchosin volcanics in the type area. In spite of the wide lithologic variation within the unit, the petrographic characteristics of the Metchosin basalts are thought by the writer to be fairly constant over the wide area in which these rocks are exposed.

Distinctive Petrographic Features

Microscopically, the Metchosin basalts are characterized by the relative abundance of alteration products and secondary minerals, and by the nature of the alteration. Secondary minerals—chiefly chloritic minerals and zeolites—constitute at least 10 percent of all the twenty-six thin sections examined, and average a little more than 20 percent. The rocks of the younger Tertiary volcanic units in this region are relatively unaltered, rarely containing more than 10 to 15 percent of alteration products.

The secondary minerals of the Metchosin volcanic rocks are distinctive also in that they may occur in and replace all parts of the rock, either selectively or indiscriminately. The alteration products in the younger Tertiary basalts fill vesicles, replace volcanic glass, or replace irregularly the fine-grained minerals in the groundmass, but they rarely replace the phenocrysts, with the exception of olivine. In the Metchosin basalts, on the other hand, the secondary minerals fill vesicles and fractures and replace volcanic glass, fine mineral grains, and large phenocrysts, wholly or in part. Chloritic alteration products are found throughout many of the thin sections. Zeolites are found in all parts of some of the rocks, commonly forming pseudomorphs after large plagioclase crystals. Clay minerals are present in many thin sections and may replace large plagioclase phenocrysts. In short, these secondary minerals are characteristic of the Metchosin volcanic series, and they represent the chief criterion for differentiating these rocks from the younger Tertiary volcanics in thin section.

FIGURE 11.

FIGURE 12.

FIGURE 13.

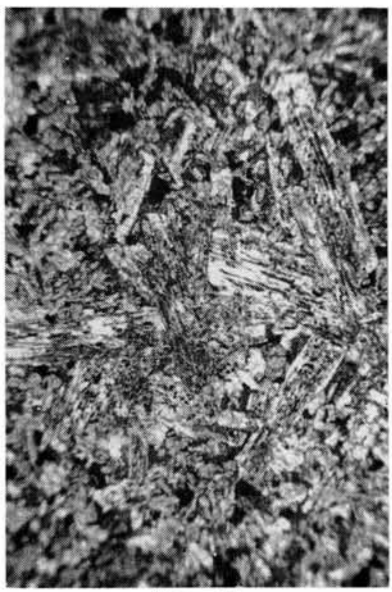

FIGURE 14.

FIGURE 11. Intergrowths in diabasic Metchosin basalt (photomicrograph). ×63. Plain light.

FIGURE 12. Metchosin pillow basalt, showing typical texture and alteration (photomicrograph). ×22. Plain light.

FIGURE 13. Porphyritic Metchosin olivine basalt (photomicrograph). ×63. Plain light.

FIGURE 14. Corroded plagioclase in altered diabasic Metchosin basalt (photomicrograph). ×22. Plain light.

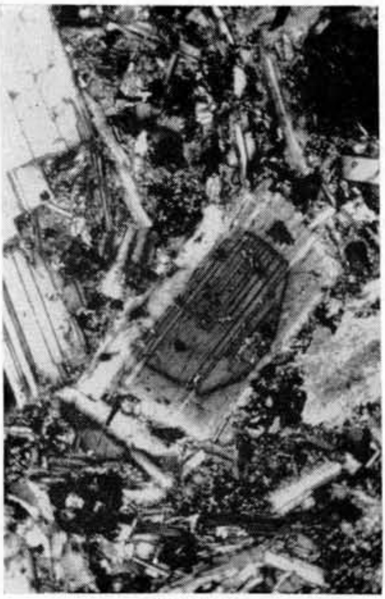

FIGURE 15.

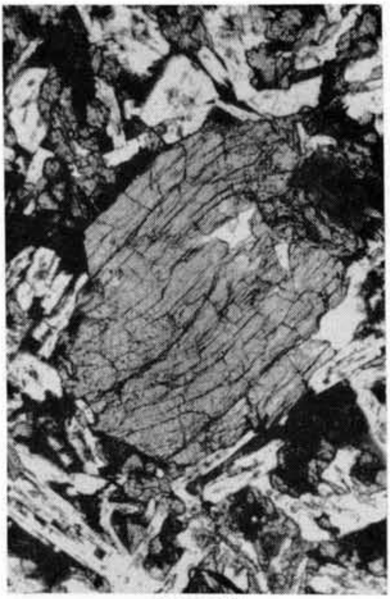

FIGURE 16.

FIGURE 17.

FIGURE 18.

FIGURE 15. Zoned plagioclase phenocryst in Metchosin basalt dike (photomicrograph). ×63. Crossed nicols.

FIGURE 16. Sheared augite phenocryst in Metchosin basalt (photomicrograph). ×111. Plain light.

FIGURE 17. Skeletal ilmenite in diabasic Metchosin basalt (photomicrograph). ×63. Plain light.

FIGURE 18. Chloritic alteration products in Metchosin basalt (photomicrograph). ×63. Plain light.

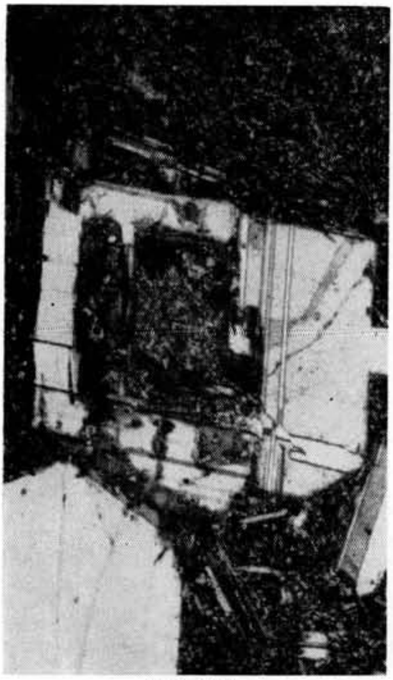

FIGURE 19.

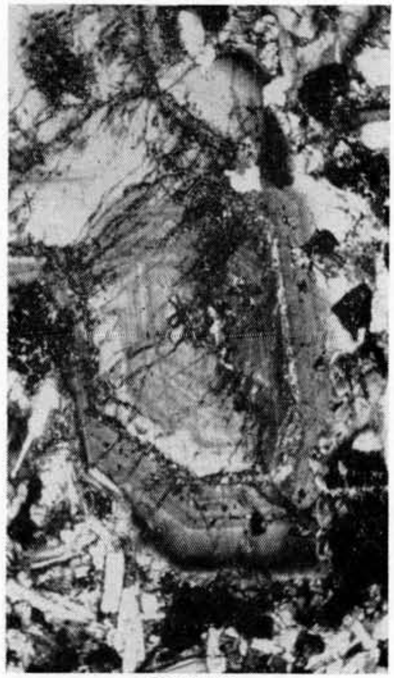

FIGURE 20.

FIGURE 21.

FIGURE 22.

FIGURE 19. Two sets of twin lamellae in plagioclase phenocryst (photomicrograph). ×63. Crossed nicols.

FIGURE 20. Zoned, altered plagioclase phenocryst in Metchosin basalt dike (photomicrograph). ×63. Crossed nicols.

FIGURE 21. Zoned plagioclase with core altered to chloritic minerals, Metchosin basalt (photomicrograph). ×63. Plain light.

FIGURE 22. Zeolite amygdule in Metchosin basalt (photomicrograph). ×22. Crossed nicols.

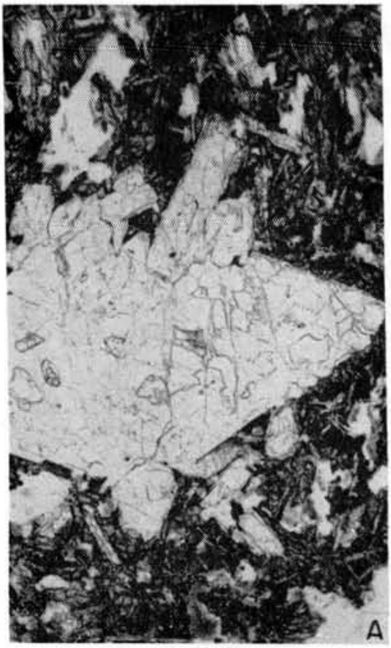

FIGURE 23a.

FIGURE 23b.

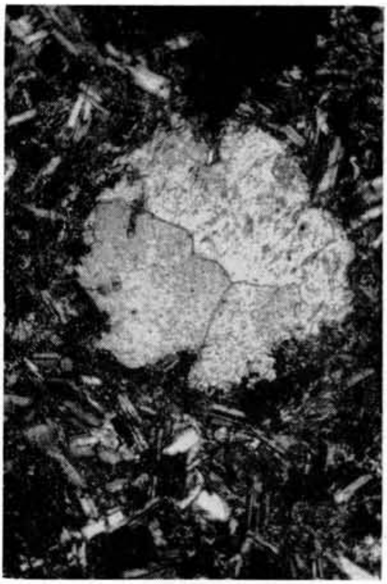

FIGURE 24.

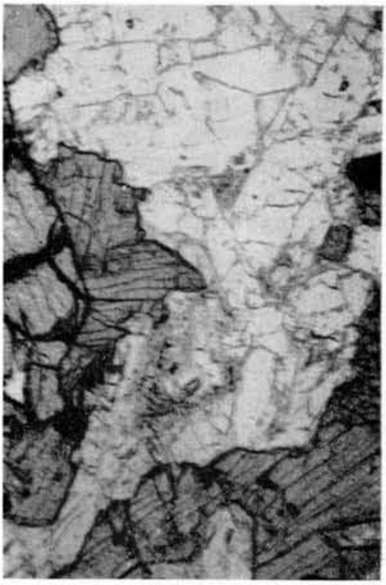

FIGURE 25.

FIGURE 23. Plagioclase phenocryst largely replaced by zeolite in Metchosin pillow basalt (photomicrographs). ×63. A. Plain light. B. Crossed nicols.

FIGURE 24. Calcite amygdule in Metchosin basalt (photomicrograph). ×63. Crossed nicols.

FIGURE 25. Baw Faw Peak olivine gabbro intrusive; plagioclase partly altered to clay minerals (photomicrograph). ×63. Plain light.

Northcraft Formation

Rock Types

It has previously been noted that only one thin section of a Northcraft lava was examined. The lavas and associated rocks of the Northcraft formation are lithologically rather distinctive and are less widely distributed in southwestern Washington than the other major volcanic rock units. The Northcraft volcanics have been adequately described (Snavely, Roberts, Hoover, and Pease, 1951). They differ petrographically from the other volcanic units and are easily recognizable in thin section.

The rock sectioned was collected from a dense fine-grained flow showing well-developed platy jointing. This flow is exposed on the east slope of Crawford Mountain, in the type area of the Northcraft formation. In that area (idem), "The Northcraft formation consists chiefly of ferromagnesian lavas, flow breccia, and pyroclastic rocks in the upper part, and basaltic conglomerate, sandstone, and pyroclastic material in the lower part." The total thickness is 700 to 1,000 feet. The Northcraft formation underlies much of the eastern half of the Centralia-Chehalis coal district southeast of Tenino, in Thurston County, and is exposed for some distance eastward from that area. The volcanics apparently thin and wedge out toward the west.

Petrographic Description

The Northcraft lava examined in thin section is a fine-grained calcic andesite. It is hypocrystalline and highly feldspathic, with trachytic texture (fig. 26). The rock is predominantly even grained. It consists essentially of plagioclase (An_{40} to An_{50}, andesine), augite, chloritic alteration products, magnetite, and volcanic glass.

Plagioclase is the dominant mineral, constituting nearly 75 percent of the rock. It occurs mainly as laths and microlites 0.1 to 0.2 mm. long, although a few larger crystals, 0.3 to 0.5 mm. long, are present. The plagioclase laths and microlites have parallel or subparallel orientation; they are largely subhedral in outline. Albite and Carlsbad twinning predominate, and some of the larger crystals show poorly developed zoning. The composition of the plagioclase ranges from An_{40} to An_{45} in the smaller laths and to slightly more basic than An_{50} in some of the larger crystals. Thus the plagioclase is predominantly calcic andesine.

Augite constitutes 10 to 15 percent of the rock and occurs as granules and short prisms generally less than 0.1 mm. long. The grains are anhedral to subhedral, and some are twinned.

Chloritic alteration products are present in small amounts throughout the thin section, constituting about 5 percent of the rock. They are mostly interstitial to the primary minerals and

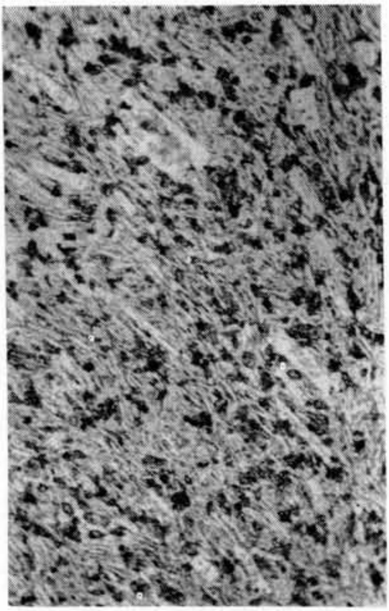

FIGURE 26.

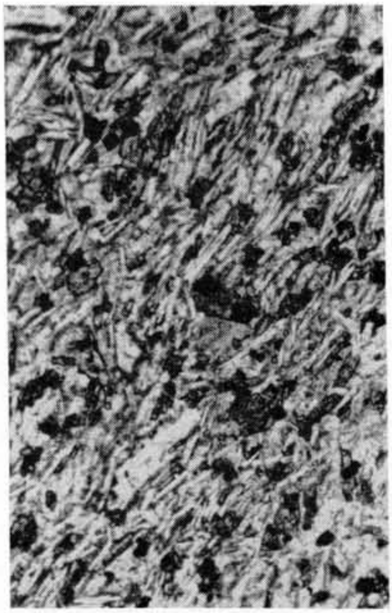

FIGURE 27.

FIGURE 26. Trachytic texture in Northcraft andesite (photomicrograph). ×63. Plain light.

FIGURE 27. Northcraft augite andesite, showing texture and alteration (photomicrograph). ×111. Plain light.

probably formed largely as the products of partial alteration of volcanic glass (fig. 27).

Magnetite, which makes up about 5 percent of the rock, is present as equant, angular grains. These are small, averaging less than 0.05 mm. in diameter.

