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Bulletin No. 52

LIMESTONE RESOURCES OF WESTERN WASHINGTON

By

WILBERT R. DANNER

With a section on the
LIME MOUNTAIN DEPOSIT

By GERALD W. THORSEN

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FOREWORD

Since the early days of Washington's statehood, limestone has been recognized as one of the important mineral resources of the State. The second annual report of the Washington Geological Survey, published in 1903, gave details on the State's limestone deposits, and in later years five other reports published by the Survey and its successor agencies have given additional information on this resource. Still other reports by Federal and private agencies have been published in response to demands for data on limestone here. Although some of the earlier reports included analyses to show the purity of the rocks, very few of the samples for analysis were taken systematically in a way that would fairly represent the deposits sampled.

Prior to 1900 limestone was produced for use as building stone here, and another important use was for the production of burned lime. Portland cement plants soon became leading consumers of limestone, and they continue as such to the present time. Limestone is used in large quantities in the pulp industry in the Northwest, and in 1966 there was one commercial lime-burning plant in the State.

Recognizing the potential for industrial development in Washington based on more intensive use of our mineral resources, and recognizing the need to up-date the State's knowledge of raw material resources in order to channel those resources into the State's growing economy, the Industrial Raw Materials Advisory Committee of the Department of Commerce and Economic Development in 1958 recommended that a comprehensive survey be made of the limestone resources of Washington. It was suggested that the investigation should determine the amount and quality of stone available in the largest and most accessible deposits in both the eastern and western parts of the State.

With the interest and support of the Industrial Raw Materials Advisory Committee, a limestone market survey was completed by the Department of Commerce and Economic Development and a survey of the limestone deposits was commenced in 1959 by the Division of Mines and Geology of the Department of Conservation. The Division of Industrial Research at Washington State University was engaged to analyze some 750 samples. We were fortunate to obtain the services of Dr. Wilbert R. Danner, Professor of Geology at the University of British Columbia, to make the survey of limestone in western Washington, which is reported here as Bulletin 52 of the Division of Mines and Geology. A report on high-calcium limestones of eastern Washington was published in 1962 as Division of Mines and Geology Bulletin 48.

Marshall T. Huntting, Supervisor
Division of Mines and Geology

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LIMESTONE RESOURCES OF WESTERN WASHINGTON

By Wilbert R. Danner

ABSTRACT

Limestone occurrences in San Juan, Whatcom, Skagit, Snohomish, King, Pacific, Jefferson, Clallam, Lewis, Mason, Grays Harbor, and Chelan Counties of western Washington were studied during the summers of 1959 and 1960 for the purpose of determining the size, grade, and geologic setting of all deposits that might be of economic value. A compilation of published descriptions of a few small limestone occurrences in Kittitas County is also included.

The general geologic setting of the limestone occurrences and the details of deposits in 202 areas are described in the text and illustrated in 128 geologic maps, of which 99 are original with this report, 7 are partial revisions of previously published maps, and 22 are maps generously donated by companies and individuals for publication in this bulletin. Of the limestone occurrences in the 202 areas, 39 are considered to be of Devonian age; 24, Pennsylvanian age; 72, Permian age; 1, Triassic; 4, Jurassic or Cretaceous; 5, Tertiary; 39 are of unknown age; and 18 are of various ages but contain only traces of carbonate rock. Thirty-nine reported occurrences not visited are also listed; these were compiled from published and unpublished literature.

Three hundred and seventy-four limestone chip samples were taken and chemically analyzed for CaO, MgO, SiO_2, R_2O_3, and P_2O_5. Selected groups of samples were analyzed for TiO_2, Na_2O, K_2O, and S. On the basis of analyses made for this report, the larger deposits rank in purity according to geologic age as follows: Devonian, 53.90 percent CaO; Jurassic-Early Cretaceous, 52.20 percent CaO; late Permian, 51.50 percent CaO; Eocene of southwestern Washington, 48.89 percent CaO; Early Pennsylvanian, 47.70 percent CaO; Triassic, 39.87 percent CaO; and Eocene Metchosin Formation, 36.17 percent CaO. All known chemical analyses from the published literature and many private analyses are also listed.

All samples were spectrochemically analyzed. All samples contain Al_2O_3, Fe_2O_3, MnO, and CuO, and all but five contain SrO. No element or group of elements seems to be characteristic of any distinctive limestone unit, formation, or geologic age, although the red-weathering argillaceous limestones of the Metchosin Formation of the Olympic Peninsula are usually high in manganese and iron. There appears to be a concentration of vanadium in the limestones of northwestern Whatcom County and a concentration of copper, silver, and lead in limestones on the east side of Orcas Island, San Juan County. Limestones of San Juan County appear to contain larger amounts of strontium, chromium, and manganese than do limestones from other parts of western Washington, and they are also lower than average in their aluminum content. The argillaceous red-weathering limestones of the Eocene Metchosin Formation contain the highest percentages of trace elements.

Twenty-one of the deposits investigated appear to contain more than one million tons of limestone each, but the largest deposits are usually in mountainous and relatively inaccessible terrain. Only one deposit in San Juan County contains one million tons or more, and it is partly dolomitized. Six of the investigated deposits in Whatcom County each contain more than one million tons. Two of these are being quarried at the present time (1965), and two are undeveloped and relatively inaccessible. Of the remaining two, one is of about 2 million tons and is suitable for cement or pulp rock, and the other, containing

an estimated 20 million tons, appears suitable only for cement rock. Skagit County contains five deposits of over one million tons. One of these, at Concrete, is being quarried; the others are in relatively inaccessible country and range from 2 million to an estimated 50 million tons. Snohomish County contains three deposits of over one million tons, ranging from 35 million to an estimated 400 million, but all are located in remote mountainous terrain. King County contains one deposit at Denny Mountain comprising an estimated 6 million tons, but its quality is not suitable for most uses. Chelan County has five deposits of over one million tons, but most of this limestone contains sufficient impurities so that it would have to be quarried selectively, even for cement. In southwestern Washington the largest deposit of even fair quality is at Bear River, in Pacific County. It contains less than 100,000 tons. In 1964 there were nine active limestone quarries in western Washington: three producing cement rock; three, pulp rock; and three, agricultural stone.

The largest undeveloped deposits lie in the high mountain country of eastern Whatcom, Skagit, Snohomish, and King Counties, and it would be expensive to develop, quarry, and transport limestone from these deposits to the large industrial centers of Puget Sound.

Many of the smaller deposits of western Washington are suitable for small-scale quarrying for agricultural stone, pulp rock, and decorative stone. All deposits should be examined carefully and explored by drilling to determine their size before development work is attempted. Extensive folding and faulting and the lenticular shape of most western Washington limestone bodies render surface estimation of their size difficult. Prospecting for limestone is most promising in areas underlain by Devonian, Pennsylvanian, or Permian rock sequences.

Thirteen tufa deposits are listed. Six of these were visited, and five were sampled. Three deposits are described in detail with geologic maps.

INTRODUCTION

Limestone is one of the most commercially important industrial rocks. A knowledge of its occurrence, quality, and availability is essential for the economic development of a region. This bulletin is intended to provide this information. It includes reports and surveys of most of the known limestone occurrences of the western part of Washington and also of Chelan and Kittitas Counties in the eastern part of the State.

Because of the relative rarity of easily accessible large limestone deposits in western Washington, investigations of all reported occurrences, regardless of size, was planned, but this goal was not quite attained. However, during the course of field work many previously unreported deposits were discovered, and their descriptions are included. A considerable amount of new stratigraphic and paleontologic information useful in outlining limestone-bearing sequences for future prospecting was obtained during this investigation and is included in the section on stratigraphy. However, much of the paleontologic work is only in its preliminary stages of study and will be published later.

Field work was conducted by Division of Mines and Geology field parties during the months of July, August, and September 1959 and June, July, August, and September 1960. To make this report as comprehensive as possible, there has also been included information that was obtained from company reports, Federal and State publications, geological journals, theses, and the writer's private field investigations.

ACKNOWLEDGMENTS

The writer gratefully acknowledges the assistance given him by operators and owners of the various deposits and in particular Miss Ruth Brown; Gordon C. Clauson of the Mitchell Bay Lime and the Everett Lime companies; Leslie B. Miller of the Miller Lime Company; Gordon Tongue, Vice President, Northwestern Division, and John Wolfe, Chief Geologist, Ideal Cement Company; E. J. Baldwin of the Olympic Division of Permanente Cement Company; Nova Langell; W. A. Moore; F. D. Fobes; Robert Breining; Harris M. Thomason; Stanley Niemcziek; and James Crook.

Aid in the location of previously unreported limestone occurrences was given by Peter Misch and Joseph Vance of the faculty of the University of Washington, Department of Geology, Ross Ellis of the faculty of the Western Washington State College Department of Geology, and Robert Wiebe, a graduate student. They, along with W. H. Mathews, Wayne S. Moen, and Gerald M. Miller, were of invaluable assistance in interpreting the geology of many of the deposits. Dr. William R. Halliday, noted cave explorer, also furnished maps and information.

Field notes of a previous western Washington limestone survey by A. K. Guard were obtained from the Washington Division of Mines and Geology, and descriptions of deposits not visited by the writer were supplied by Wayne S. Moen, G. W. Thorsen, Weldon W. Rau, and W. A. G. Bennett of the Washington Division of Mines and Geology and by Walter L. Gonnason.