Colorless to pale brownish volcanic glass constitutes 5 percent or less of the rock. It is of intermediate composition, with a refractive index of 1.52, and is partly devitrified.

Distinctive Petrographic Features

The description of the Northcraft formation by Snavely, Roberts, Hoover, and Pease (1951) is more complete and shows more variation than the foregoing description. However, the distinctive features of the rock described above are similar to those of all the lavas exposed in the type area of the formation.

In thin section the Northcraft volcanics are characterized by the abundance and composition of the plagioclase and by the trachytic texture. The plagioclase ranges in composition from An_{40} (andesine) to An_{60} (labradorite) and is typically An_{40} to An_{50} (calcic andesine). It usually constitutes 60 to 75 percent of the rock. Trachytic texture is well developed and is responsible for the flow cleavage seen in many of the flows.

Goble Volcanics

Rock Types

The term "Goble volcanics" is used here for both the Goble member of the Cowlitz formation in the mapped area and the Goble volcanic series (Wilkinson, Lowry, and Baldwin, 1946, p. 4) in the type area. The unit consists largely of basaltic flows with subordinate flow breccia and pyroclastic rocks.

Of the eight thin sections examined, seven were prepared from specimens of the Goble flow rocks and one from a vesicular flow breccia exposed along Olequa Creek south of Vader. Two of the flow rocks sectioned were collected from the sequence of Cowlitz sediments and intercalated lavas exposed along the Northern Pacific Railway main line and the banks of the Cowlitz River between Vader and Castle Rock. The other five were collected from exposures along both sides of the Columbia River in the type area of the Goble volcanic series.

Petrographic Description

Microscopically, the Goble volcanics are largely normal basalts. However, one of the rocks examined in thin section contains about 5 percent partly altered olivine and is considered an olivine basalt. The vesicular flow breccia is sufficiently distinctive petrographically to warrant a separate description, which is presented in a subsequent paragraph.

All of the basalts are hypocrystalline, and all but one are markedly porphyritic, the exception being a trachytic basalt which is only slightly porphyritic (fig. 29). The texture of the groundmass ranges from intersertal to intergranular or, rarely, trachytic. Most of the rocks are cumulophyric (fig. 28), and a few are somewhat vesicular. The essential constituents are plagioclase (labradorite and bytownite) and augite, with olivine present in one thin section. Magnetite, volcanic glass, and chloritic alteration products occur in all thin sections. Calcite occurs in small amounts in two of the basalts, and an unidentified zeolite is present in two others.

Plagioclase is the dominant mineral in the Goble flows, constituting 50 to 60 percent of the rocks and averaging more than 55 percent. The composition ranges from An_{60} (labradorite) to An_{77} (bytownite). Average composition of the plagioclase laths in the groundmass is An_{60} to An_{65}, and the composition of the phenocrysts is An_{70} to An_{77}. All of the sections examined contained some phenocrysts which are zoned. Most of the plagioclase shows albite twinning or combined Carlsbad-albite twinning. The phenocrysts, and especially the more calcic cores of zoned crystals, are commonly corroded and altered (figs. 30 and 31).

The average length of the plagioclase phenocrysts is about 0.5

mm., although crystals as much as 2.5 mm. long are present. They are euhedral to subhedral in outline and typically tabular in habit, as are some of the smaller crystal grains (fig. 31). The tabular form of the plagioclase is distinctive. The laths and plates in the groundmass are 0.1 to 0.3 mm. long and have predominantly subhedral outlines.

Augite phenocrysts are present in all of the flow rocks studied but are not as abundant as plagioclase phenocrysts. Together with the granules and small crystals in the groundmass they constitute 15 to 25 percent of the thin sections, averaging a little more than 20 percent. The phenocrysts are 0.2 to 2.0 mm. long, averaging 0.4 mm. Augite grains in the groundmass are small, typically less than 0.1 mm. long. Many of the larger crystals are twinned, and weak to well-developed zoning is seen in some of the phenocrysts.

Where olivine occurs in these rocks, it is present as strongly altered and corroded phenocrysts, with seams and rims of alteration products (fig. 32). These include chloritic minerals and serpentine.

All the thin sections contain volcanic glass, in amounts ranging from 3 to 15 percent. The glass is pale brown to dark reddish brown in color and usually is partly devitrified.

Magnetite is the chief accessory mineral. It occurs as equant angular grains and as dust-size particles in the volcanic glass.

Alteration products generally constitute less than 10 percent of these volcanics. Chloritic material is the most abundant of the secondary minerals, averaging 7 percent of the flows; it occurs in vesicles (fig. 33) and as a product of alteration of some primary constituents, especially volcanic glass. Minor amounts of zeolite or calcite also are present in four of the seven thin sections studied.

The flow breccia which was examined in thin section is a highly vesicular, somewhat altered basaltic rock with porphyritic to cumulophyric texture (fig. 35). The primary constituents and the percentage of each are: plagioclase (An_{60} to An_{65}, labradorite), 45 percent; augite, 15 percent; magnetite, 5 percent; and volcanic glass, 5 percent. The phenocrysts consist of labradorite as much as 0.5 mm. long and augite as much as 1.5 mm. long. They are set in a fine-grained groundmass composed of labradorite laths and plates 0.1 mm. long, granules of augite and magnetite, and glass. In this rock, as in the Goble flows, the plagioclase is commonly tabular in habit and the phenocrysts are somewhat corroded.

About 30 percent of the flow breccia consists of secondary minerals, largely calcite (20 percent) and chloritic alteration products (10 percent). These minerals occupy many large vesicles in the rock and also form patches in the groundmass (fig. 34). The vesicles are filled with concentrically layered, banded, or massive calcite, chloritic minerals, magnetite, and subordinate clay minerals.

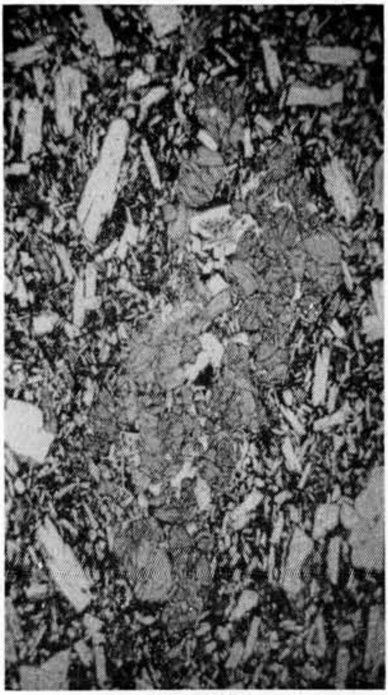

FIGURE 28.

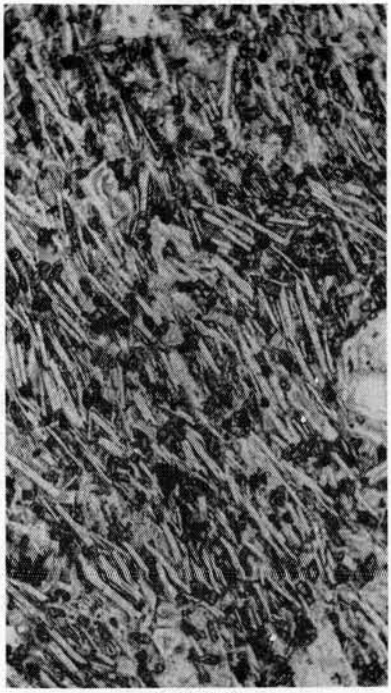

FIGURE 29.

FIGURE 30.

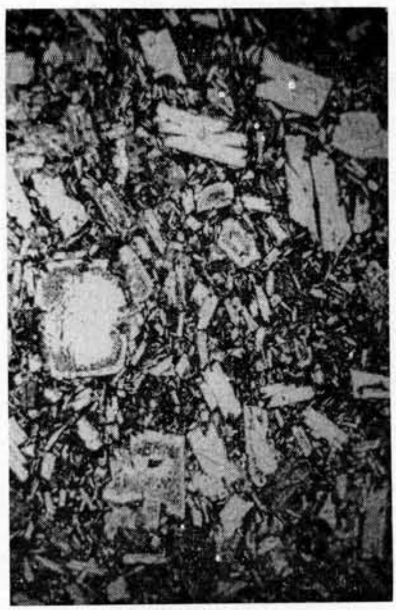

FIGURE 31.

FIGURE 28. Cumulophyric texture in Goble basalt (photomicrograph). ×22. Plain light.

FIGURE 29. Trachytic groundmass in Goble basalt (photomicrograph). ×63. Plain light.

FIGURE 30. Altered tabular plagioclase phenocrysts in Goble basalt (photomicrograph). ×63. Plain light.

FIGURE 31. Feldspathic Goble basalt with corroded tabular plagioclase phenocrysts (photomicrograph). ×22. Plain light. Substage diaphragm partly closed.

FIGURE 32.

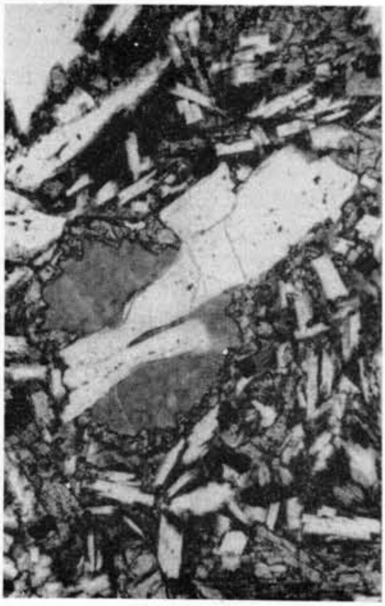

FIGURE 33.

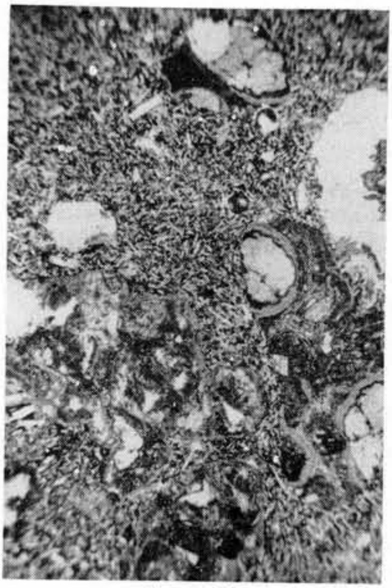

FIGURE 34.

FIGURE 35.

FIGURE 32. Goble olivine basalt; olivine phenocryst almost completely altered to dark chloritic mineral (photomicrograph). ×41. Plain light.

FIGURE 33. Plagioclase phenocryst penetrating chlorite-filled vesicle (photomicrograph). ×111. Plain light.

FIGURE 34. Vesicular, altered Goble flow breccia (photomicrograph). ×22. Plain light.

FIGURE 35. Cumulophyric texture in Goble flow breccia (photomicrograph). ×41. Plain light.

Distinctive Petrographic Features

The Goble volcanic rocks in thin section are distinguished largely by the abundance and form of the plagioclase. As noted previously, these rocks are highly feldspathic, plagioclase constituting at least 50 percent of the flows sectioned and averaging more than 55 percent. This figure compares with an average of 45 percent in both the Metchosin volcanics and the Astoria basalts. The latter are discussed on succeeding pages. The plagioclase of these rocks is considerably more calcic and more coarsely crystalline than that of the Northcraft lavas.

Tabular plagioclase is common in the Goble volcanics, both as phenocrysts and in the groundmass. This feature serves to distinguish the Goble flows from some of the Astoria basalt flows which are similar in other respects.

Other petrographic characteristics which may be helpful in distinguishing the Goble volcanic rocks are: (1) the partly corroded plagioclase phenocrysts, which typically appear pitted; and (2) the cumulophyric texture, which is more common in these rocks than in the other volcanic units.

Astoria Basalts

Rock Types

The massive sandstones and intercalated basalt flows which overlie unconformably the Eocene formations along the southern boundary of the mapped area have been assigned by Weaver (1937B, pp. 175-180 and pl. 8) to the Astoria formation, of middle Miocene age. The Astoria basalts also overlie the belt of Oligocene sediments which mark the northern boundary of the area, and the lavas capping peaks and ridges in the central low hills are remnants of the same basaltic flows. These rocks are widely distributed in other parts of southwestern Washington.

Thin sections were prepared from Astoria basaltic rocks collected from lava cappings and dikes within the area and from the flows exposed north and south of the area. In addition, three of the thin sections of "unknown" basalts previously noted have been assigned to the Astoria on the basis of their petrographic characteristics. These "unknown" specimens were collected from flows exposed in the vicinity of the North River south of Aberdeen, in Grays Harbor County. Altogether, fifteen thin sections of basaltic rocks assigned to the Astoria formation have been examined.

Petrographic Description

The Astoria basalts fall naturally into two groups which are petrographically quite distinct from each other. These groups are: (1) glassy, generally even grained basalts characterized in thin section by an abundance of black to dark brown volcanic glass;

and (2) largely crystalline, porphyritic basalts, which show marked petrographic similarities to the Goble volcanics. Of the fifteen thin sections studied, eight belong to the first group and seven to the second. The two groups are discussed separately in succeeding paragraphs.

The glassy basalts are predominantly even grained, with intersertal to hyalo-ophitic texture (fig 36). Most of them are vesicular. They consist essentially of plagioclase, volcanic glass, and augite and are relatively unaltered. In all sections examined, the most striking feature is the abundance of volcanic glass.

Plagioclase is the dominant mineral in most of these rocks, constituting 35 to 50 percent of the thin sections and averaging slightly more than 40 percent. It occurs as laths 0.1 to 0.8 mm. long, with an average length of 0.4 mm., and generally subhedral in outline. The laths typically show albite and Carlsbad twinning, and commonly form intergrowths with augite crystals. The composition of the plagioclase is An_{60} to An_{65} (labradorite).

Volcanic glass constitutes 25 to 45 percent of these rocks, averaging a little more than 30 percent. In two thin sections glass is slightly more abundant than plagioclase. The glass is interstitial to the crystalline minerals in most sections, although it completely surrounds them in places. It is predominantly black in color and opaque, appearing dark brown on thin edges and in devitrified portions. The color is probably due in large part to finely divided magnetite dust and crystallites scattered through the glass. The refractive index ranges from 1.55 to 1.58, indicating intermediate to basic composition. The glass is partly devitrified in places, and in a few of the sections it is slightly altered to chloritic minerals.

Augite constitutes 15 to 30 percent of the glass basalts, averaging 25 percent. The subhedral to anhedral crystals and granules are 0.1 to 1.0 mm. long. Many of the larger crystals are twinned.