Fossil collections were examined and identified by J. Thomas Dutro, Jr., and Helen Duncan of the United States Geological Survey; John W. Skinner of the Humble Oil Company; Prof. M. Lecompte of the Institut Royal des Sciences Naturelles de Belgique; V. Standish Mallory of the University of Washington; Weldon W. Rau of the Washington Division of Mines and Geology; Kenji Konishi Geological Institute, Kanazawa University, Japan; Margaret L. Steere of the Oregon Department of Geology and Mineral Industries; and David A. Bostwick of Oregon State University.

Other aid and courtesies were extended by Mrs. Lucile McDonald, Howard A. Coombs, Harry E. Wheeler, Fred Jensen, R. J. Tarte, Byron Halverson, Kiefer Fobes, Orville Ferry, the Scott Paper Company, the Nettleton Timber Company, and officials of the Mount Baker National Forest.

Thin sections and polished sections of the limestone were prepared by James Donnan and Edward Montgomery, technicians of the Department of Geology, University of British Columbia, and by graduate students Darcy Scott, Gordon Davis, and Kenneth Northcote.

Excellent assistance in the field was provided by Charles McKillop and Alder Rivisto during 1959, and Clyde Smith, Chester Royce, Jr., and Evan Adams during 1960. Their cooperation, energy, and devotion to the project were outstanding and extended far beyond what they were actually required to do. Some of the deposit descriptions are a result of their independent work.

Field investigation was often conducted under rather trying conditions in the dense jungle-like temperate rain forest of western Washington. Frequent periods of heavy rainfall made mapping of some deposits difficult and at times hazardous. During the summer of 1960 a forest closure by the State Department of Natural Resources resulted in disruption of field work and prevented some areas from being examined thoroughly.

The writer wishes to express his thanks to Marshall T. Huntting for his direction and encouragement of this project and to Mrs. F. McDonald, Mrs. D. Fieldwalker, Miss L. Myers, and Miss S. McFaul, all of whom did the preliminary typing, and to Miss Dorothy Rinkenberger, upon whom fell the task of editing the manuscript.

CLASSIFICATIONS AND DEFINITIONS

Limestones can be classified in a number of ways, which include their chemical composition, amount and type of impurities, petrography (usually based on study of the textures and structures as viewed through the microscope), mode of origin, or a combination of the above. All such classifications have a certain amount of merit and validity for particular purposes and are often important in indicating the most suitable uses and the deficiencies of a particular limestone. Sometimes they indirectly furnish valuable clues to the possible size, extent, and structure of the deposit and the methods most suitable for its exploitation.

A textbook could be written about the various types of limestone classifications, but for the purpose of this investigation they will be simplified to include information most applicable to the limestone deposits of western Washington and to the characteristics that can be readily identified. The reader is referred to the bibliography for further information on more detailed and highly technical classifications.

CHEMICAL CLASSIFICATION

Limestone is the name given to rock of sedimentary origin consisting mainly (at least 50 percent) of calcium carbonate (the mineral calcite). Limestones may be subdivided on the basis of chemical composition into various classes. The classes used in this bulletin follow in general those of Mathews (1947), as follows:

High-calcium limestone denotes a limestone containing at least 95 percent by weight of calcium carbonate ($CaCO_3$) and not more than 2 percent magnesium carbonate ($MgCO_3$); these are equivalent to 53.3 percent lime (CaO) and 0.96 percent magnesia (MgO). Pure limestone containing 100 percent $CaCO_3$ is extremely rare as a deposit, but small parts or layers of a limestone body may be of this composition. A rock containing less than 50 percent calcium carbonate is not considered to be a limestone, though quite commonly it may resemble one in appearance.

Calcium limestone denotes a limestone the calcium content of which greatly predominates, but that cannot be classed as high-calcium limestone. Calcium limestone may contain up to 4.79 percent magnesia, equivalent to 10 percent magnesium carbonate.

Magnesian limestone denotes a limestone containing more than 4.79 percent and less than 19.15 percent magnesia.

Dolomitic limestone denotes a limestone containing more than 19.15 percent and less than 21.86 percent magnesia, the theoretical magnesia content of the mineral dolomite.

Dolomite. This term is restricted to the pure mineral $CaMg(CO_3)_2$ and is not actually a type of limestone, though most classifications include it as such. The term dolostone is sometimes used for a rock made up predominantly of the mineral dolomite.

CLASSIFICATION BASED ON MAJOR IMPURITIES

Many of the impurities within a limestone are deposited along with the calcium carbonate at the time of formation, but some of them may chemically replace the limestone during and after its deposition. When the impurities are sufficiently abundant to be visible, a classification may be established that is based on their composition.

Argillaceous limestone contains a high proportion (up to 50 percent) of clay (argillaceous) or shaly material interbedded or mixed with the limestone. If over 50 percent argillaceous material is present, the rock may be a calcareous shale or calcareous mudstone.

Siliceous or cherty limestone is limestone interbedded with ribbon chert, or partially replaced by secondary chert (jasperoid) or flint (a black and transluscent variety of chert).

Ferruginous limestone contains iron oxides in sufficient amount to give the limestone a yellowish or reddish color.

Bituminous limestone contains hydrocarbon material in sufficient amount to color the limestone dark gray or black. Often this type of limestone gives off a strong bituminous or oily odor when freshly broken. More rarely, a dark-colored limestone may be carbonaceous and contain carbonized fragments of vegetation.

Arenaceous limestone contains abundant quartz grains.

Tuffaceous limestone contains abundant small fragments of ash and volcanic rock.

There are other, rarer types of impurities such as the minerals glauconite and pyrite, but they are seldom in sufficient amount to alter the appearance of the limestone and thus be easily recognizable as impurities.

PETROGRAPHICAL CLASSIFICATIONS

Physical Appearance in Hand Specimen or Outcrop

Dense limestone shows no visible grains or crystals.

Crystalline limestone is composed of a visible interlocking mesh of calcite crystals. If the crystals are a millimeter or less in diameter, the rock is said to be finely crystalline or sugary textured. If the crystals range in size from 1 millimeter to 5 millimeters, it is medium crystalline; and if larger than 5 millimeters, coarsely crystalline.

The term "crystalline limestone" is used in this report for limestones that have been recrystallized. Recrystallization usually takes place at the time the surrounding rocks are being metamorphosed or when a body of limestone is heated by a nearby intrusion of igneous rock. The term "marble" is often used in geological reports for recrystallized limestone, but the term is also used commercially to signify limestones and other rocks, such as serpentine, that have a pleasing appearance and that take a good polish. The use of the term "marble" should be restricted to carbonate rocks that are actually used for polished stone (Brooks, 1954). This restricted usage of the term is desirable in view of the present-day tax laws and customs regulations.

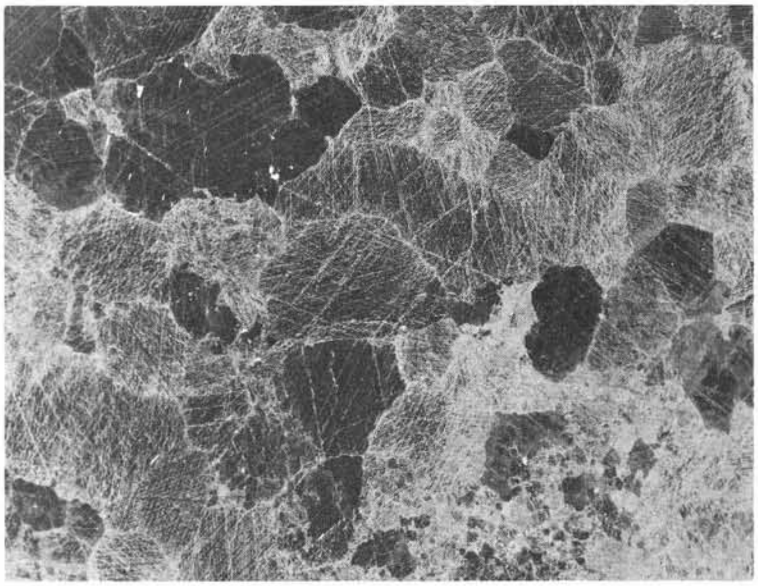

FIGURE 1.—Crystalline limestone. Acetate peel negative print of crystalline limestone from Maloney quarry, Grotto area, King County. X $3\frac{1}{2}$.

Oölitic limestone is made up predominantly of small, chemically precipitated ball-like masses (spherical or elliptical) of calcium carbonate, usually less than 2 millimeters in diameter.

Clastic limestone is composed of broken fragments of a pre-existing limestone cemented together to form a new limestone body. In hand specimen, usually the coarser fragments are all that are readily identifiable, and such rock is classed as a limestone conglomerate.

Fossiliferous or organic limestone contains fragments or entire remains of fossil shells or other organic structures. If the fossils are predominantly of one type, such as coral, it may be called a corralline limestone; if of crinoid debris, a crinoidal limestone, etc. The term "coquina" is applied to a limestone that is composed predominantly of shells or shell fragments.

Appearance When Viewed Under the Microscope

Many different microscopic classifications have been devised. The classification used in this publication is a simple descriptive one and will serve to delineate a limestone that may exhibit one or a combination of textures when examined in thin section under a microscope.

Dense limestone is composed of very small calcite crystals or fragments, so tiny that under ordinary microscopic magnification the individual particles cannot be readily distinguished.

FIGURE 2.—Fossiliferous limestone (coquina). Shells of pelecypod ?Volsella, Oligocene age in limestone of Bear River deposit, Pacific County.

Microcrystalline limestone is composed of tiny crystals visible under the microscope but not ordinarily visible in the hand specimen.

Crystalline limestone contains crystals large enough to be visible in both hand specimen and under the microscope.

Organoclastic limestone is composed of fossils or shell fragments, the broken and abraded condition of which indicates transportation.

Bioclastic limestone is composed of fragmented shells that were broken by other organisms and usually show no abrasion or other evidences of transportation.

Organic limestone is composed of shells or organic structures showing little, if any, abrasion or breakage.

Oölitic limestone is composed of oölites.

Pelletoid limestone is composed of generally ovoid grains lacking significant internal structure such as that of oölites. These bodies are often referred to as pseudo-oölites.

Clastic limestone is composed of broken fragments of limestone.

Sparry limestone contains interlocking crystals of calcite filling vugs or cavities. If the filling is incomplete, the limestone is vuggy.

VARIETIES OF LIMESTONE

Limestone has a hardness of about 3 in the Moh hardness scale and can be easily scratched or cut by a knife. The specific gravity varies from less than 2.0 to 2.7, and the weight ranges from 110 to 170 pounds per cubic foot, depending upon the porosity and the amount of impurities present. It takes about 12 cubic feet of the average limestone to weigh a ton.

In texture, limestone varies from dense to coarsely crystalline. The color is determined largely by the impurities present and may vary from pure white to green, blue gray, yellow, red, or black. Most limestone is bluish gray to dark gray on freshly broken surfaces, but it commonly weathers to a buff or brownish-yellow color. When touched with dilute hydrochloric acid it will react with a very brisk foaming or effervescence. This due to the release of carbon dioxide gas (CO_2). A similar but much less noticeable reaction can be obtained with weak acids such as vinegar or lemon juice.

Certain terms are applied to limestones that have distinctive textures and physical properties or special modes of origin. These varieties of limestones often have special uses, and a few of the commoner types are listed below.

Oölitic limestone is a limestone composed of small spherical or elliptical grains of calcium carbonate having concentrically laminated or radially and concentrically laminated internal structure. The grains resemble fish roe in size and shape, and the name oölite is derived from a Greek word meaning "eggstone." Individual oölites commonly contain some object such as a sand grain or shell fragment that served as a nucleus around which the layers of carbonate were deposited. If the spherical bodies are over 2 millimeters in diameter they are termed "pisolites" and the rock is a pisolitic limestone.

However, pisolites of different origin and composition are present in other rocks, such as bauxite, and pisolite-like structures are formed by algae in some limestones. These latter are termed algal pisolites.

Chalk is a white to light-gray, fine-grained, very porous limestone composed mostly of minute shells of foraminifers and plates and discs of planktonic calcareous algae in a matrix of finely crystalline or dense calcite. The rock is usually powdery.

Marl is a loose earthy material composed chiefly of calcium carbonate intermixed with varying amounts of clay and other impurities and commonly containing small shells. It is usually a shallow lake deposit, but the term is also used for marine limestones along the Atlantic and Gulf Coast regions of the United States.

Lithographic limestone is an exceedingly fine grained, homogeneous, dense, or finely crystalline limestone similar in appearance to the limestone once used in lithography. It is characterized by a conchoidal fracture.

Tufa is a spongy, porous, and chalky variety of limestone that forms deposits at springs, in stream beds, and in some places along the shores of lakes.

Travertine is a dense banded limestone common in caves, where it forms flowstone, dripstone, stalactites, and stalagmites. It may also form at springs and seepages and along streams.

Calcarenite is a technical term for a limestone composed of sand-sized grains of calcite deposited mechanically.

Calcilutite is a technical term for a limestone composed of fine-grained calcite mud.

Calcirudite is a technical term for a limestone conglomerate, a rock composed of limestone pebbles.

MINERALOGICAL COMPOSITION OF LIMESTONE AND COMMON IMPURITIES

The mineral calcite ($CaCO_3$) is the essential constituent of limestone. It is a brittle mineral with a hardness of 3 and a specific gravity of approximately 2.71. It crystallizes in the rhombohedral class of the hexagonal system and has rhombohedral cleavage. The luster is vitreous and sometimes pearly or iridescent on

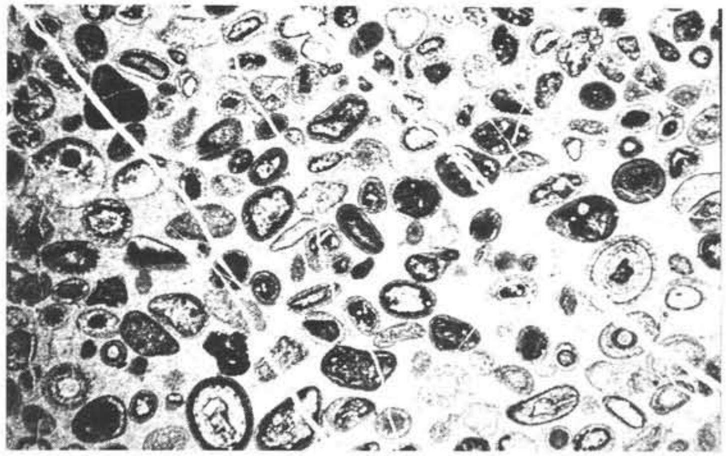

FIGURE 3.—Oölitic limestone. Photomicrograph of Permian limestone from Limestone Point, San Juan Island, San Juan County. X 6½.

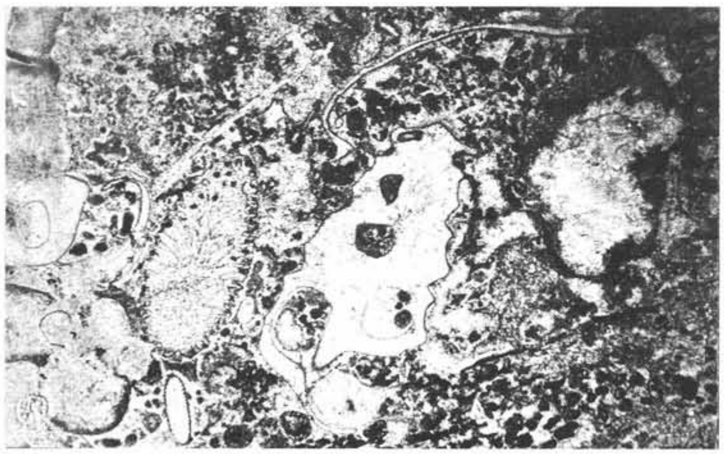

FIGURE 4.—Organic oölitic limestone. Photomicrograph of Permian(?) limestone, Langdon deposit (south part), Orcas Island, X 8.

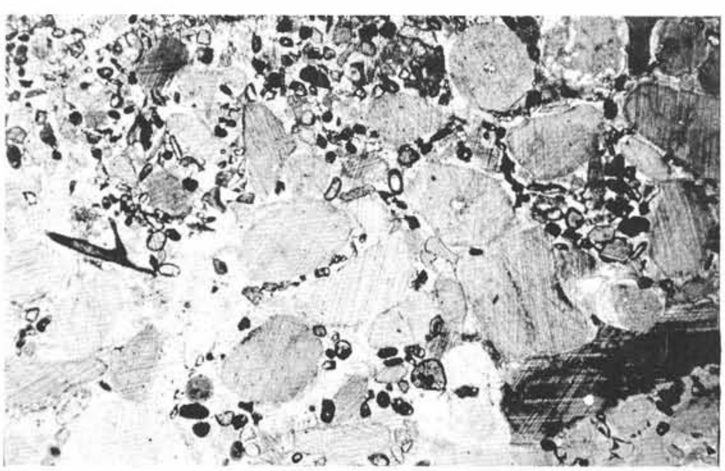

FIGURE 5.—Organoclastic oölitic pelletoid limestone. Photomicrograph of Lower Pennsylvanian limestone, Chilliwack Group, Red Mountain, Whatcom County. Coarse fragments composed of crinoid debris. X 6½.

cleavage surfaces. The mineral is colorless and transparent or white if pure, but calcite containing impurities may have a wide variety of colors. Due to the similarity of the effective ionic radii of magnesium and calcium ions, a limited amount (4 percent) of magnesium can substitute for calcium in the calcite crystal lattice.

Most of the calcite in limestone is in the form of crystals too small to be visible even under ordinary microscopic magnification. However, larger crystals are produced when limestone is buried and subjected to heat and pressure; a recrystallization takes place that produces crystalline limestone. Coarsely crystalline calcite may also be present in limestone as a secondary cement filling pore spaces, as a filling of vugs or cavities, or as broken fragments or entire frameworks of shells. Some caves in limestone and other rocks contain very large crystals of calcite, and a crystal 20 feet by 6½ feet in size was found in Iceland (Eiriksson, 1920), and crystals weighing as much as 25 tons have been mined in New Mexico (Kelley, 1940).