Magnetite occurs as discreet crystal grains in only one of the thin sections examined. In that thin section it forms delicate strings of small euhedral grains in the black glass (fig. 38).

Chloritic alteration products are present in more than half of the sections in amounts ranging from 1 to 10 percent and averaging about 5 percent. The color of these minerals ranges from green to yellow or brown. They replace volcanic glass (fig. 37), usually where it is devitrified, and they also fill vesicles. In one thin section a brown chloritic mineral alters and replaces grains of augite. Three sections contain no alteration products.

The largely crystalline, porphyritic group of the Astoria basalts is similar in most respects to the Goble basalt flows. They are slightly to strongly porphyritic, and some show cumulophyric (figs. 40-A and 40-B), vesicular, and diabasic textures as well. The diabasic rocks in this group are three dikes of Miocene basalt injected into Eocene sediments. Phenocrysts in the porphyritic basalts consist of plagioclase, augite, and, in two of the sections, olivine; they are set in a groundmass of fine-grained plagioclase laths and augite granules, with interstitial volcanic glass and alteration products. The texture of the groundmass is typically intersertal, and a few of the sections show poorly developed trachytic texture as well (fig. 39).

Plagioclase is the most abundant mineral, constituting 35 to 55 percent of these rocks and averaging 45 percent. It occurs as small to large phenocrysts 0.2 to 1.2 mm. long, and as laths and grains with an average length of 0.1 to 0.2 mm. Plagioclase phenocrysts are present in all but one of the sections examined. They are euhedral to subhedral in outline and may be partly corroded. They show some complex twinning, in addition to albite and Carlsbad twinning, and are not commonly zoned. The plagioclase laths in the groundmass exhibit simple twinning. The composition of the plagioclase ranges from An_{58} to An_{65} (labradorite) in most of the sections. A few of the phenocrysts, however, are as basic as An_{70} (labradorite-bytownite).

Augite occurs as phenocrysts in all thin sections of this group. It is also present as granules and small crystals in the groundmass, constituting altogether 15 to 40 percent of the rocks and averaging slightly more than 25 percent. The phenocrysts are 0.3 to 3.5 mm. long. Many of the larger crystals are twinned (fig. 42), and some show pronounced zoning (fig. 41); dispersion may be strong, producing anomalous interference colors.

Olivine is present in phenocrysts in two of the seven thin sections, constituting 3 percent of one rock and 8 percent of the other. The olivine crystals are euhedral to subhedral in outline and 0.5 to 4.0 mm. long. They are considerably corroded and altered, being replaced along fractures and around their edges by bowlingite, serpentine, and chloritic minerals (fig. 44).

Magnetite and ilmenite occur in all of the rocks, in amounts ranging from 3 to 10 percent and averaging 7 percent. Of this amount nearly half is skeletal ilmenite. Magnetite forms angular, equant grains, generally small, in most of the rocks. It also occurs as minute grains and crystallites in the volcanic glass of the groundmass.

Volcanic glass constitutes 5 to 15 percent of the groundmass of all but one of the basalts, averaging about 7 percent. It is colorless to brownish, considerably devitrified, and in part replaced by chloritic alteration products (figs. 43-A and 43-B).

Secondary minerals and alteration products are present in all sections in amounts ranging from 10 to 25 percent and averaging nearly 15 percent. Chloritic alteration products constitute 12 percent (average) of these rocks, filling vesicles and replacing devitrified glass and fine-grained minerals in the groundmass. The chloritic minerals commonly show well-developed radiating and banded structures (figs. 43-B, 45, and 46). Calcite occurs in four rocks in amounts ranging from 2 to 15 percent. It forms radiating to massive vesicle fillings (fig. 47) and, in the thin section in which it is most abundant, replaces some of the primary constituents, especially devitrified glass.

Distinctive Petrographic Features

The glassy group of the Astoria basalts is characterized in thin section by an abundance of black volcanic glass. These flows are petrographically quite different from any other lavas exposed in the Coast Range of southwestern Washington.

The largely crystalline group of Astoria lavas, as noted previously, shows marked petrographic similarity to the Goble volcanics. However, the latter are generally more feldspathic, and the form of the plagioclase is predominantly tabular. The plagioclase of these Astoria basalts is typically prismatic or lathy, and it is generally less calcic than the plagioclase of the Goble flows. The latter criterion cannot be used with assurance, however, because of the variations in composition in rocks of both units.

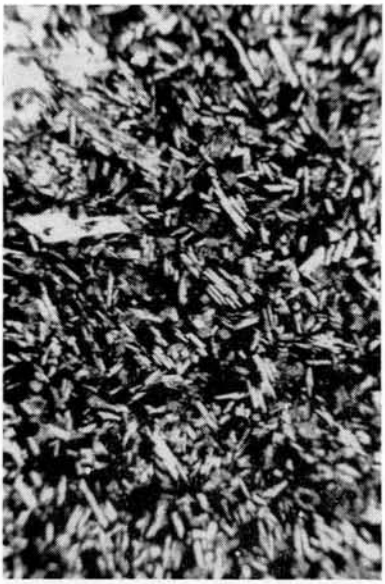

FIGURE 36.

FIGURE 37.

FIGURE 36. Typical texture of glassy Astoria basalt (photomicrograph). ×22. Plain light.

FIGURE 37. Black volcanic glass in groundmass of Astoria basalt (photomicrograph). ×63. Plain light.

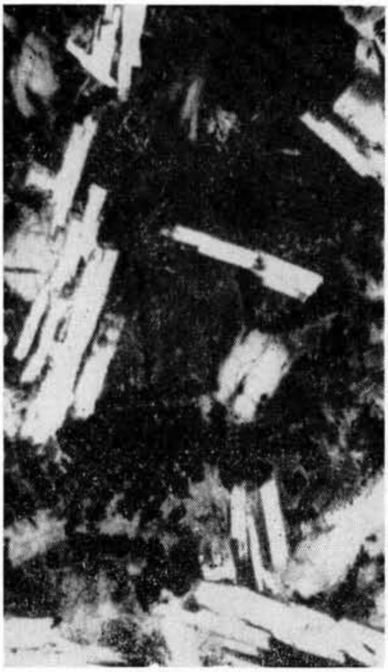

FIGURE 38.

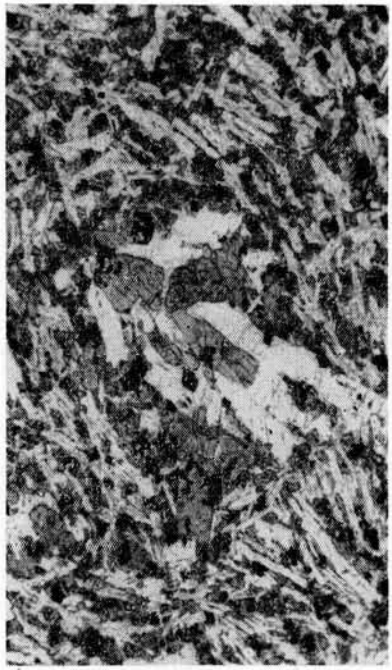

FIGURE 39.

FIGURE 40a.

FIGURE 40b.

FIGURE 38. Magnetite crystals in black volcanic glass (photomicrograph). ×111. Plain light. Condensing lens in.

FIGURE 39. Typical texture of predominantly crystalline Astoria basalt (photomicrograph). ×63. Plain light.

FIGURE 40. Cumulophyric texture in Astoria basalt (photomicrographs). ×41. A. Plain light. B. Crossed nicols.

FIGURE 41.

FIGURE 42.

FIGURE 43a.

FIGURE 43b.

FIGURE 41. Zoned augite phenocryst in porphyritic Astoria basalt (photomicrograph). ×41. Crossed nicols.

FIGURE 42. Twinned augite phenocryst in porphyritic Astoria olivine basalt (photomicrograph). ×22. Crossed nicols.

FIGURE 43. Texture of chloritic minerals partly replacing devitrified glass (photomicrographs). ×63. A. Plain light. B. Crossed nicols.

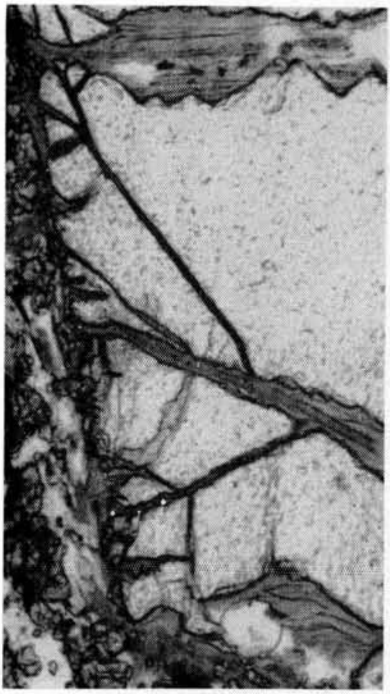

FIGURE 44.

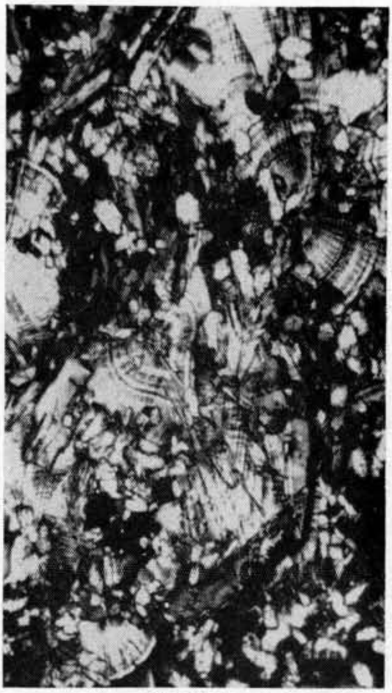

FIGURE 45.

FIGURE 46.

FIGURE 47.

FIGURE 44. Bowlingite partly replacing olivine phenocryst in Astoria basalt (photomicrograph). ×111. Plain light.

FIGURE 45. Chloritic alteration products in groundmass of Astoria basalt (photomicrograph). ×111. Crossed nicols.

FIGURE 46. Banded chloritic alteration products and calcite filling vesicle in Astoria basalt (photomicrograph). ×63. Plain light.

FIGURE 47. Radiating calcite filling vesicles in Miocene basalt dike (photomicrograph). ×22. Crossed nicols.

Summary of Petrographic and Lithologic Criteria for Differentiating the Major Volcanic Rock Units

Metchosin volcanic series.—In thin section the Metchosin volcanics are characterized by an abundance of secondary minerals and alteration products and by the nature of the alteration. These minerals, including zeolites, chloritic alteration products, and clay minerals, typically constitute more than 20 percent of the rock. They fill vesicles and fractures, replace volcanic glass and fine-grained minerals in the groundmass, and alter and replace large phenocrysts. In short, they may replace any of the primary constituents of the rock, selectively or at random, wholly or in part. Chloritization and zeolitization are particularly effective; in some places the former has progressed so far that the rock may be classified as a greenstone.

The intrusive in the vicinity of Baw Faw Peak is a relatively unaltered olivine gabbro. It is distinctive not only in thin section but also in the field.

In southwestern Washington, pillow lavas occur only in the Metchosin volcanic series, which is, therefore, distinguished in part by the presence of pillow lavas.

Flow breccia is found in both the Metchosin volcanic series and the Goble volcanics. However, the Metchosin flow breccia is readily distinguished, lithologically and microscopically, by an abundance of chloritic alteration products, zeolites, and altered palagonitic glass.

Northcraft formation.—The Northcraft lavas are recognized in thin section by the composition of their plagioclase, which is largely calcic andesine. These rocks are essentially augite andesites, whereas the other volcanics of the region are basalts. The high percentage (60 to 75 percent) of plagioclase and the well-developed trachytic texture also serve to distinguish the Northcraft lavas from other volcanic rocks.

The trachytic texture gives rise to flow cleavage, which is a distinguishing feature of many of the lavas. In addition, most of the flows exhibit weak to well-developed platy jointing, which is useful in differentiating these rocks from all other volcanics except the Goble.

Goble volcanics.—Microscopically, the Goble volcanic rocks are characterized chiefly by the tabular form of the plagioclase. This feature and the relative abundance (55 percent) of plagioclase serve to distinguish these rocks from Astoria basalt flows which are in other respects quite similar. The composition of the plagioclase (labradorite and bytownite) and strongly porphyritic or cumulophyric texture differentiate the Goble volcanics from the Northcraft lavas.

In the type area, lavas of the Goble volcanic series are reported (Wilkinson, Lowry, and Baldwin, 1946, p. 8) to be distinguished from similar-appearing Miocene basalts partly by "the platy jointing of some of the basalts and the [presence of] associated pyroclastic rocks." In the mapped area as well, the platy jointing and presence of flow breccia and subordinate interbedded pyroclastics aid in distinguishing the Goble volcancs from the crystalline group of Astoria flows.

Astoria basalts.—The Miocene basalt flows, which are locally interbedded with sediments of the Astoria formation, are subdivided into two groups; (1) highly glassy, even-grained basalts; and (2) largely crystalline, porphyritic basalts. The two groups are quite different from each other in thin section.

Rocks of the glassy group are characterized by an abundance (average 30 percent or more) of volcanic glass, predominantly black and opaque, and only slightly devitrified. These flows are generally even grained and relatively unaltered. They are petrographically quite unlike any other lavas of the region.

The largely crystalline Astoria basalts are similar to the Goble flows, from which they are distinguished in thin section chiefly by lack of the tabular plagioclase which characterizes the Goble volcanics. In addition they generally contain a smaller percentage of plagioclase (45 percent). In the field the Astoria basalts are more massive, lacking the platy jointing of the Goble flows. They commonly show crude columnar jointing.

GEOLOGIC STRUCTURE

Regional Features

The lower Cowlitz River-eastern Willapa Hills area is a part of the Coast Range of the North Pacific Coast of America, and major folds in the area conform generally to the northwesterly Coast Range structural trend. The Eocene formations in this portion of southwestern Washington comprise parts of two major folds, a broad syncline and a complex anticline. The structural picture is complicated by the presence of numerous small folds on the flanks of the major folds. A few small faults cut the Eocene rocks, but faulting has apparently played a minor role in the structural development of the area. Several stages of deformation are recognized.

The Eocene sediments and volcanic rocks within the mapped area have been gently folded to form part of the eastern end and northern limb of the broad, eastward-plunging Willapa Hills anticlinal uplift. This major structural upwarp constitutes the southwestern margin of the Centralia-Chehalis structural basin, which is filled with folded Tertiary sediments and volcanics. The Willapa Hills anticline is bifurcated in this area, and the northern branch of the fold plunges eastward and fades out in the vicinity of Vader. The southern branch, which includes the main axis of the fold, lies largely south of the mapped area. The axis of the Willapa Hills anticline apparently bifurcates in the high, rugged hills southwest of Pe Ell, and the northern branch of the anticline begins its eastward plunge at that point. The southern branch of the fold plunges toward the east at a low angle and extends southeastward for many miles.

The northeastward-dipping sediments and volcanic rocks in the upper part of the Eocene section represent part of the southern limb of a broad synclinal fold termed the North River-Dryad syncline (Weaver, 1937B, p. 94). The axis of this major syncline lies north of Winlock and trends in a northwesterly direction through Doty, north of Pe Ell.

Several faults, none of which show large displacement, were mapped in the Eocene and Oligocene rocks. Most of the faults cannot be traced beyond the stream beds or road cuts in which they are exposed, usually because of the paucity of exposures. Physiographic evidence of faulting is generally weak or nonexistent, with a few notable exceptions. Many small faults, with displacements ranging from a few inches to several feet, are exposed in some of the larger road cuts and stream-bank outcrops. These small faults are common in the loosely compacted sediments and may be due in part to local slumping rather than regional tectonic forces.

Structural features in the lower Cowlitz River-eastern Willapa Hills area cannot be determined on the basis of plotted dips and strikes alone. Landsliding and slumping, on a large scale in places, result in anomalous attitudes. Because of the thick soil mantle, dense forest and underbrush, and local covering of alluvium, exposures are scarce or lacking in many localities, and structural trends can be traced only with great difficulty, if at all. In addition, the structure of the Eocene rocks south and east of Ryderwood is masked by the overlapping Miocene rocks.

Folds

General Statement

The Eocene rocks of the mapped area have been gently deformed along axes which have a general northwest-southeast trend, becoming nearly east-west locally. Dips as high as 45° have been measured, but most are less than 25°. The average dip of the beds in the limbs of the two major folds ranges from 10° to 20°.

The structural trends in the Eocene rocks are transverse to the roughly north-south axis of the present-day Coast Range. Tertiary rocks as young as middle Miocene in age are included in these northwestward-trending folds. Hence, the tectonic activity which raised the Coast Range along its present north-south axis occurred subsequent to the northwest-southeast folding and was superimposed upon earlier folds.

Willapa Hills Anticline

The most prominent structural feature in the area is here referred to as the Willapa Hills anticlinal uplift. This name is the one most commonly used by geologists in the southwestern Washington region, although the fold has also been called the South Bend anticlinal upwarp (Weaver, 1937B, p. 199).

The Willapa Hills anticlinal uplift is a large complex bifurcate anticline, which plunges eastward in this area. The axis of the fold trends S. 35°-60° E. from Willapa Harbor to the hills southwest of Pe Ell. There the anticline bifurcates, with a smaller northern branch of the fold separating from the main southern branch. The axis of the northern branch passes approximately 9 miles south of Pe Ell, trending S. 70° E. to eastward from that point and fading out a short distance south of Vader. From the point of bifurcation the axis of the southern branch of the fold trends approximately S. 45°-60° E., passing beneath the overlapping Miocene rocks about 16 miles south of Pe Ell.

The southern branch of the Willapa Hills anticlinal uplift extends southeastward for many miles beyond the eastern limit of the mapped area. The writer has not studied the easterly continuation of the Willapa Hills anticline, but Weaver (1937B, p. 199) states that it "appears to continue to the vicinity of Mount St. Helens in eastern Cowlitz County."

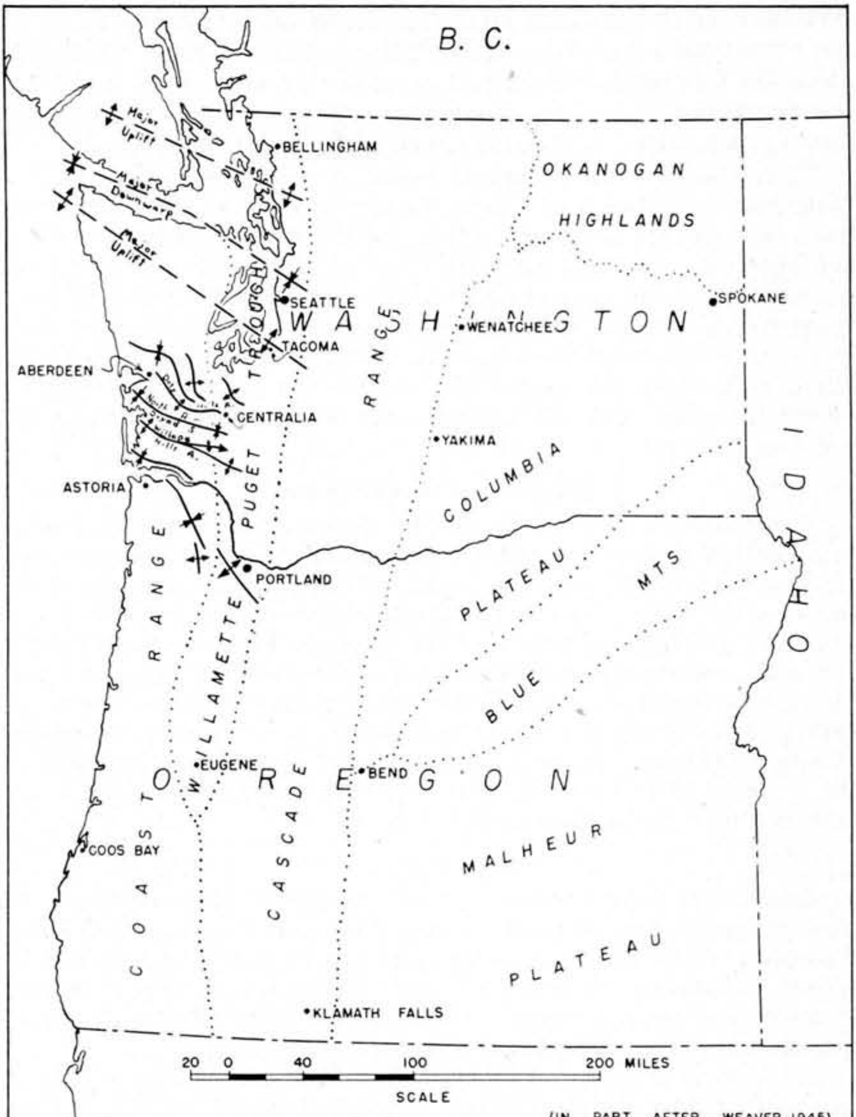

FIGURE 48. Physiographic provinces and major Coast Range structural features of Washington and Oregon.

Both branches of the fold plunge toward the east, the northern branch more steeply than the other. The northern branch plunges eastward at an angle of about 15° to a point south of Vader, east of which this part of the anticline can no longer be traced. The southern branch, which is the major axis of the fold, plunges southeastward at a low angle.

Along the banks of the Cowlitz River, which marks the eastern boundary of the mapped area, the folded upper Eocene rocks do not reflect the bifurcation of the Willapa Hills anticline. The strata along the Cowlitz River dip rather uniformly toward the north and northeast, in marked contrast to the eastward- and southeastward-dipping beds along Stillwater Creek and lower Olequa Creek.

The Willapa Hills anticlinal uplift is expressed mainly in the Metchosin volcanics, which form the core of the fold and from which have been eroded the sharp ridges and steep-walled canyons of the Willapa Hills. At least 6,000-8,000 feet of Metchosin volcanic rocks are exposed in this central part of the uplift. The Eocene beds overlying the Metchosin volcanic series dip northward and northeastward on the northern flank of the anticline; they form a broad anticlinal nose about the eastward-plunging end of the north branch of the bifurcate fold. This anticlinal nose flattens and disappears towards the east.

North River-Dryad Syncline

The southern limb of the North River-Dryad synclinal fold is composed of the northwestward-trending Eocene and younger Tertiary sediments and volcanic rocks. These are well exposed along the Cowlitz River, Olequa Creek, Stillwater Creek, and the South Fork of the Chehalis River, and the Chehalis River north of Pe Ell, also along certain roads and streams in the intervening areas. A maximum thickness of more than 8,000 feet of Eocene sediments and volcanics, dipping generally northeastward to northward at angles averaging between 10° and 20°, is exposed in the southern limb of the syncline. The axis of the fold is located in the Miocene outcrop belt, north of the mapped area.

Minor Folds

Small folds were mapped in many localities. They appear to be local in extent and generally cannot be traced for more than short distances. These minor anticlines and synclines are mappable only where exposures are more or less continuous, as along certain streams and logging roads. Other small folds similar to those mapped may be present but not exposed in the area.

A small, northeastward-plunging anticlinal nose occurs in Eocene sediments exposed along the bed and west bank of the South Fork of the Chehalis River about ¾ of a mile southwest of Klaber. Within a horizontal distance of 300 yards, as one moves downstream (northwestward), the direction of the measured dips changes gradually, albeit rapidly, through an angle of 120°. The beds in the downstream limb of the fold dip S. 60° E. at angles of 15° to 20°, whereas the beds in the upstream limb dip northward at angles of 15° to 30°. The nose plunges northeastward at an angle of 10°. This minor fold is reflected in the abrupt bend in the contact between the Stillwater Creek and Olequa Creek members southwest of Klaber (pl. 1).

Typical of the minor folds in the Eocene rocks of the area are the small anticline and syncline in sec. 29, T. 11 N., R. 2 W., and the syncline in sec. 33, T. 12 N., R. 2 W., along Olequa Creek; and the small syncline and anticline in sec. 26, T. 11 N., R. 3 W., along Stillwater Creek. Because of their small size and limited extent, the minor folds are not named. They are merely local upwarps and downwarps in the limbs of the major folds; many may be associated with faulting at depth.

Faults

General Statement

Faulting apparently has played a relatively minor role in the structural development of the lower Cowlitz River-eastern Willapa Hills area. Doubtless the apparent lack of faults in the area is due in part to the lack of continuous rock exposures, a deficiency which may cause the structural picture to appear more simple than it actually is. However, the faults which have been mapped are generally of small displacement and have little effect on the major structural features. Most of them trend in a northwesterly direction, roughly parallel to the strike of the beds which they displace.

Crego Hill Fault Zone

Probably the largest fault or fault zone in the area is the Crego Hill fault zone. This feature is restricted to the outcrop belt of Oligocene rocks immediately north of the mapped area. The fault zone trends northwestward from a point south of Sam Henry Peak in sec. 23, T. 12 N., R. 3 W., to a point east of Klaber in sec. 32, T. 13 N., R 3 W. The Crego Hill fault zone consists of a number of small parallel or en échelon faults, along each of which there has been some displacement. The total displacement along the fault zone is not large, probably amounting to less than 100 feet. The scant surface geologic evidence does not indicate whether movement was normal or reverse.

Evidences of faulting may be observed in several places where roads cross the fault zone. In addition, the fault zone can be mapped in part on the basis of its physiographic expression; for example, the prominent bench on the steep south face of Crego Hill, at an elevation of about 900 feet, is situated on the fault zone.

Other Faults

Several faults of minor importance occur in the mapped area. These small faults show slight displacement and are of little significance in the structural picture of the region.

A small fault branches off the Crego Hill fault zone near its southeastern terminus, in secs. 15 and 22, T. 12 N., R. 3 W. This fault trends approximately north-south, cutting both Oligocene and

Eocene rocks. It is poorly exposed in the field and was mapped partly on the basis of its weak physiographic expression.

A well-exposed fault crosses the channel of the South Fork of the Chehalis River 1½ miles southeast of Wildwood. It cuts well-bedded marine siltstones of the Stillwater Creek member and trends N. 70° W., transverse to the strike of the beds. The plane of the fault is indicated by a layer of light-gray pyritized limy gouge 3 inches in thickness; it dips 45° in a northeasterly direction. There is a marked difference in the attitudes of the strata on opposite sides of the fault, which is apparently a reverse fault along which part of the movement was rotational. The total displacement is not large. Alluvium and soil cover the Eocene rocks on both sides of the river; hence the continuation of the fault beyond the banks of the river is not exposed.

Faulting accounts for the presence of a narrow wedge of marine mudstones and siltstones in the upper part of the Pe Ell volcanics member along the Chehalis River and Sand Creek in Pe Ell. The marine sediments constitute a small block which has been faulted into the pyroclastic rock unit. The anomalous southeasterly dip of the sedimentary strata is also thought to be due to faulting. The faults which bound the wedge of sediments were not observed in the field because of the lack of exposures.

In the northeast corner of the area the Cowlitz formation and the lower Oligocene Gries Ranch beds are separated by a well-exposed fault in the southeast bank of the Cowlitz River at the abrupt bend 2½ miles southwest of Toledo. The fault trends N. 40° W. and dips southwestward at an angle of 80°. It is a reverse fault, along which the total displacement is not large. The highly fossiliferous Oligocene conglomerates and grits on the upstream side of the fault dip northwestward at a low angle. The well-bedded Eocene sandstones downstream from the fault dip southwestward at angles ranging from 5° to 10°.

Other minor faults were mapped along Stillman Creek, Stillwater Creek, Olequa Creek, and the Cowlitz River; they cannot be traced beyond their exposures in the stream valleys. Movement along these faults apparently was slight. Small faults in this area are generally marked by an abrupt steepening of dip in the beds adjacent to the faults.

Structural Development

Several stages of deformation have been involved in the structural development of the lower Cowlitz River-eastern Willapa Hills area. The present structural features are the result of several Eocene and younger Tertiary periods of diastrophism; these are discussed in succeeding paragraphs.

Any statement concerning structural conditions at the beginning of Eocene time in this area is necessarily conjectural. The base of the Metchosin volcanic series is not exposed in southwestern Washington, and it is not known whether these volcanics were the first rocks deposited during Eocene time. However, it has been noted previously that the Metchosin volcanic series elsewhere lies unconformably upon Cretaceous and older rocks, and it is probable that the Metchosin volcanics similarly represent the oldest Tertiary rocks in this region.