Aragonite is a type of calcium carbonate crystallizing in the orthorhombic system. It is not common in limestone except in those bodies that are formed by hot springs and geysers or by recent accumulations of some types of shells. Aragonite slowly reverts to calcite at ordinary temperatures and pressures. It is a brittle mineral with a hardness of 3½ to 4 and a specific gravity of 2.947. It has a vitreous luster and is white or colorless when pure but may occur in a variety of colors with small amounts of impurities. Aragonite may occur in caves as stalactites and helictites. Along with calcite it makes up the material composing pearls and is the main constituent (nacreous layer) of most shells. Older fossil shells have usually changed to calcite.

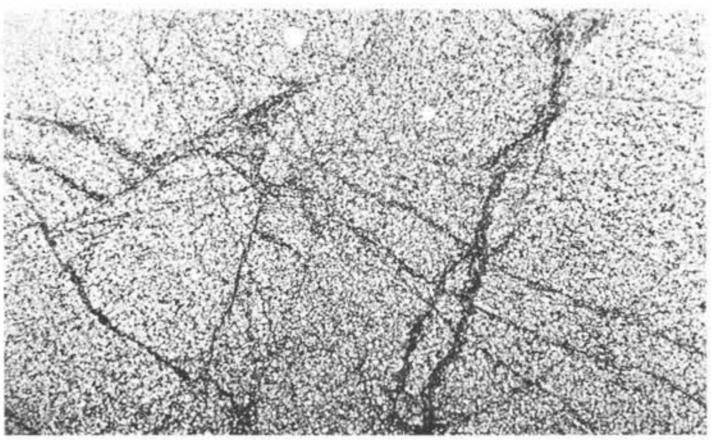

FIGURE 6.—Dolomite. Photomicrograph of dolomite exposed in bed of Pilchuck Creek, Skagit County. X 6.

Dolomite is a double carbonate of calcium and magnesium and is present in small amounts in several of the limestones of western Washington. However, pure or even relatively pure beds of it are extremely rare. Dolomite crystallizes in the rhombohedral system and has a hardness of 3.5 and a specific gravity of 2.8 to 2.9. It is difficult to distinguish from calcite, but if a fragment is composed of pure dolomite, touching it with dilute cold hydrochloric acid will cause no effervescence or only a very faint reaction, whereas calcite and aragonite will effervesce strongly. However, if the cold acid is added to powdered dolomite or if the acid is heated, effervescence will be brisk for dolomite as well as for calcite and aragonite.

Silica-bearing minerals.—Silica may occur in limestone in the form of grains of quartz (SiO_2) deposited with the original sediment, in the form of lenticular layers of chert alternately deposited with layers of limestone, or as nodules and irregular masses of chert formed by chemical replacement after the deposition of the limestone. Interbedded chert and chert impurities usually stand in relief on the weathered surfaces of limestone outcrops. Silica may also be present in limestone in the form of hydrothermal quartz stringers, veins, and irregular and dikelike masses. When intruded dikes of igneous rock give off silica-bearing solutions, the calcium metasilicate wollastonite ($CaSiO_3$ or $CaO \cdot SiO_2$) forms. Small radiating clusters of wollastonite crystals are found in several of the limestone outcrops on the west side of Proctor Creek, in Snohomish County.

Silica may also exist in limestone in combination with other elements, as for example, in clay minerals and feldspar grains accumulated as part of the original sediment. Silica may also exist in combination with other elements in minerals (especially mica, amphibole, garnet, and epidote) that may have accumulated in the original sediment in minute amount but that might also be present in larger amounts by reconstitution of the original sedimentary components during metamorphism or by being introduced during metamorphism and alteration of the strata by hydrothermal waters subsequent to deposition.

The distribution of silica-bearing minerals may be concordant with the limestone stratification and bedding or may be completely independent of it. Most of the silica-bearing minerals are insoluble in nitric, sulfuric, or hydrochloric acid.

Aluminum-bearing minerals. — The aluminum-bearing minerals present in limestone include clay minerals, mica, feldspars, garnets, and other silicate minerals. The clay minerals were deposited at the same time as the calcium carbonate in the form of disseminations or distinct thin films and beds of shale. Argillaceous and some tuffaceous limestones are rich in alumina. In some limestones clay minerals are concentrated along stylolitic seams. Most of the other aluminum-bearing minerals are the products of metamorphism.

Iron-bearing minerals. — Iron may exist in limestone in the form of: carbonates (siderite, $FeCO_3$; and ankerite, $Ca(Mg,Fe)(CO_3)_2$), sulfides (pyrite, FeS_2; chalcopyrite, $CuFeS_2$; and marcasite, FeS_2), oxides (limonite, $Fe_2O_3 \cdot nH_2O$; hematite, Fe_2O_3; and magnetite, Fe_3O_4), and silicates (garnet, chlorite, olivine, etc.). Some of these minerals were original, some were formed by recombination, and some were subsequently introduced. Normally, iron minerals are present only in small amounts. Limestone bodies near to or intruded by igneous rocks in western Washington contain small pods of magnetite along with iron and iron-copper sulfides and various iron silicates such as garnet and epidote. One such limestone body on Denny Mountain, King County, contains crystals of specular hematite. In the spectrographic analyses given in this report, the Fe_2O_3 reported is the total iron in the sample, calculated to Fe_2O_3. The R_2O_3 is the total iron, calculated to Fe_2O_3, and alumina (Al_2O_3) combined.

Sulfur. — Sulfur occurs in limestone in combination with iron as the sulfides pyrite or marcasite, as sulfates, as hydrogen sulfide, or in hydrocarbons within the rock. Limestone may contain sulfur in combination with copper and iron and with other base metals. Ethanethiol (ethyl mercaptan), C_2H_5SH, is reported to occur in the crystalline limestone at the Soda Springs limestone deposit in Chelan County, and parts of the limestone there and in the Rainy Creek deposit to the south release a strong odor when freshly broken or crushed. Sulfur may occur in limestone as native sulfur, but none was found in western Washington.

Carbon. — Carbon, which presumably was derived from organic matter entombed during sedimentation, contributes the gray color to most limestone and the black color to some. The dark-gray color of most limestone has little or no bearing on the value of the limestone for most uses. The carbon will be driven off by the calcining process. Some of the chemically purest limestones in western Washington are quite black. Carbon in the form of hydrocarbons occurs in many western Washington limestones, and a bituminous odor is often detectable when these limestones are freshly broken. This is particularly true of the limestones of Devonian and Permian ages. Vugs containing small amounts of semiliquid hydrocarbon were found in limestone at the Cowell quarry on the west coast of San Juan Island. Carbon in the form of shiny graphite flakes or crystals is common in limestone of the Soda Springs and Rainy Creek deposits, and at some outcrops of the Rainy Creek deposit carbon forms 1 to 2 percent of the total material. Carbon is also concentrated along stylolitic seams in limestone.

Phosphorus. — Phosphorus in very small quantities was found by chemical analysis in all samples taken in western Washington during this study. The mineral or combination in which it occurs has not been determined.

Alkalies. — Soda (Na_2O) and potash (K_2O) are found in very small quantities in some of the limestones sampled during this study, but only a few samples were analyzed for their content of these materials. Potash is generally more abundant, and ranges from approximately $1\frac{1}{2}$ to 5 times as abundant as soda. The limestones containing the largest amounts of alkalies occurred mostly in Chelan County, where muscovite mica is a visible impurity in some outcrops, and it, along with grains of feldspar disseminated through the limestone, may be the source. In other samples the combinations in which soda and potash occur are unknown.

ORIGIN

Limestone deposits may be formed in more different ways than any other type of rock, and often it is very difficult to determine the mode of origin of any particular deposit. However, most carbonate beds are formed on the sea floor by one or a combination of three processes:

Organic and organoclastic— the accumulation of shells and skeletal remains of animals and, in some cases, plants.
Physiochemical, organochemical, and chemical clastic— the inorganic or indirect organic precipitation.
Erosion and clastic redeposition of previously formed limestone bodies.

For at least the last 500 to 600 million years of the earth's history, the first process, that of accumulation of animal- and plant-formed calcareous material, appears to be the most important mode of origin for limestone bodies. The main role in limestone formation, by this method, is performed by organisms living in the sea. Many of these, both plant and animal, secrete calcium carbonate as calcite or aragonite in the form of shells or "skeletal frameworks" for protective covering and support of their soft body parts. Some of these organisms are attached to the sea floor, either as individuals or as attached colonies, so that as they grow and die their remains accumulate and are preserved in large concentrations. Other organisms are mobile but restricted to a local area of habitation along with almost countless others of similar type, and their remains also accumulate with time in quantity sufficient to form a layer of limestone. Sometimes undersea currents move and concentrate the shells into beds or fill up local depressions with them on the sea floor.

The calcareous shells of micro-organisms, such as those types of Foraminifera that live above the sea bottom, sink to the bottom when the animal dies. If they are abundant and the water is not too deep, or if other material is not being deposited in sufficient amount to dilute them, they accumulate and form beds of calcareous ooze or mud, which later become a bed or beds of limestone.