It has been suggested that the pre-Metchosin surface was a relatively flat plain which was largely submerged beneath the ocean. Weaver (1937B, p. 27) states:

> The basal contact relations of the Metchosin volcanics, as observed on both the Vancouver Island side as well as in the northern margin of the Olympic Mountains, suggests that the lavas and tuffs were poured out on a relatively plane surface which for the most part was slightly below sea level. This surface may represent a part of the coastal plain which is believed to have extended from Vancouver Island southward through Washington and Oregon and possibly into northern California during the earliest Eocene. It may correspond to a similar plain in Southwestern Oregon which has been described by Diller (1894; 1902; 1903) as the Klamath peneplain.

It is not unreasonable to assume that similar conditions prevailed in the lower Cowlitz River-eastern Willapa Hills area at the beginning of Eocene time.

The environment of deposition of the Metchosin volcanic series was largely shallow marine. Since the exposed thickness of the volcanics in this area is at least 6,000-8,000 feet, there must have been continuous and gradual subsidence of the earth's crust in western Washington and Oregon during Metchosin time, and in later Tertiary time as well. The total volume of the Metchosin volcanic rocks in western Washington and Oregon has been calculated (Weaver, 1939) as nearly 10,000 cubic miles. This figure is probably much too low, as it is based on an average thickness of 1,000-3,000 feet for the Metchosin volcanic series. The significance of this great volume of lower and middle Eocene volcanic rocks is further discussed under the heading "Geologic History."

Although the Metchosin volcanics accumulated mostly below sea level, subaerial flows are locally interbedded with the predominantly submarine volcanic rocks and sedimentary interbeds. The change of depositional environment from submarine to subaerial, and then to submarine again, indicates at least minor tectonic movements during Metchosin deposition.

The initial uplift along the Willapa Hills anticline apparently began shortly after the close of Metchosin volcanism and continued intermittently through late Eocene time. This tectonic activity was relatively minor and local, and did not have widespread effects. It did, however, restrict the Cowlitz Basin of deposition to some extent, and in later Eocene time the Willapa Hills volcanic mass may have supplied some of the detrital material making up the Cowlitz sediments. That there was deformation contemporaneous with deposition of the Cowlitz formation is indicated by: (1) thin intraformational breccias and basaltic conglomerates in the Cowlitz sediments in places; (2) local, minor angular unconformities within the Cowlitz formation; and (3) rapid facies changes and oscillation of the shoreline during deposition of the Olequa Creek member. The Willapa Hills uplift may have reached a stage of considerable structural relief by the end of Cowlitz time.

The first major deformation which affected the Eocene formations occurred near the end of Eocene time. This diastrophism took place after Cowlitz deposition and prior to deposition of the lower Oligocene Gries Ranch beds (Weaver, 1937B, pp. 108-109). At this time the Eocene rocks were gently folded along axes corresponding roughly to the present northwest-southeast structural axes. During the late Eocene stage of deformation the Willapa Hills anticlinal uplift reached approximately its present dimensions. It remained a structurally high area until Miocene time, when it was again covered in part by marine waters.

After this folding and uplift there was considerable erosion of the Eocene rocks. All Oligocene and Miocene formations rest unconformably upon the Eocene sediments and volcanics in this area.

The middle Miocene volcanic rocks overlie the Oligocene sediments with unconformity northwest of Winlock. This contact relationship indicates that there was further diastrophism after deposition of the Oligocene formations.

The second major stage of deformation occurred in late Miocene time, subsequent to deposition of the basalts and sediments of the Astoria formation. At this time there was further gentle folding of the Eocene and younger formations, and westward retreating of the Miocene sea. The surface of the lower Cowlitz River-eastern Willapa Hills area rose above sea level, and it has remained above sea level since late Miocene time.

In discussing the geologic structure of western Washington and northwestern Oregon, Weaver (1937B, p. 198) states:

> The structural features in Western Washington and Oregon are the result of 2 epochs of diastrophism, the older of which occurred during the lower part of the upper third of the Miocene, and the latter at or near the close of the Pliocene. The forces operating during the late Miocene resulted in the complete withdrawal of oceanic waters from the states of Washington and Oregon and in the compression of all the formations into anticlinal and synclinal folds whose axes trend from N. 60° W. to N. 75° W.

Weaver (1937B, p. 199) attributed the origin of the Willapa Hills anticlinal uplift, which he called "The South Bend anticlinal upwarp," to this late Miocene deformation. However, the Willapa Hills anticline had been a structurally high area before late Miocene time. The Miocene diastrophism caused renewed folding along the major anticlinal and synclinal axes initiated during late Eocene time, increasing the dip of the limbs of the folds. Most of the northwestward-trending faults in the mapped area were formed during the late Miocene.

The third and final major epoch of diastrophism occurred at or near the close of the Pliocene and produced most of the major topographic features of western Washington and Oregon. Weaver (1937B, p. 198) summarized the effects of this late Pliocene stage of deformation as follows:

> The forces which affected the western portion of the North American continent near the close of the Pliocene resulted in the development of 2 major north-south uplifts and an intervening downwarp. The present day Cascade Mountains of Oregon and Washington represent one of these upwarps and the Olympic Mountains and Coast Ranges of Western Washington and Oregon the other. The Puget Sound Basin and the Willamette depression of Oregon lie within the intervening north-south downfold. These late Pliocene north-south structures were superimposed upon the late Miocene northwest-southeast synclinal and anticlinal depressions and uplifts. The major movements produced also numerous secondary flexures auxiliary to the major ones. The topography of Western Washington and Oregon is fundamentally the result of these structural movements and the sculpture resulting from subsequent erosion and glaciation during the Pleistocene.

During the late Pliocene diastrophism the structural features of the lower Cowlitz River-eastern Willapa Hills area reached their present relief. The easterly plunge of the Willapa Hills anticline in this area is probably due in part to depression of the fold along the late Pliocene north-south downwarp which includes the lower Cowlitz River Valley. Some of the minor folds in the limbs of the major anticline and syncline of the area may have been formed during the late Pliocene deformation.

PHYSIOGRAPHY

Topographic Divisions

General Statement

The lower Cowlitz River-eastern Willapa Hills area comprises three natural topographic divisions, as follows: (1) the rugged, mountainous upland in the southwestern part and along the southern border of the area; (2) the central belt of low hills, which trend in a northwesterly direction across the area; and (3) the relatively broad, flat river flood plains and terraces.

Mountainous Upland

The rugged upland division consists of the high Willapa Hills, which constitute the southwestern two-fifths of the mapped area and border it on the south. The Willapa Hills extend for many miles toward the west and south. This division is bounded on the north and east by the valleys of Sand Creek and Halfway Creek between Pe Ell and Camp McDonald; by the valley of the South Fork of the Chehalis River and Black Creek, from Camp McDonald southward to Stillwater Creek; and by the valleys of Stillwater Creek, lower Olequa Creek, and the Cowlitz River to and beyond the southeast corner of the area. South and west of this boundary the relief is high and the topography is mountainous; to the north and east the relief is much lower.

The maximum relief in this part of the Willapa Hills is 2,800 feet, and the average relief ranges from 1,000 to 1,500 feet. Numerous peaks reach elevations in excess of 2,000 feet, and Baw Faw Peak, highest summit in the Willapa Hills, rises to an elevation of 3,110 feet. This region of high relief is cut by the steep-walled canyons of the Chehalis and Elochoman Rivers and their tributaries and the tributaries of the Cowlitz River. In many places the precipitous slopes and sheer canyon walls make access difficult.

Low Hills

The middle topographic division is a belt of low hills 2 to 9 miles wide, trending in a northwesterly direction across the mapped area. Although the Eocene-Oligocene contact is the northern and northeastern boundary of the area, the low hills extend northward for several miles beyond this contact. The division is bounded on the south and southwest by the previously described line marking the northern and eastern boundary of the Willapa Hills upland. The belt of low hills is terminated on the west by the broad valley of the Chehalis River and on the east by the valley of Olequa Creek.

The highest point in this belt of hills within the mapped area is only 1,100 feet above sea level, but a short distance to the north of the area the hills reach their maximum elevation, at Sam Henry

Peak (1,492 feet) and Crego Hill (1,447 feet). The maximum relief is about 900 feet, and the average is a little less than 500 feet.

Although the relief is much less than that of the high rugged Willapa Hills, the slopes are more commonly steep than gentle. Many of the ridges and low summits are flat, though not broad. Most of the stream valleys are sharpely V-shaped in cross section.

Flood Plains and Terraces

The three major streams of the area have cut relatively broad, flat valleys trending in a general north-south direction. These are the Chehalis River, the South Fork of the Chehalis River, and the Cowlitz River. They have well-developed flood plains along parts of their valleys. The Cowlitz River has eroded a series of terraces on the low interstream divide between the river and Olequa Creek.

The broad Chehalis River Valley north of Pe Ell is the western border of the mapped area in that vicinity. There the flood plain reaches a maximum width of 1½ miles, and the average width of the valley floor is nearly ¾ mile. The river flows in a northerly direction, and its channel is close to the west edge of the valley. The average elevation of the flood plain north of Pe Ell is about 380 feet. The edges of the valley are 20 to 40 feet higher than the river channel.

The South Fork of the Chehalis River flows northward across the central part of the area. It has a well-developed flood plain from a point about 2 miles south of Wildwood northward to its confluence with the Chehalis River near the town of Ruth. The flood plain ranges from a few hundred feet to more than a mile in width, averaging slightly more than half a mile. Average relief of the flood plain ranges from about 40 feet in the upper part of the valley to less than 20 feet farther north.

The Cowlitz River is the largest stream in the southwestern Washington region, if the Columbia River is excepted. In this area the river is more than 200 yards wide in places. The flood plain is not well developed here, reaching a maximum width of less than a mile. However, the river has cut a series of terraces covering about 12 square miles in the northeast corner of the area and extending northeastward for several miles in a broad belt on both sides of the river. The average elevation of the surface of the river near Vader is 60 feet, and the flood plain rises as much as 40 feet above the river.

There are three well-defined terrace levels on the interstream divide between the Cowlitz River and Olequa Creek, all sloping gradually southward toward the river. The youngest terrace level, less than 100 feet above the present flood plain, ranges in elevation from 140 to 200 feet. Remnants of this terrace are present in sec. 23, T. 11 N., R. 2 W., and along a wide strip southeast of the river. Terrace remnants of the second level range in elevation from 260 to 300 feet. These occur in secs. 15, 22, and 27, T. 11 N., R. 2 W. The same terrace level is well developed north of Toledo, where it gradually increases in elevation from 280 feet to 350 feet. The oldest terrace level ranges in elevation from 400 feet, near the river, to more than 500 feet, several miles to the north. Its surface has been largely dissected, but excellent remnants of this terrace level may be observed in secs. 15 and 21, T. 11 N., R. 2 W., and farther north.

These three terrace levels, together with the present Cowlitz River flood plain, indicate that there have been at least three interruptions in the geomorphic cycle of the Cowlitz River in its present stage.

Relation of Topography to Lithology and Structure

The lithology and structure of the formations of the lower Cowlitz River-eastern Willapa Hills area have markedly affected the topographic forms. This relationship is useful in tracing the formations and their contacts in sections along which exposures are especially poor.

The high peaks, sharp ridges, and steep-walled canyons of the Willapa Hills in the southwestern part of the area are underlain predominantly by hard basaltic rocks of the Metchosin volcanic series. These resistant rocks were folded and uplifted, then dissected by numerous streams. The topography is extremely rugged, with cliffs, precipitous slopes, and difficult terrain in many places.

Along the south edge of the area, from the high ridge west of Olequa westward past Abernathy Peak to Elochoman Lake and the Incline Lookout, the long ridges and steep-walled canyons are underlain by hard Miocene basalts and sandstones dipping gently southward. The peaks and ridges are generally flat topped, with the ridges sloping southward at a low angle. They are remnants of the gently folded and largely dissected late Miocene surface. The topography south of the Miocene contact contrasts markedly with that of the Willapa Hills toward the northwest (fig. 49-A and 49-B).

The central belt of low hills is underlain by sandstones and siltstones of the Cowlitz formation. These rocks are only moderately resistant to erosion, and the topography is not as rugged as it is in the areas underlain by basalt. The highest peaks and sharpest ridges of these low hills are capped by a thin veneer of resistant Miocene basalt. Sam Henry Peak, whose twin summits are remnants of a thin flow of dense, glassy basalt, is a prominent physiographic feature.

The major streams generally cut across the regional structure but are locally adjusted to lithology and structure. The valley of the Chehalis River north and south of Pe Ell illustrates the adjustment of topography to lithology. In its upper course, south of Pe Ell, the river flows in a deep, steep-walled, sharply V-shaped canyon eroded in the hard basaltic rocks of the Metchosin volcanic series. As the

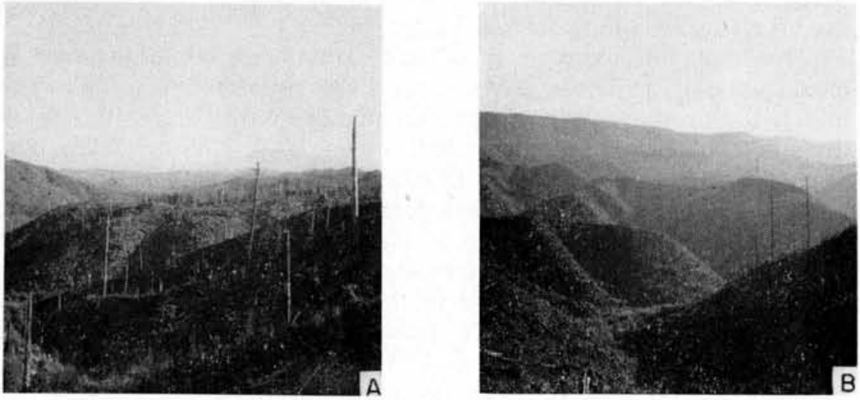

FIGURE 49. Contrasting physiographic expression of folded Metchosin volcanics and gently southward-dipping Astoria formation.

A. Rugged canyons and ridges underlain by Metchosin volcanics in foreground and middle ground. Abernathy peak (gentle slope to south) underlain by Astoria formation in background. View looking southeast from Long Bell Road 856, north of Ferrier Peak.

B. View looking southwest across eroded Metchosin volcanics (foreground) toward nearly flat topped Astoria escarpment (background) east of Elochoman Lake.

river passes the contact between the basalts and the Cowlitz formation, 1¼ miles south of the highway bridge in Pe Ell, the valley becomes less constricted. The river then crosses the outcrop belt of the Pe Ell volcanics, in which resistant pyroclastic rocks it has carved a narrow gorge with sheer walls as much as 60 feet high. A few hundred feet north of the highway bridge in Pe Ell the volcanic member is succeeded by relatively soft sediments of the Stillwater Creek member. Here the Chehalis River Valley reaches its maximum width. For 3½ miles northward from this place the valley is broad and flat, with a well-developed flood plain. However, where the river crosses the narrow belt of northward-dipping Miocene basalts ½ mile south of Doty, the valley becomes constricted, widening again where sediments overlie the basalts.

The course of the South Fork of the Chehalis River is largely independent of regional structure but is in part lithologically controlled. The valley parallels the contact between the Metchosin volcanic series and the Cowlitz formation along part of the northeastern border of the Willapa Hills. The river has eroded a broad valley, predominantly in relatively soft siltstones of the Stillwater Creek member. More resistant sandstones and sandy siltstones underlie the east wall of the valley, and hard basaltic rocks constitute the steep west wall.

The course of the Cowlitz River appears to be wholly independent of lithologic or structural control in the mapped area. Although the sharp bend in the river 2¼ miles southwest of Toledo coincides with the fault contact between the Eocene and Oligocene rocks, there is no fault or change in lithology at the much sharper bend in the river 1½ miles east of Vader.

Physiographic expression of faulting is weak or nonexistent in most of the area. There are, however, two notable exceptions. The first is the prominent bench which coincides with the fault zone on the steep south slope of Crego Hill, in sec. 4, T. 12 N., R 3 W. The sharp break in slope on the south side of Sam Henry Peak, in sec. 23, T. 12 N., R. 3 W., and other less prominent features in this part of the area, are also attributable to structural control by the Crego Hill fault zone. The second example of the physiographic expression of faulting is the abrupt bend in the South Fork of the Chehalis River where it crosses the previously described fault southeast of Wildwood, in sec. 17, T. 11 N., R. 3 W.

The basalt flows and intrusives in the lower part of the Cowlitz formation generally stand out as low ridges. Stream valleys are typically constricted where they cross these resistant rocks, and in places steep cascades, rapids, or low falls result. The basaltic dike intruded into the sediments of the Stillwater Creek member about ½ mile north of Camp McDonald has caused Stillman Creek to make an abrupt bend towards the east at that point. The stream did not have sufficient eroding power to cut across the resistant basalt and was forced to flow around the obstacle.

In contrast, the thick siltstone interbeds in the upper part of the Metchosin volcanic series represent irregular beds of relatively soft strata between resistant layers. In places they form shallow depressions or swales between adjacent ridges of basaltic rock. Many small stream valleys follow these belts of weak rocks. Locally, ponds or marshes occupy the shallow depressions.

Miocene basalt dikes cut the Eocene and Miocene sandstones in the southern part of the area. These dikes are considerably more resistant to erosion than the sedimentary rocks into which they have been intruded. In places they have caused waterfalls, abrupt bends in streams, sharp-crested ridges, and constricted, steep-walled canyons.

The drainage pattern is largely dendritic, although orientation of the streams with the regional strike of the strata has resulted in a rectangular drainage pattern in places. The streams are mainly consequent, with the exception of the South Fork of the Chehalis River (in part) and certain smaller streams which have cut their valleys along belts of relatively soft rock between resistant strata. These are subsequent streams.

Stage of Development

A few observations concerning the geomorphic cycle in the mapped area are essential for an understanding of the physiographic features described previously.

Most of the area is in early maturity in the regional geomorphic cycle. Except along the southern border, the interstream divides are sharply crested and the surface is entirely in slope. The flat-topped, southward-sloping ridges along the southern edge of the mapped area are remnants of the gently folded late Miocene basalt surface, which has been youthfully dissected. This part of the region is in late youth.

The streams in this part of the Willapa Hills are in the stage of youth in the fluvial cycle. They are characterized by sharply V-shaped valleys, in which the stream occupies the entire floor of the valley; by steep gradients, especially in their upper reaches; by abundant rapids and waterfalls; and by steep or sheer valley walls.

Many streams in the belt of low hills have similar youthful characteristics. However, others have relatively broad valleys and long graded reaches. The latter are in late youth, not far removed from maturity in the fluvial geomorphic cycle.

The Cowlitz River is a mature stream; the Chehalis River and South Fork of the Chehalis River are mature in their lower courses. These streams appear to be graded, with broad valleys and well-developed flood plains in places. The lower reaches of Olequa and Stillwater Creeks also exhibit some characteristics of mature streams.

The terraces cut by the Cowlitz River have been described previously. They are strath terraces covered with a veneer of river gravels and other alluvial deposits. The three distinct terrace levels indicate that there have been at least three interruptions in the geomorphic cycle of the river. Each of the interruptions caused rejuvenation of the graded stream. The older terraces are unpaired and are probably due to rejuvenation of the river by uplift in its source area or by lowering of base level. The youngest terrace remnants appear to be paired and are probably the result of local uplift and renewed downcutting.

In the vicinity of Pe Ell the Chehalis River flows along or near the west wall of its northward-trending valley for about 5 miles. The crowding of the river against the west side of the valley has probably been caused by recent slight westward tilting of the land surface. Other major north-south streams show no effects of any such tilting. The movement must, therefore, have been local in scope.

GEOLOGIC HISTORY

General Statement

The succession of geologic events which have shaped this part of southwestern Washington is discussed on the following pages. Various phases of the geologic history of the area have been mentioned previously, and evidence in support of several conflicting theories has been cited and evaluated. Such conflicting evidence is not discussed again here. Hence, certain things presented as facts are, in reality, only strong probabilities.

As the primary subject of this report is the Eocene stratigraphy of the mapped area, the geologic events of the Eocene are described in greater detail than those of subsequent epochs. However, the events of younger Tertiary and Quaternary time have played a large part in determining the present geologic and topographic features and are briefly discussed here.

Eocene

Early Eocene.—In southwestern Washington, the oldest rocks from which fossils have been identified are of middle Eocene age. It is not definitely known whether lower Eocene rocks are present in this region. It is difficult, therefore, to reconstruct geologic conditions during the early Eocene. However, Metchosin volcanism probably began in early Eocene time, with basaltic lavas being poured out on a coastal plain or erosion surface of low relief predominantly below sea level.

Middle Eocene.—Extrusion of the Metchosin volcanics continued, with a thick series of pillow basalt, basalt flows, volcanic breccia, and pyroclastic rocks, together with tuffaceous sedimentary interbeds, accumulating mostly under shallow marine conditions. Subsidence of the ocean floor mostly kept pace with deposition of the volcanic series, although local minor tectonic activity and rapid accumlation of lavas in places produced small land areas from time to time. During early and middle Eocene time crustal subsidence amounted to not less than 6,000-8,000 feet and was probably considerably greater.

The Metchosin basaltic rocks were extruded from groups of volcanic vents or fissures extending from southern Vancouver Island southward to the Klamath Mountains of southwestern Oregon. Volcanic activity persisted in some of these volcanic centers long after it had ceased in others; hence the age of the upper part of the Metchosin volcanic series varies from place to place. The Willapa Hills volcanic area was one of the longest lived of the Metchosin volcanic centers.

Volcanism continued until about the end of middle Eocene time, the last eruptions producing flows interbedded with the lower upper

Eocene marine sediments. Many intrusive bodies were injected in the last stages of the igneous activity, including the large plug-like mass which underlies the summit and slopes of Baw Faw Peak. The uppermost Metchosin flows accumulated under shallow marine conditions, as did most of the volcanic series.

By the time volcanism ceased, a great thickness of lower and middle Eocene basaltic rocks had piled up in the Coast Range region of the Pacific Northwest. Weaver (1945, p. 1407) described the extent of the Metchosin volcanics as follows:

> These volcanics originally formed one vast lava field extending from Vancouver Island southward to the north slope of the Klamath Mountains and eastward to the present site of the western foothills of the Cascade Mountains. By the close of Metchosin time there had accumulated a volume of volcanic material more than 500 miles long north and south by 150 miles wide east and west and with a probable minimum average thickness of at least 3,000 feet. The cubic content of this lava is as great as, if not larger than, that of the well known Columbia River lavas of eastern Oregon and Washington. Although these later flows are known to geologists throughout the world, very seldom have the Metchosin lavas of early Eocene age been referred to in published reports.

Late Eocene.—Deposition of the marine sediments of the lower part of the Cowlitz formation may have begun locally in late middle Eocene time. Accumulation of this thick, predominantly sedimentary unit had certainly begun by the early part of late Eocene time. Marine tuffaceous sediments were deposited as interbeds in the Metchosin volcanic series, and marine sedimentation continued as volcanism ceased.

Relatively minor volcanic activity in the early part of late Eocene time produced the Pe Ell volcanics member and the basalt flows, dikes, and sills in the Stillwater Creek sediments. The Pe Ell pyroclastic rocks were erupted from volcanic vents in the Doty area, north of Pe Ell, and the other basaltic rocks in the lower part of the Cowlitz formation are the products of the last stage of Metchosin volcanism in the Willapa Hills.

The late Eocene was a time of predominantly marine deposition; a maximum thickness of more than 8,000 feet of sediments and subordinate volcanics accumulated in this area. Conditions were favorable for rapid and continuous sedimentation, and as a result the thickest largely marine Eocene section in the Pacific Northwest is exposed here.

Slow and intermittent upwarping of the Willapa Hills volcanic mass along its anticlinal axis probably began during the early part of late Eocene time, contemporaneous with marine sedimentation which produced the Stillwater Creek member.

In later Eocene time, there was a gradational change from predominantly marine to predominantly brackish-water and continental sedimentation in part of the mapped area. Extrusion of the volcanic rocks of the Northcraft formation in the district toward the northeast took place at about this time.

Brackish-water, marine, and continental sedimentation forming the sandstone-siltstone-coal facies of the Olequa Creek member proceeded contemporaneously with shallow marine deposition, producing the richly fossiliferous "type Cowlitz" (Weaver, 1912, 1937A, 1937B; Beck, 1943) mudstones and siltstones along the Cowlitz River and Olequa Creek, where the two facies are interfingered. In the northwestern part of the mapped area the Cowlitz sediments are thinner and generally finer grained, indicating a deepening of the sea in that direction.

Deposition of the upper part of the Cowlitz formation was contemporaneous with extensive volcanic activity toward the south. This volcanism produced the thick Goble volcanic series along the Columbia River, and some of its products were deposited in the mapped area. The basaltic flows, flow breccia, and pyroclastics intercalated with the Olequa Creek member along the Cowlitz River and lower Olequa Creek are products of the same late Eocene eruptions.

Late Eocene deposition was accompanied by continued intermittent rise of the Willapa Hills anticlinal uplift and other local tectonic activity. These earth movements caused fluctuation of the shoreline in the Olequa Creek area and led to irregularly rhythmic deposition of the coal-bearing strata.

Cowlitz deposition continued until nearly the end of late Eocene time. The great thickness of the Cowlitz formation indicates an additional crustal subsidence of about 8,000 feet. Hence, the total subsidence in this area during the Eocene was at least 15,000 feet and probably a greater amount.

The first of three major Tertiary stages of diastrophism occurred near the close of late Eocene time, gently folding the Eocene rocks along northwest-southeast axes and greatly restricting the seas in southwestern Washington. Deformation and uplift of the Eocene formations of the lower Cowlitz River-eastern Willapa Hills area at that time caused withdrawal of the sea. The Eocene rocks were considerably eroded before Oligocene deposition began.

Oligocene

The Oligocene sea transgressed from the north during the early part of the epoch. Oligocene time was mainly characterized by deposition of variable fine clastic marine sediments. They are generally more massively bedded than the Eocene sediments and were probably deposited in relatively deep marine waters, well offshore.

Oligocene sedimentation was accompanied by gradual subsidence of the deformed and eroded Eocene rocks. Late Oligocene sediments covered most of the region north of the Willapa Hills uplift.

Minor deformation at or near the close of the Oligocene caused uplift of much of the area and withdrawal of the sea, probably toward the west. The sediments were then slightly folded and subsequently eroded, resulting in local unconformable contacts with the overlying Miocene formations.

Miocene

The surface of the region remained above sea level during early Miocene time, although there was local deposition in restricted embayments farther west. Erosion and removal of the folded Eocene and Oligocene rocks continued during this time.

Middle Miocene time brought widespread deposition in seas which encroached from the west. Marine sedimentation and local terrestrial and brackish-water deposition were accompanied by extensive volcanism. Clastic sediments and interbedded basaltic lavas of the Astoria formation blanketed a large part of the area, although much of the Willapa Hills uplift remained above the Miocene depositional surface.

The middle Miocene sediments did not cover as large an area as the volcanic rocks with which they are interfingered. The thin glassy basaltic lavas which cap peaks and ridges in the low hills belt of the mapped area are remnants of extensive flows. The middle Miocene sea did not encroach over most of that part of the area.

The second major Tertiary diastrophism, in late Miocene time, caused complete withdrawal of the seas and played a major role in the development of the present structural framework of the region. The folding which had begun in late Eocene time was resumed with renewed vigor in this stage of deformation. The Willapa Hills anticline, the North River-Dryad syncline, and the other broad northwestward-trending folds reached most of their present structural relief during the late Miocene diastrophism. Most of the faulting in the lower Cowlitz River-eastern Willapa Hills area occurred at this time. Erosion subsequent to this deformation greatly reduced the areal distribution of the Miocene lavas and sediments in the mapped area.

Pliocene

No rocks of Pliocene age are exposed in the area under investigation, and it is likely that this part of Washington remained above sea level throughout Pliocene time. Toward the northwest, the Quinault formation (Arnold, 1906A, p. 465) was deposited during this epoch, and deposition of the Montesano formation (Weaver, 1912, pp. 20-22), which probably began in late Miocene time (Weaver, 1937B, p. 191), continued until middle Pliocene time.

The third major Tertiary stage of deformation occurred near the close of Pliocene time. The axial trends of the orogeny were roughly north-south; two major uplifts with an intervening downwarp were developed during this time. The late Pliocene diastrophism completed the structural development of the Coast Range and Olympic Mountains and produced the Puget Sound-Willamette Valley depression and the Cascade Mountains.

Pleistocene

After the building of the great Cascade volcanoes, Pleistocene time was one of widespread glaciation, as indicated by the thick mantle of glacial drift and outwash deposits over much of western Washington. However, no direct effects of glaciation were observed in the lower Cowlitz River-eastern Willapa Hills area.

Post-glacial erosion and alluviation have completed the topographic development of the region, the present surface features of which are a result of the geologic processes and events previously described.