Most of the limestone deposits of western Washington, the origin of which may be at least partially established, appear to belong mostly to the first category of limestone formation— those formed by accumulations of shells— and they can be subdivided into several types:

Reef or bank-complex limestones composed of broken and attached fragments of bottom-dwelling incrusting organism hard parts, such as corals, bryozoans, stromatoporoids, and calcareous algae.

Coquina limestones composed of entire shells or fragments of shells of bottom dwellers such as pelecypods, brachiopods, gastropods, fusulinids, and crinoids.

Pelagic limestones composed of the shells (tests) of microscopic foraminifers such as Globigerina, embedded in a limy mud matrix or, more rarely, the thin filament-like shells of large and small free-swimming pelecypods such as the Triassic Halobia.

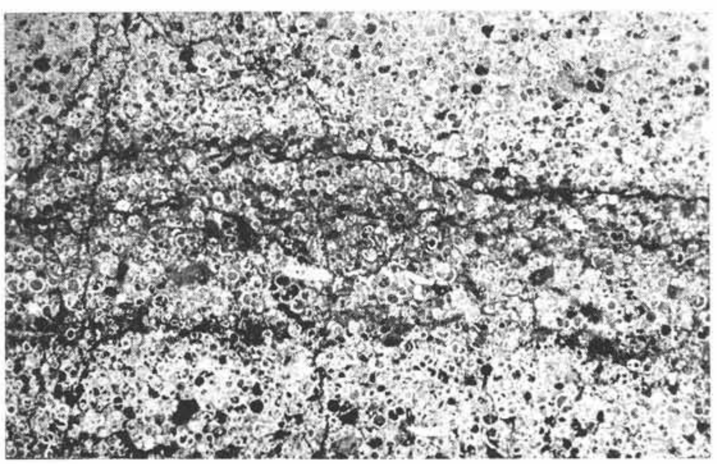

FIGURE 7.— Pelagic limestone. Photomicrograph of Globigerina limestone near base of Metchosin Formation between Marmot and Buckhorn passes, Olympic Mountains, Jefferson County. X 6.

Sea waters normally contain considerable amounts of calcium carbonate, and its precipitation may be favored by (1) increase in temperature, (2) a decrease in the CO_2 (carbon dioxide) content of the water, (3) higher than normal salinity, or (4) alkalinity, or relatively high pH.

Shallow water, which is likely to be more easily warmed and subjected to aeration and agitation, resulting in the loss of CO_2, provides a favorable setting for precipitation. Marine organisms, especially marine algae, remove CO_2, also causing carbonate precipitation. The relative importance of organism-caused precipitation in comparison to physicochemical or inorganic precipitation is not well known, and no dogmatic statement can be made as to which is more important. "Algal structures," so prevalent around the world, especially in older limestones, and similar structures forming today indicate that algae are important contributors. Most modern investigators believe the major source of lime muds to be a combination of organic processes, and they de-emphasize physicochemical precipitation.

Oölitic limestones may be considered to be a variety of the chemically precipitated limestones, as the formation of the individual oölites is an inorganic process. Calcium carbonate is precipitated around a nucleus; one layer or more than one layer may be formed. Some oölitic limestones contain oölites that do not appear to have a nucleus, but in most of them a pellet, fossil fragment, quartz grain, etc. is present (Fig. 3). Oölitic limestones are believed to form in shallow, warm, and agitated saline waters.

Purely clastic limestone is the rarest type, as it is a result of a pre-existing limestone outcrop being subjected to erosion and relatively rapid redeposition. There are many areas in present-day seas where clastic lime muds, sands, and gravels are being formed, but in older deposits, except for the coarse gravels, it is difficult to identify the limestone as being of clastic origin except when examined in thin section under the microscope. In western Washington a marine limestone conglomerate forms a bed in the Proctor Creek deposits, in Snohomish County. Limestone talus deposits are present below many outcrops in the Cascade Mountains, and one on Boulder Creek, in Whatcom County, was quarried for several years.

POST-DEPOSITIONAL CHANGES

The limestones of western Washington were originally formed as horizontal or nearly horizontal layers, mounds, and lenses on the sea floor. They have since been lifted above the sea and tilted, complexly folded, squeezed into irregular shapes, and broken by faulting (Fig. 8). Consequently, it is very difficult, if not impossible in most places, to determine the former extent of the limestone and the shape and extent of the present-day deposit. Dynamic and thermal metamorphism have acted on the limestone, resulting in a coarse crystallization that in many areas has destroyed all trace of the textures, structures, and fossils of the original rock. New minerals have been formed by the recombining of chemical ingredients of impurities, and new impurities have been added where fluids and gases have penetrated the limestones from intruding hot igneous rocks. In many deposits silica (SiO_2) has been added or locally reconcentrated, forming irregular masses of jasperoid or replacement chert. A few deposits have been changed from calcium limestone to magnesian limestone and even to dolomite by the addition of the element magnesium, but this post-depositional change is not nearly as common in western Washington as it is in eastern Washington, and no deposits of dolomite that are large enough to be of commercial value are known in western Washington. No major ore deposits are associated with the limestones of western Washington; only some small pods of the iron mineral magnetite, traces of copper and iron sulfides, and a few silicate minerals such as garnet and epidote have been found in the limestone along contacts with intrusive dioritic and granodioritic igneous rocks. Most of the limestone deposits have proved to be very disappointing to collectors seeking mineral specimens similar to those found in many limestone areas of other parts of North America.

FIGURE 8.—Faulted limestone. Exposure in wall of one of Cowell quarries on west coast of San Juan Island. Dark rock is volcanic.

Although many of the limestones of western Washington show their original texture, changes in texture have taken place in some parts of almost all deposits. The limestones of Chelan and eastern Skagit and Snohomish Counties within the belt of regionally metamorphosed crystalline rocks have undergone a considerable amount of change, and no traces of their original textures remain. Some have become coarsely crystalline, whereas others have become finely crystalline and intensely sheared. Limestone that is near the contacts of intrusive igneous rocks has been recrystallized by the heat emanating from these bodies, and may contain crystals as much as an inch or more in length, as at Maloney Mountain, near Grotto, or as at Denny Mountain, where calcite crystals a foot or more in length have been found. Even in areas generally considered to be not much affected by metamorphism, parts of the limestone bodies may show recrystallization.

Stylolites are irregular lines cutting the limestone, and are believed to be formed by pressure-solution. Other modes of origin have been postulated, but whatever the origin, the stylolite is marked by a black layer of insoluble material usually composed of carbon and clay minerals and some sulfides. In western Washington, stylolites are mostly of the microstylolite variety and are commonly seen in thin section rather than on the surface of the limestone outcrop.

Veinlets of white calcite are common in almost all of the limestone bodies, and in some places may compose 50 percent or more of the rock.

WEATHERING OF CALCAREOUS DEPOSITS

Limestone is more susceptible to the solution process of weathering than most of the other rocks of western Washington. In areas where the ground surface has not been glaciated it is commonly covered by a layer of residual soil made up of insoluble matter remaining from the dissolved limestone. Only the small deposits of southwestern Washington show this. The northern part of western Washington, where most of the limestone deposits occur, was glaciated, and any such residual soil that may have been developed prior to the glaciation has since been stripped away. However, many of the limestone outcrops have been partly covered with till, clay, sand, and gravel of glacial origin or with water-laid sediments of rivers and streams. Soils largely developed by decomposition of vegetation form a partial cover in a few places.

Where exposed as bare knobs and outcrops, most of the limestones of western Washington show only a slight amount of post-glacial weathering and solution. The crystalline limestones appear more susceptible to weathering and are commonly quite crumbly on exposed surfaces. This physical breakup of coarse calcite crystals is most noticeable at high elevations. Exposures along streams and shorelines show many pits, jagged ridges, and cavities (Fig. 9), and the limestone surfaces are polished by abrasion and solution. Small-scale solution features are present on the surfaces of almost all outcrops, but large internal solution features such as caves are relatively rare. Sinkholes (funnel-shaped solution depressions) are common on many of the deposits, and in some areas, as on the Rainy Creek deposits, in Chelan County, they are formed by the collapse of overlying glacial sediments into solution cavities below. A few sinkholes have streams draining into them and indicate active abrasion and solution within the limestone body. In rare instances a jumble of limestone blocks indicates the collapse or breakdown of the pre-existing outcrop into an area of solution beneath it. The stripping of overlying glacial sediments and soils from the limestone often reveals a typical solution (karst) topography of ridges, grooves, and pits on the previously buried limestone surface.

Limestone is usually regarded as a relatively weak rock, weathering into low areas, depressions, and valleys in moist vegetated areas and standing up as resistant ridges in dry areas. However, in western Washington, where the massive limestones were more resistant to the plucking type of glacial erosion than the surrounding, usually strongly jointed, sedimentary and volcanic rocks, the limestones form knobs and ridges rising higher than the immediately surrounding bedrock. The massive nature of much of the limestone and its softness apparently also account for the lack of limestone fragments in western Washington glacial tills. Pebbles of limestone in streams and on beaches are present only in the vicinity of limestone outcrops—further evidence of its softness and the ease with which it is worn down by abrasion under such conditions.