ECONOMIC CONSIDERATIONS

General Statement

The mineral resources of the lower Cowlitz River-eastern Willapa Hills area are commercially exploited only to a limited extent. The rocks of the area have not been mineralized, and metallic ores of possible economic importance are apparently lacking. Coal and industrial minerals have been mined and quarried in the past, and the latter—chiefly crushed rock, gravel, and sand—are produced and utilized at present.

Probably the greatest source of possible future mineral wealth in this area is petroleum. There has been intermittent interest in oil and gas in southwestern Washington for many years, and many dry holes have been drilled. However, no exploratory wells have been drilled for oil within the mapped area, although during May-July 1955 the Shell Oil Company drilled nine core holes for stratigraphic data in the valley of the South Fork of the Chehalis River.

The economy of the area in the past has been based predominantly upon one industry—lumbering. At present (1956) most of the timber has been cut, and only one large-scale logging operation is still being carried on. Other operations have ceased, with the local economy suffering as a result. Until new trees can grow to replace those which have been cut, there is a real need for new industries and new sources of income. Attempts will undoubtedly be made to find new uses for the meager mineral resources of the area, and the search for commercial accumulations of petroleum will probably be accelerated. However, the outlook for large new sources of mineral wealth is not encouraging.

Brief discussions of the present and possible future commercially valuable rock and mineral deposits in the area, together with a discussion of possible oil and gas occurrences, are presented in succeeding paragraphs.

Minerals

Coal.—In some places, small amounts of subbituminous coal have been mined from the rocks of the Olequa Creek member of the Cowlitz formation. The Vader coal field lies entirely within the mapped area, and the northern edge of the Kelso-Castle Rock field is within 1½ miles of the southern boundary. Both fields have records of past production.

Valentine (1949, p. 26) reported as follows on the production of coal from the Vader field:

> The Vader field covers about 15 square miles in T. 11 N., R. 3 W. No mines are now operating, but the Winlock-Vader mine near Vader produced 88 tons of coal in 1932 and 1933.

The past production of coal in the Kelso-Castle Rock field has come from several mines, although only one has been operating in recent years. The northernmost of the productive mines in this field (Valentine, 1949, p. 27)—the Dobson Creek mine, in sec. 24, T. 10 N., R. 3 W.—is 3 miles southwest of Ryderwood. The mine has had no commercial production since before World War II.

Elsewhere in southwestern Washington there has been large-scale coal mining from Eocene strata, and in some places the mines are still in operation. Large reserves exist in the region, but most of the coal cannot be mined at a profit under present conditions. In the Centralia-Chehalis coal district alone, the original reserves of coal are estimated (Snavely et al., 1954) at 3.5 billion tons.

Most of the southwestern Washington Eocene coal will never be mined for use as fuel. Unless new uses are found for this coal—for example, in the production of chemicals, plastics, or wax—it probably will never have marked economic value.

Sand and gravel.—Sand and gravel, found at many localities, have been quarried from several pits in the mapped area. They are used largely in building and heavy construction—for concrete aggregate, plaster sand, mortar sand, building sand, macadam, and fill.

Sand and gravel pits currently producing and those which have produced in the past have been listed by Valentine (1949, pp. 80, 83, pl. 33). These pits are operated by the Washington State Department of Highways and the Lewis County and Cowlitz County Road Districts.

Crushed rock (basalt).—Basalt is quarried, crushed, and utilized for road building in many parts of the area. It is used for surfacing, in macadam, as ballast, as fill, and as asphalt aggregate. In other parts of southwestern Washington basalt has been used as riprap in river bank protection and for breakwaters and is also used in the construction of buildings.

The most important road-building material is dense fine-grained basalt, obtained from quarries in the Metchosin volcanic series, the Goble volcanics, and the Miocene basalts. Crushed basalt is widely used by the Weyerhaeuser Timber Company and the Lewis County and Cowlitz County Road Districts.

Clays and shales.—Clays and shales (including mudstones and siltstones) have been utilized in the manufacture of brick and tile. Common clays and shales are found in almost all parts of southwestern Washington (Shedd, 1910; Glover, 1941) and have been widely used. Valentine (1949, p. 21) noted that there are few places in Washington where brick clays of this kind do not occur.

An active brick and tile plant, using local clay, formerly existed at Vader. However, the plant ceased operations during the early 1930's, and production has never been resumed. In listing this occurrence and use of clay in the lower Cowlitz River-eastern Willapa Hills area, Glover (1941, p. 184) gave the location of the deposit as ½ mile east of Vader [in sec. 33, T. 11 N., R. 2 W.] and mentioned the operation as a large pit or open cut in Willapa Pleistocene clay, from which material was obtained by the Little Falls Fire Clay Company for use in making sewer pipe, paving brick, drain tile, and dry press brick.

In addition to the common clays noted above, refractory and semirefractory clays and shales occur at two locations (Glover, 1941, pp. 169, 170-172) along the Cowlitz River near the northeast corner of the mapped area. These clays are not exploited commercially at present but might prove usable in the future.

Silica sand.—The term silica sand is employed here for sand high in quartz and classified, by use, as glass sand, blast sand, and grinding sand. Two occurrences investigated by Skinner and Couch (1942) are considered not to be commercial. Both localities are exposures of massive to crossbedded arkose of the Cowlitz formation; one of the sandstone layers is in the Stillwater Creek member, the other, in the lower part of the Olequa Creek member. They are located in the vicinity of Vader and Ryderwood. Other Eocene silica sands in this area may prove to have future commercial value.

Oil and gas.—Geologic exploration for possible commercial occurrences of petroleum has been carried on in southwestern Washington for many years. As yet, no indications of accumulation of oil and gas in commercial quantities have been found. However, in terms of detailed geologic work and scientific drilling, exploration of the region is still in its early stages. Past exploration has done little to settle the question of the existence of commercial oil and gas.

The first test well for oil in Washington was drilled about 1890, and exploration in the state has been periodically intensive since about 1910. Glover (1947, pp. 2-5) reported that approximately 244 wells had been drilled for oil or gas by mid-1947. Of that number, only 27 were drilled at sites based on careful geologic investigation. Between 1947 and 1953 some 35 additional wells have been drilled, most of them in the southwestern part of the state; about half of this number were located on the basis of thorough geologic studies. Thus, although more than 275 exploratory wells have been drilled for oil and gas, only a few have been of value to geologists in determining whether oil and gas exists in commercial quantities in Washington. Glover (1947, p. 5) concluded that, "The oil potentialities of the state are yet to be determined."

Of the wells drilled in southwestern Washington, several have had interesting, but not commercial, showings of oil. The Union Oil Company State No. 3 (Moody, 1951, p. 1142) produced a small amount of high-gravity oil from Miocene beds, and the Oil and Gas Development Company Hawksworth-State No. 4 (Moody, 1952,

p. 996) produced quantities of condensate from about the same horizon. These wells are located near Ocean City, Grays Harbor County.

Several wells have penetrated Eocene formations in the region, but no showings of oil were reported from these beds. The results obtained to date are, however, far from conclusive.

No wells have been drilled for oil within the lower Cowlitz River-eastern Willapa Hills area, and geologic exploration, as noted previously, has been predominantly of a reconnaissance nature. Although oil and gas seeps have been reported from other parts of the state, no surface indications of petroleum have been found here. Moreover, structural closure in the upper Eocene sediments is lacking; the Metchosin volcanics are exposed at the surface along the major anticlinal axis, as they are elsewhere in southwestern Washington. Similarly, the volcanic rocks locally interbedded with the upper Eocene sediments are thought to decrease the possibility of commercial accumulations of petroleum.

However, the thick, predominantly marine upper Eocene sedimentary section contains abundant possible source beds and reservoir rocks, and offers almost limitless possibilities for stratigraphic traps. Lateral and vertical facies changes have caused lithologic variations, giving rise to shoestring sands, pinch-outs, and changes in permeability along potential reservoir beds. In addition, the marine mudstones and siltstones of the Cowlitz formation are generally rich in organic matter, both animal and vegetal. These rocks could certainly have been source beds for the generation of petroleum.

If suitable trap conditions can be demonstrated, the Eocene sedimentary section in this area should be tested by drilling. Drilling for stratigraphic-trap accumulations is not likely to be undertaken in southwestern Washington in the near future, however, for most oil companies and independent operators are unwilling to risk the expense of such ventures unless commercial production has previously been established in similar rocks in adjacent districts. In the opinion of the writer, further geologic and geophysical exploration for oil in the mapped area and other parts of southwestern Washington is warranted.

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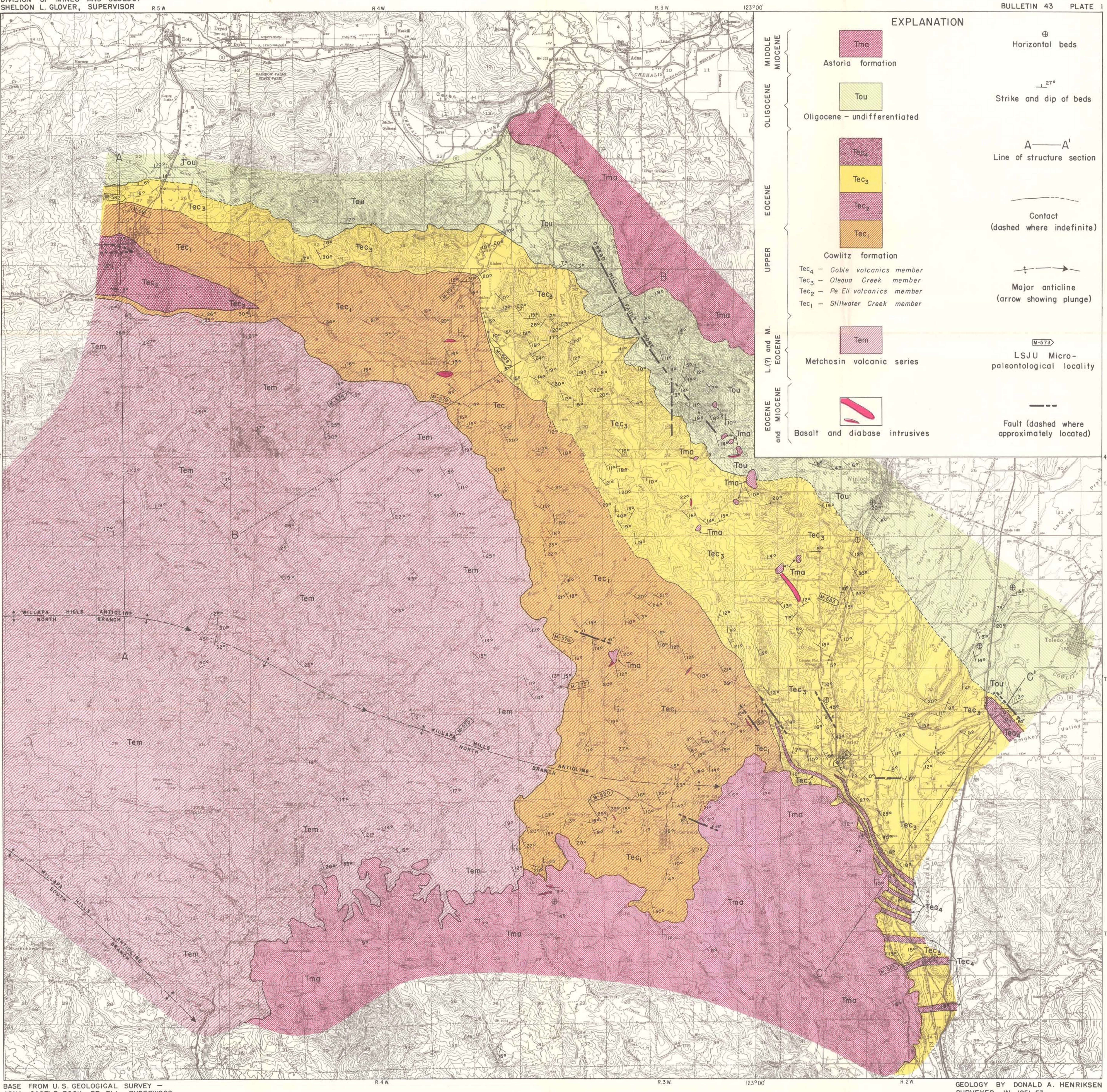
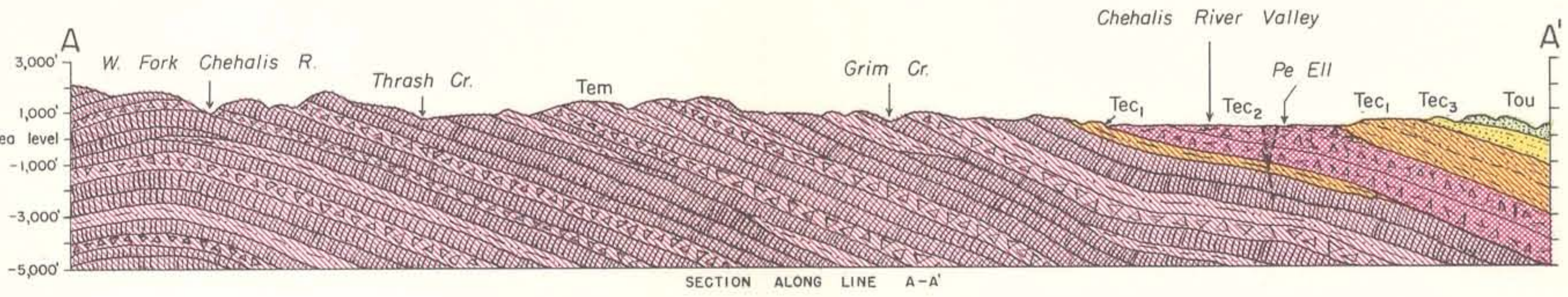
DEPARTMENT OF CONSERVATION AND DEVELOPMENT
DIVISION OF MINES AND GEOLOGY
SHELDON L. GLOVER, SUPERVISOR

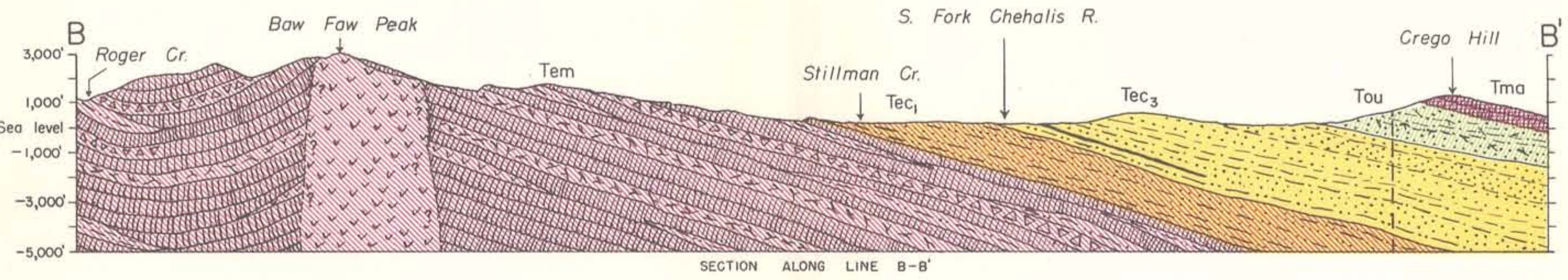


BASE FROM U.S. GEOLOGICAL SURVEY — ADNA, CASTLE ROCK, PE ELL, RYDERWOOD, SKAMOKAWA QUADRANGLES

GEOLOGY BY DONALD A. HENRIKSEN
SURVEYED IN 1951-53
GEOLOGIC DRAFTING BY G. L. GOULD



SECTION ALONG LINE A-A'



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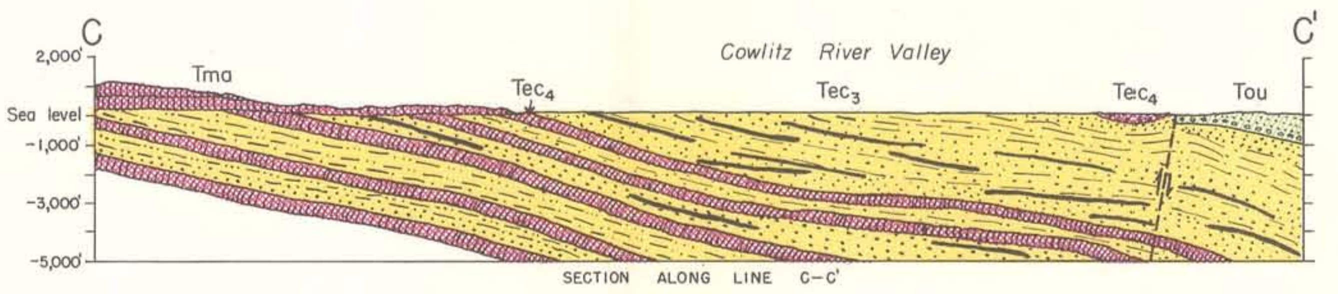
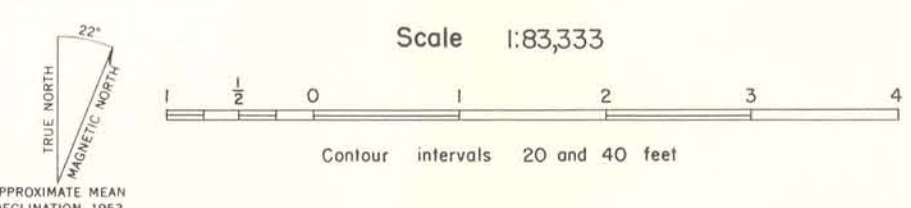


SECTION ALONG LINE C-C'

GEOLOGIC MAP AND SECTIONS OF THE LOWER COWLITZ RIVER - EASTERN WILLAPA HILLS AREA

Lewis, Cowlitz, and Wahkiakum Counties, Washington

Scale 1:83,333



APPROXIMATE MEAN DECLINATION, 1953

Contour intervals 20 and 40 feet

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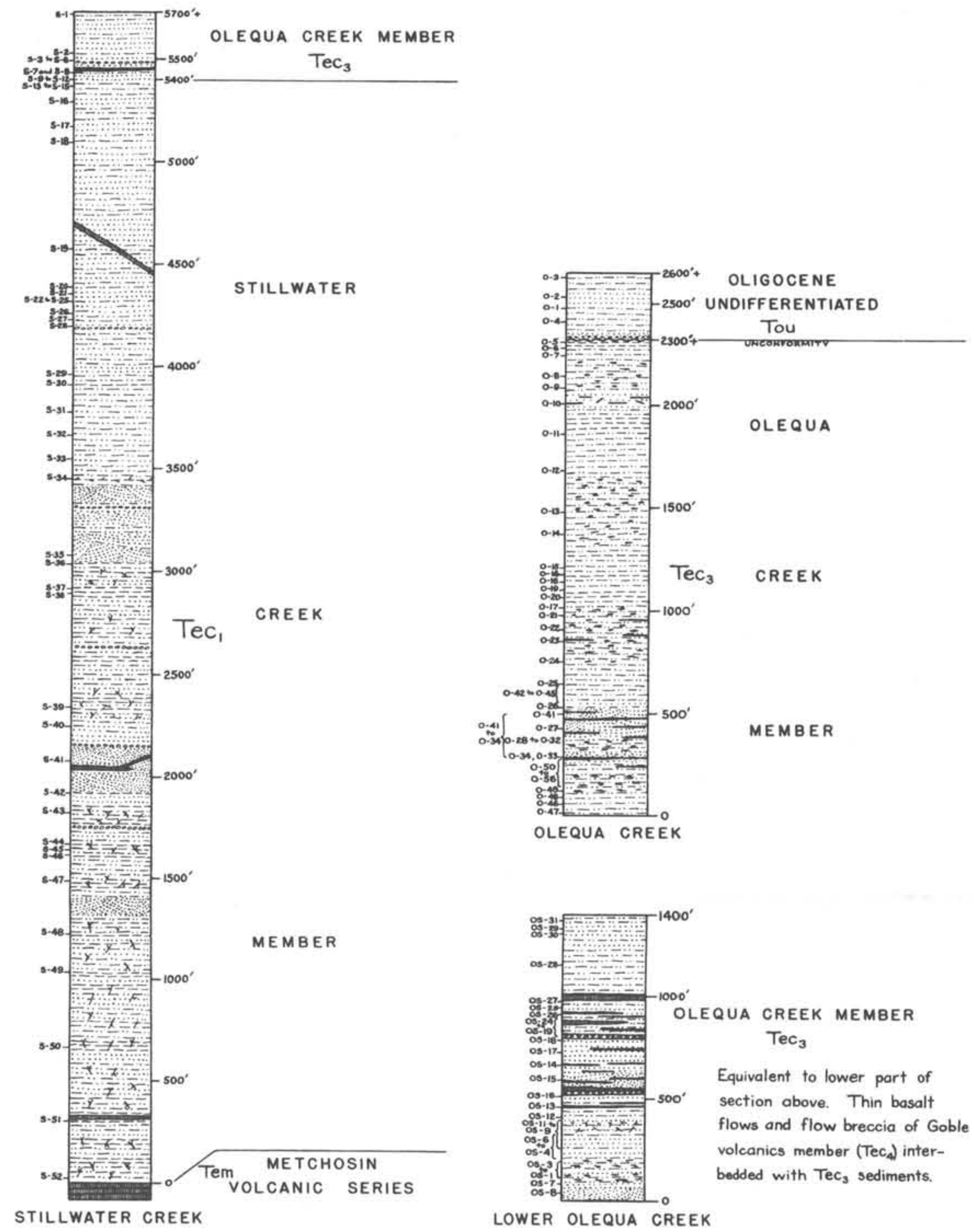
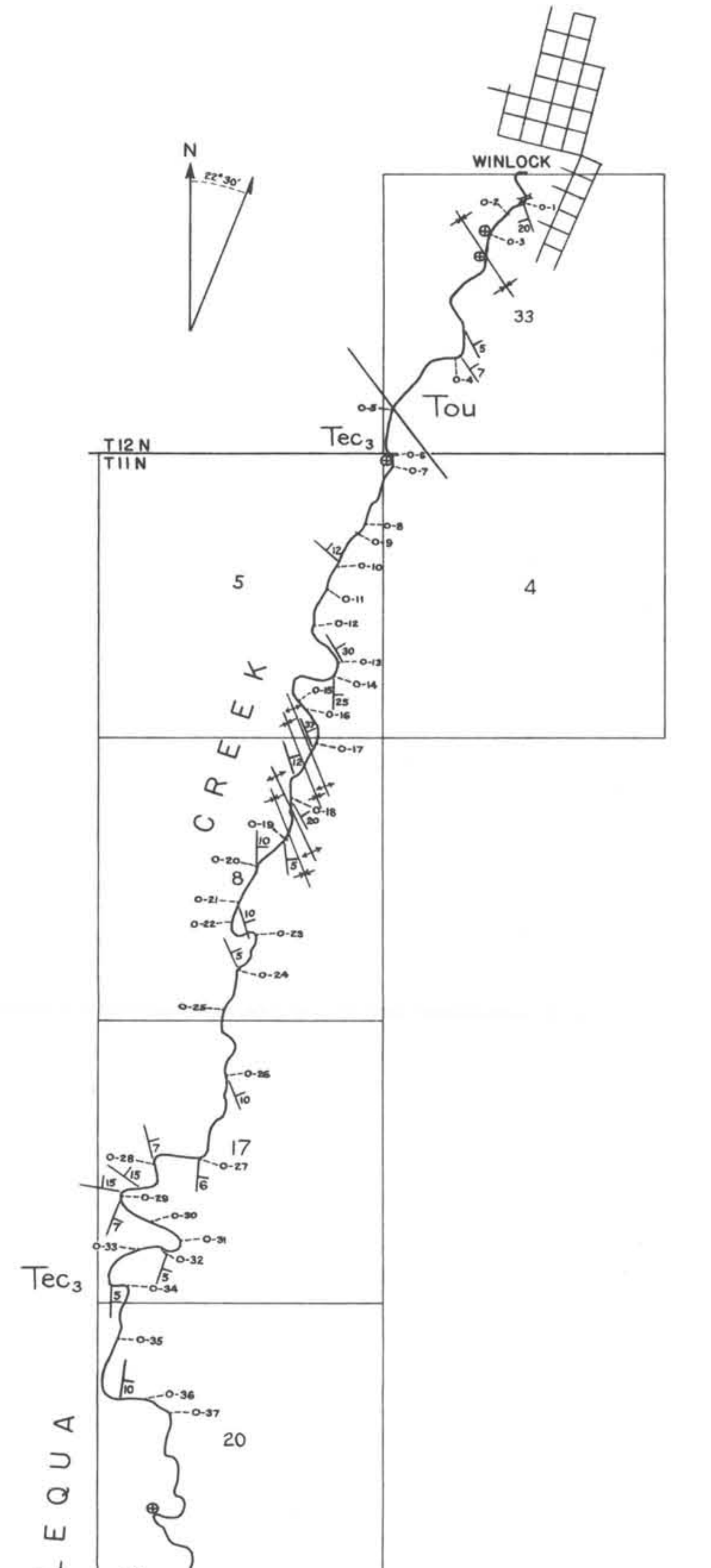
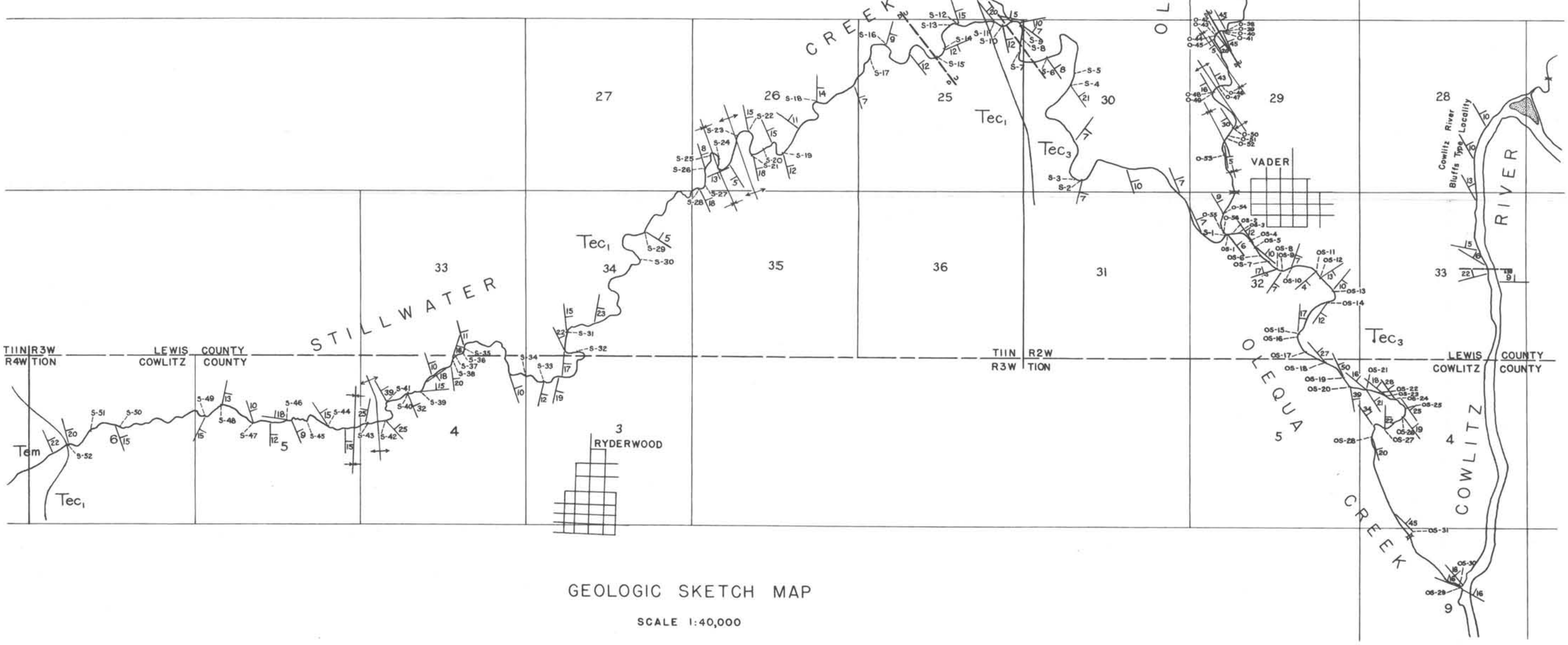
TYPE SECTION OF THE COWLITZ FORMATION
ALONG OLEQUA AND STILLWATER CREEKS
LEWIS AND COWLITZ COUNTIES, WASHINGTON



COLUMNAR SECTIONS

SCALE: 1 INCH = 800 FEET

GEOLOGIC SKETCH MAP

SCALE 1:40,000

D.A.H., 1954