Accumulations of limestone talus or float are common below outcrops exposed in cliffs and on steep slopes at high altitudes. Where the outcrops are fractured and poorly exposed, it is often very difficult to determine what is outcrop in place and what is broken off and not in place.

Impurities in the limestone such as jasperoid and chert are almost insoluble and stand out in sharp relief on the weathered surfaces. The differing resistance to solution of calcite crystals and fossils often causes the fossils to either stand out in relief if less soluble or to weather as an indentation where they are more soluble. Dolomite is crystalline and usually produces a sugary texture on the weathered surfaces. However, in some of the deposits the dolomite crystals are so small that the surface composed of them looks quite smooth.

FIGURE 9. — Solution surface on limestone. Solution along joints and bedding. Orcas Knob, Orcas Island, San Juan County. Devonian limestone.

INTRUSIONS WITHIN THE LIMESTONE

Dikes and sills of various volcanic rocks, mostly andesite and basalt, are present in many of the western Washington limestones. These bodies were injected as molten rock along fractures in the limestone, either cutting across or parallel with the bedding. Dikes of granitic rock and pegmatite are also present, and pegmatite is especially common in the Soda Springs and Rainy Creek deposits, in Chelan County. Some dikes have altered the limestone along their contacts, the limestone has been recrystallized to coarser crystals, and new minerals have formed from the combination of the elements in liquids and gases emanating from the intrusion and combining with the limestone. In parts of Snohomish and King Counties, large bodies of granodiorite and related igneous rocks have intruded several limestone deposits and recrystallized them completely.

Where dikes and sills are abundant, they may cause difficulty and additional expense in the quarrying and treatment of the limestone.

FIELD CHARACTERISTICS AND IDENTIFICATION

Limestone is relatively easy to distinguish from most other rocks in western Washington. Its smooth to pitted solution surface and the light bluish gray to gray weathering color of its outcrops separates it visually from the darker volcanic rocks and clastic sedimentary rocks with which it is usually associated. However, many ribbon cherts, when seen from a distance, appear similar in color on weathered surfaces, and some types of volcanic rocks and graywackes weather to light colors, so that it is wise to examine an outcrop carefully and not assume from distance that because of its color a rock is limestone. Stressing this point may seem unnecessary, but the writer knows of several instances where light-colored rock outcrops in the vicinity of known limestone deposits or along the strike of limestone bodies were assumed to be limestone by both prospective buyers of the deposits and by geologists mapping them.

Another common assumption concerns the quality or purity of a limestone in relation to its color. It is not necessarily true that a dark-colored or black limestone is impure. Some of the dark-gray and black limestones in western Washington are among the highest in calcium carbonate content. Conversely, there is a common belief that a white crystalline limestone is pure because of its white or light-gray color and its crystallinity. Such a limestone might contain sufficient magnesium to make it unsuitable for most chemical uses.

The presence of chert, argillaceous or tuffaceous material, and most other impurities in limestone may usually be recognized by examination of the weathered outcrop, as these insoluble materials stand out in relief. Minerals such as pyrite (iron sulfide) break down upon weathering and stain the outcrop orange or brown with iron hydroxides and oxides.

The distinction between high-calcium limestone and dolomitic limestone is difficult for the untrained but relatively easy for the practiced observer. In western Washington the weathered surface of a high-calcium limestone is mostly smooth and has a solution "polish." The weathering color is normally light gray to bluish gray, except where weathering of iron minerals stains it to brown or buff. Dolomitic limestone commonly shows a sugary texture formed by the tiny crystals of dolomite, and the rock weathers to light brown, buff, gray brown, or cream. No large masses of pure dolomite are known in western Washington, but bands of dolomitic limestone occur in a few deposits, and some deposits contain irregular patches and veinlets of dolomite. The dolomitic bands usually are very sugary in texture and weather into slabby layers. Where the dolomite occurs in veinlets and patches, it stands in relief above the high-calcium limestone and can be recognized both by this difference and by its distinctive buff-brown to cream color.

Where the limestone has been crystallized, it may also have a sugary texture, but only where it is coarsely crystalline will the crystals stand out in relief on the normally weathered surface. The crystalline limestones in general do not show any good weathered surface feature or physical indication of their magnesium content, and the presence of magnesium must be determined by chemical tests or analyses.

Limestone can be distinguished from dolomite on freshly broken surfaces by the application of cold dilute hydrochloric acid. Calcite and calcium-rich limestone effervesce vigorously in such acid, whereas dolomite reacts very feebly or not at all. However, where calcite and dolomite are mixed in the specimen, strong effervescence will also be observed, so the specimen must be examined carefully to note if the reaction is confined to certain parts of it only.

Mathews (1947, p. 27) noted the distinctive surface texture produced by the action of hydrochloric acid on limestone, and this is also a useful identifying test:

> If . . . a specimen of limestone to be tested is immersed in the cold dilute (1:5 hydrochloric) acid for a period of from ½ to 1 minute, then rinsed and dried, a characteristic texture is produced. Calcite and high-calcium limestone in this test develop a smooth glazed surface resembling that of vein-quartz or paraffin. Insoluble minerals, including dolomite, which is almost unaffected by the treatment, retain the texture of the original surface and stand up in relief above the calcite (after Goudge, M. F., 1940, p. 484).

Similar methods have been outlined by Ireland (1950) and Lamar (1950), who stress that the acid should not be too dilute for best results in producing the glazed surface. For a detailed study of the components of a limestone having different solubilities, a more dilute acid solution is better. Hydrochloric acid produces the best results, as acetic acid or citric acid sometimes coats the etched surface with a fine white powder. Oxalic and sulfuric acid produce relatively insoluble reaction products with calcite or dolomite. An immersion time longer than the ½ to 1 minute time indicated by Mathews will produce a better glazed surface, and Lamar advocated up to an hour of digesting.

Chemical staining methods can also be used to differentiate calcite from dolomite. Mathews (1947, p. 27) describes a quick method suitable for field use:

> A cold saturated solution of ferric chloride in water reacts with calcite within ½ to 1 minute to produce a surface film of ferric carbonate. If calcite so treated is rinsed in water to remove excess ferric chloride and immersed in a solution of ammonium polysulphide, the reaction with the ferric carbonate film gives rise to a conspicuous black coating of ferric sulphide in the calcite. Dolomite remains almost unaffected, but longer immersion in ferric chloride permits the development of a weak ferric sulphide stain. Insoluble matter, silica, etc., do not respond to this test no matter how long they are immersed in ferric chloride. On drying, the ferric sulphide stain reverts to brown ferric carbonate (after Holmes, A., 1930, p. 264, 265).

Several other staining methods are available (Fairbanks, 1925; Friedman, 1959; and Holmes, 1930, p. 265-268), but because they require heating of solutions they are used more often in the laboratory than in the field.

The amount of insoluble impurities can be determined by breaking a fresh specimen of about 50 grams of limestone into small chips and placing them in a beaker. Slowly pour over the chips a solution of quarter- to half-strength hydrochloric acid and dissolve the limestone. Additional acid may be necessary to bring about complete solution. Cold acid reacts very slowly with dolomite, but heating will speed up the reaction. In the laboratory, this procedure can be carried out with some exactness and the percentage by weight of insoluble material determined. Clay and sand-silt fractions of insoluble material are separated by decanting or wet sieving, and a microscopic examination is made of the insoluble residues to identify minerals and fossils that might be present. Insoluble residue examinations of this type have proved very useful in regional studies of limestones, especially in the interior of North America. Insoluble materials in most western Washington limestones consist primarily of replacement chert or jasperoid and argillaceous and tuffaceous materials of various sorts. For study of larger fossils or fossil structures made insoluble by replacement with silica or other minerals, it is best not to break the specimen into chips, as this might damage the fossil structures.

Most limestone deposits of western Washington occur as outcrops forming knobs, cliffs, or ridges and are fairly conspicuous, especially in alpine areas near or above timberline or where exposed along coastal cliffs, as in the San Juan Islands. In heavily forested lowlands and foothills, roadcuts and logging operations commonly uncover small knobs of limestone previously unknown. As the areas of western Washington geologically favorable for limestone occurrence are logged in the years to come, it is probable that many additional small limestone bodies will be uncovered.

There are no great flat-lying sheets of limestone in western Washington like those that exist in the central parts of North America, nor are there steeply inclined and tilted layers of widespread extent like those in the Appalachian and Rocky Mountains. Geological conditions in western Washington appear never to have been favorable for this type of limestone deposition.

Layering or bedding is seen in only a few deposits of western Washington and ranges from laminae less than a centimeter in thickness to beds several feet in thickness. These different layers of limestone are formed as a result of changes in the type of limestone deposition, as at Limestone Point, on San Juan Island, where different beds are composed of limestone having dense, oölitic, or organoclastic textures. Beds in other deposits are separated from each other by thin layers of impurities and non-limestone rocks such as shale or chert. Still other beds are a result of solution on the sea bottom interrupting periods of limestone deposition, and of the beds being separated by thin layers of black carbon-rich insoluble residues. However, most of the limestone bodies of western Washington do not show any easily recognizable bedding even on well-weathered surfaces, though many such limestones do show a crude layering when examined closely or under the microscope in thin section.

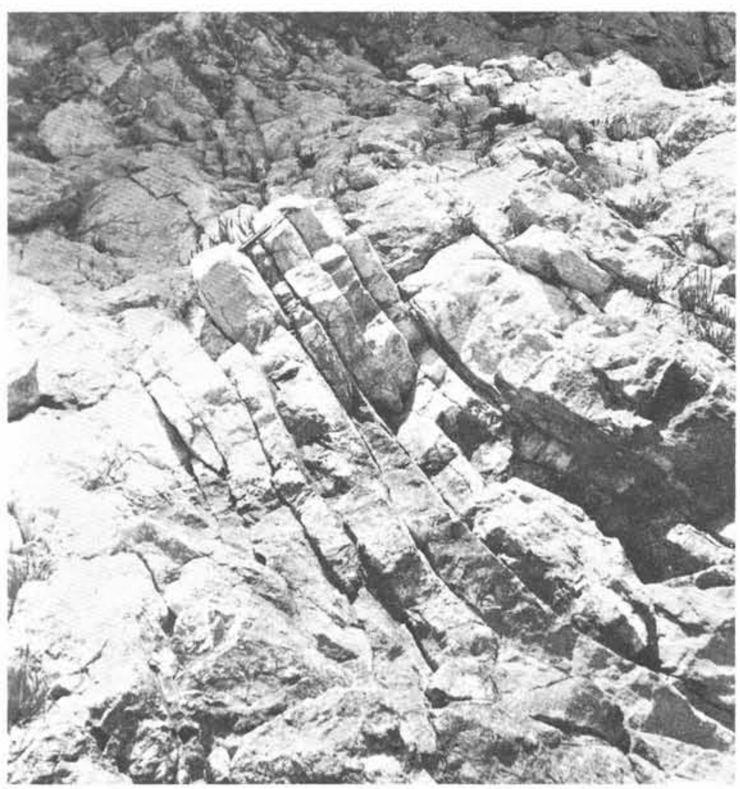

FIGURE 10. — Bedded limestone. Limestone Point, San Juan Island, San Juan County. Permian.

SAMPLING

The sampling of a limestone deposit involves many factors, among which are the geology of the deposit, the uses to which the limestone may be put, the time available for sampling, and the accessibility of the surfaces to be sampled. In this study most deposits of size sufficient to have some possible commercial use even on a small scale were sampled. Some very small deposits were also sampled, especially where they had been reported as being "large" or "pure." Most of the abandoned quarries were also sampled if no record of their quality could be found. It was hoped that through sampling of this nature some indication of chemical composition and its relation to geologic age could be established that would assist evaluation of the deposits in the future and indicate the rock sequences most suitable for prospecting in order to locate high-calcium limestone.

Samples of a limestone deposit may consist of the following types:

(1) A single chunk (grab sample) of limestone taken at random from an apparently homogeneous and small deposit or outcrop.

(2) Single hand specimens taken from individual beds that appear distinctive, each specimen being analyzed separately.

(3) Chip samples averaging about 1 inch in size taken at intervals of 1, 2, 5, or 10 feet across a deposit and analyzed as a group for intervals ranging from 20 to 300 feet.

(4) Channel samples of continuous chips taken across the deposit and analyzed as a group or subdivided into two or more equal lengths and analyzed separately.

(5) Chips taken at random from various parts of the outcrop to form a composite of as much of the exposure as possible.

In western Washington very few limestone bodies show stratification well enough to determine the attitude and structure of the deposit. Normally, chip samples were taken across the thickness of beds at right angles to their strike so as to include the differences in composition of the different layers. Where bedding could not be determined, samples were taken across the width and length of the outcrop.

Where a limestone deposit is being explored and sampled by core drilling, it is advisable to divide the recovered core into sections 5 to 50 feet in length, depending upon the requirements of purity of the use for which the limestone is being considered, and to analyze the sections separately. A competent geologist should study the deposit before drilling commences, in order to ascertain where to drill to obtain the most representative sample that will show the variations of composition within the limestone.

ANALYSES

Chemical and spectrographic analyses were made on 374 chip samples from western Washington limestone deposits. The analyses were made by the Chemistry-Spectroscopy Laboratories of the Division of Industrial Research, Institute of Technology, Washington State University, under the supervision of Mark Adams. The principal analysts were Clarence Homi and Robert Keough. C. E. Harvey was responsible for the spectrochemical analyses. In addition to the analyses prepared for this report, there are included all previously published analyses of western Washington limestones and a few unpublished analyses obtained from private individuals and companies who graciously consented to their publication.

All samples collected during the field work for this report were chemically analyzed for CaO, MgO, SiO_2, R_2O_3, and P_2O_5 and were analyzed spectrochemically for all elements detectable.

Twenty-four single samples and eight composite samples (combinations of from three to six contiguous samples) were analyzed for Na_2O, K_2O, TiO_2, and S. These samples were chosen mostly from the largest and purest deposits of limestone.

The range in the content of these constituents is: Na_2O, 100 to 330 ppm; K_2O, 380 to 625 ppm; TiO_2, -30[1] to 1,250 ppm; and S, 15 to 1,770 ppm. No correlation has been found between the content of Na_2O, K_2O, TiO_2, or S and the content of CaO, MgO, SiO_2, or R_2O_3. However, there appears to be some difference in these constituents according to geologic age. The most pronounced differences are in the sulfur content. In the Paleozoic limestones analyzed the sulfur content appears to increase with increase in age. Three out of five of the Devonian limestones contain over 700 ppm of sulfur. Five out of seven of the Pennsylvanian limestones range from 220 to 530 ppm of sulfur. Three of the late Permian limestones range from 60 to 180 ppm of sulfur. Differences in other constituents are not as marked, but two out of three of the late Permian limestones contain less than 30 ppm of TiO_2, whereas the Devonian and Pennsylvanian limestones range mostly from 100 to 250 ppm of TiO_2. The content of K_2O is similar in limestone of all three ages. The Na_2O content appears higher in the late Permian than in the Devonian and Pennsylvanian limestones. Not enough samples were analyzed to make these differences very significant. Spectrochemical analyses of all samples give somewhat different results according to geologic age and will be discussed in a later paragraph.

	Sample no.	Na_2O (ppm)	K_2O (ppm)	TiO_2 (ppm)	S (ppm)
Late Permian ----------	SJ 7-1 ---------	260	560	325	180
	SJ 7-4 ---------	270	530	-30	60
	SJ 25-1 --------	270	610	-30	70
Early Permian ---------	W 7-1 ----------	250	500	70	245
Pennsylvanian ---------	St 22-1 to St 22-3	185	490	250	325
	W 6-1 to W 6-5--	235	540	250	220
	W 1-2 ---------	290	530	130	530
	St 21-1 to St 21-5	155	490	170	460
	St 2-1 ----------	165	450	250	375
	W 7-3 ----------	220	440	700	1770
	W 7-4 ----------	225	500	95	110
Devonian ------------	W 18-1 ---------	175	560	250	740
	W 16-12 --------	210	565	200	730
	W 4-1 ----------	250	550	65	840
	St 24-1 to St 24-3	175	490	180	195
	St 15-1 to St 15-3	150	490	100	350

The chemical analyses for CaO, MgO, SiO_2, R_2O_3, and P_2O_5 made on all the samples collected for this report that could be definitely identified as to geologic age were averaged to see what differences might be apparent. Limestones assigned to the Early Cretaceous are not definitely known to be of that age but are included in the averages, as they appear at least to be different in age from any of the others.

Limestones of Devonian age analyzed are the purest; their CaO content averages 53.90 percent, and the MgO averages 0.23 percent. They are a little higher in SiO_2 (4.21 percent) than the late Permian limestones but are lowest of all ages in R_2O_3 (0.71 percent) and in P_2O_5 (0.018 percent). None of the Devonian limestone deposits is of large size. Next in purity are the supposed Early Cretaceous limestones of the Gold Bar area, Snohomish County. They average 52.20 percent CaO, 0.52 percent MgO, 4.58 percent SiO_2, 0.84 percent R_2O_3, and 0.027 percent P_2O_5. Unfortunately, layers and lenses of ribbon chert are common in outcrops of these deposits, making it difficult to obtain pure limestone without hand sorting, and all the deposits are small. Next in purity are the late Permian limestones; their averages are: 51.50 percent CaO, 2.01 percent MgO, 3.64 percent SiO_2, 0.84 percent R_2O_3, and 0.088 percent P_2O_5. Much of the late Permian

[1] -30 means that the sample contains less than 30 ppm, the detectable lower limit.

TABLE 1.—Averages of limestone

Age	Number of samples averaged	Chemical analyses					Spectrochemical analyses			
		CaO	MgO	SiO_2	R_2O_3	P_2O_5	Na_2O	K_2O	TiO_2	Al_2O_3
Eocene (Olympic Peninsula) -----	3	36.17	1.39	21.68	12.146	0.109	1.06	1/ 0.90	0.117	2.80
Oligocene (Southwest Washington) ---	5	48.89	1.02	6.75	3.22	0.074	0.36	1.54	0.081	1.64
Early Cretaceous? 2/ -	4	52.20	0.52	4.58	0.84	0.027	3/ 0.05	-------	0.062	0.31
Late Triassic ----	2	39.87	0.44	23.79	3.24	0.055	0.76	-------	0.101	1.83
Late Permian ----	22	51.50	2.01	3.64	0.84	0.088	0.18	-------	0.038	0.30
Early Pennsylvanian --	14	47.70	1.45	10.5	1.17	0.028	0.07	-------	0.025	0.42
Devonian -------	22	53.90	0.23	4.21	0.71	0.018	0.114	-------	0.015	0.31

1/ One sample only. 2/ Age not definitely established. 3/ Two samples only.

limestone is actually as high or higher in CaO than the Devonian limestones, but the analyses do not indicate this, as most of the samples included in the averages come from the San Juan Islands, where many of the Permian limestones have been partially dolomitized. Most of the late Permian limestones of Snohomish and King Counties are lower in MgO but were not sampled during the preparation of this study because of lack of time. Many published analyses of them are available. Averages reported here are confined to samples analyzed for this report. The relatively high average P_2O_5 content (0.088 percent for the San Juan Islands) appears to be a characteristic of most of the late Permian limestones in western Washington, although the mainland deposits do not contain quite as high a percentage.

The Oligocene limestones of southwestern Washington average fourth in purity; their averages are: 48.89 percent CaO, 1.02 percent MgO, 6.75 percent SiO_2, 3.22 percent R_2O_3, and 0.074 percent P_2O_5. The high silica content is in part due to secondary silicification. Fifth in rank of purity are the Early Pennsylvanian limestones, which make up the largest easily accessible deposits in the western part of the State. They average 47.70 percent CaO, 1.45 percent MgO, 10.05 percent SiO_2, 1.17 percent R_2O_3, and 0.028 percent P_2O_5. Their high silica content is due to the more argillaceous composition of these bodies and also to partial silicification. They commonly run higher in MgO than the sample averages would indicate, but ordinarily are good sources of limestone for the manufacture of cement.

The remaining two age groups of limestone are of only minor importance. Late Triassic limestone is known at only one small area on the northwest coast of San Juan Island and appears in outcrop to be very argillaceous. It averages 39.87 percent CaO, 0.44 percent MgO, 23.79 percent SiO_2, 3.24 percent R_2O_3, and 0.055 percent P_2O_5. The argillaceous limestones of the Eocene of the Olympic Peninsula occur in small lenses and commonly weather to a reddish brown or maroon color, indicating their high iron and manganese content. The bodies sampled averaged 36.17 percent CaO, 1.39 percent MgO, 21.68 percent SiO_2, 12.14 percent R_2O_3, and 0.109 percent P_2O_5.

These analyses reflect accurately the conditions of deposition that occurred in western Washington through geologic time resulting in the formation of limestone, and they indicate the importance of knowing something about the geology of an area before attempting to search for limestone deposits and in particular for limestone deposits of high purity.

The results of the chemical analyses are reported under the heading "Quality" in the descriptions of the individual deposits and are shown in Appendix A on pages 447 to 454, inclusive. A table of spectrochemical analyses is given in Appendix B on pages 455 to 467, inclusive.

analyses according to geologic age

Spectrochemical analyses—Continued											
Fe_2O_3	MnO	Cr_2O_3	CoO	NiO	CuO	SrO	ZrO_2	V_2O_5	Ag_2O	BaO	PbO
3.81	4.51	0.0027	0.0047	0.048	0.036	0.02	0.0115	0.038	0.0015	0.0115	------
1.05	0.064	0.0015	------	0.001	0.0044	0.080	0.0039	0.0076	1/ 0.0048	0.0039	------
0.44	0.093	0.0013	------	1/ 0.001	0.0016	0.014	------	------	------	------	------
1.05	0.28	0.0025	------	0.002	0.016	0.017	0.002	------	------	------	------
0.40	0.21	0.0021	------	0.0014	0.0024	0.026	0.002	------	------	------	------
0.50	0.085	0.00118	------	0.001	0.0030	0.0126	0.002	------	------	------	------
0.33	0.10	0.007	------	0.0014	0.0022	0.0120	------	------	------	------	------

The chemical analytical procedures followed by the chemists of the Washington State University Chemistry-Spectroscopy Laboratories are reported by them (written communication, 1961) as follows:

SAMPLE PREPARATION

The sample was crushed to ¼ inch, cut in half, and ground to a fine powder. About ½ pound of the powder was dried at 110° to 112°C for several hours and used for the chemical analysis.

ANALYTICAL CHEMICAL PROCEDURES

Loss on ignition procedure.—A 1.000 g sample was weighed into a freshly ignited and weighed crucible and placed in the muffle at no more than 300° to 400°C. The temperature was increased to 1,000° to 1,100°C and held there for at least 1 hour. The crucible was transferred to a desiccator containing fresh CaO and quickly weighed as soon as cool. (Note: Samples placed in a hot furnace tend to splatter. Crucibles heated above 1,100°C may stick to sample.)

Silica procedure.—The sample from the ignition was put in an evaporating dish and moistened with alcohol. Water, then diluted HCl, was added to dissolve the sample. The crucible was rinsed into the dish with HCl. Alcohol was expelled by heating, then 5 ml of $HClO_4$ was added and the solution evaporated at below boiling. HCl was added and the hot solution filtered through No. 30 Whatman filter paper. After thorough washing with hot 1:10 HCl, the sample was ignited at 1,000° to 1,100°C and weighed. (Note: Alcohol is necessary to slow exothermic hydration of CaO. The alcohol must be removed before adding $HClO_4$ to avoid possible explosive reaction.)

R_2O_3 procedure.—The filtrate from silica was heated to near boiling in a 400 ml beaker, and 5 ml of saturated NH_4Cl was added. 1:1 NH_4OH was added until a faint odor of NH_3 persisted. (Methyl red can be used to help detect the proper pH.) After heating for 5 to 15 minutes the solution was filtered through a No. 31 Whatman paper into a 250 ml volumetric flask followed by washing with 1 percent NH_4NO_3 solution at pH 6.5 to 8.0. The precipitate was ignited at 1,000°C. (Note: The NH_4OH should be of a good quality, free from silica and carbonates.)

Ca and Mg procedures.—The filtrate from R_2O_3 was diluted to 250.0 ml, and 10 ml was pipetted into a wide-mouth flask, buffered with 3 ml of NH_4Cl - NH_4OH buffer and titrated to a pure blue with Uni-Ver indicator. Standard $CaCO_3$ and the same pipet were used to check the titer of the EDTA titrant before each group of samples was titrated. Ca was found by difference by subtracting the equivalents of Mg from the equivalents of combined Ca and Mg as determined by this EDTA titration.

Mg procedure. — Seven to 9 ml of 20 percent Na_2SO_4 were added to 100 ml of the filtrate from R_2O_3 and left to stand cold for 10 minutes. It was then warmed to 90°C for about half an hour and filtered through very fast paper. Two ml of saturated $(NH_4)_2C_2O_4$ were added. It was then heated at 70° to 80°C for 2 to 3 hours, while being kept slightly basic followed by filtration through a No. 32 Whatman paper, cooled, and titrated with EDTA.

Phosphorus procedure. — 0.284 g of sample was dissolved in a minimum amount of 1:1 HCl in a 100 ml volumetric flask. To this solution, diluted to 50 to 70 ml, 5.0 ml of 2.5 percent ammonium molybdate in $10NH_2SO_4$ was added and stirred well. After stirring, 2.0 ml of 0.15 percent hydrazine sulfate was added and the mixture shaken. The flask was placed in boiling water for 10 to 11 minutes, then removed and placed in a cold water bath until cool. The solution was diluted to volume and the absorbence was read on a DU Spectrophotometer at 830 mu with a 0.04-mm slit.

SPECTROCHEMICAL PROCEDURE

The choice of spectrochemical procedures to be applied to a problem is largely determined by the concentration range sought, and two or more techniques may have to be applied to determine separately major constituents, minor constituents, and extremely low trace elements. The latter may frequently involve a preliminary separation and concentration technique.

In the limestone problem, a single technique was applied because major constituents were determined chemically and extremely low levels down to parts-per-billion range were not sought. The procedure used would detect most elements in the samples in a range of 10 to 50 ppm. This was a simple direct-current arc technique, using standard pre-form electrodes with 10 mg of sample and 10 mg of graphite containing a constant amount of two elements whose presence in the samples was highly improbable. These elements, platinum and germanium, served as reference or so-called internal standard elements, the choice of one or the other being determined by the burning characteristics of the particular elements involved. For elements in the low to medium boiling point range, germanium was used as internal standard. High boiling point elements required platinum as internal standard.

The achievement of best quantitative results required a large number of standards, since there was considerable variation in the CaO/SiO_2 ratio in the samples submitted. This variation produces a matrix effect in changing sensitivity of detection for various elements. Consequently, a series of matrices were prepared, containing varying amounts of CaO, SiO_2, Al_2O_3, and MgO. To these in turn were added portions of standard mixes referred to as "addition mixes." These contain various elements at known levels of concentration and permitted the introduction of various minor elements in a range of 0.0001 to 1.0 percent. While the entire group of 15 addition mixes would be necessary to cover every element in the periodic system normally detectable by spectrographic methods, a group of four mixes covered the elements found in the limestones submitted. Each of these was introduced at seven levels of concentration into each matrix type and intensities studied to determine possible variations due to changes in the CaO/SiO_2 ratio.

Thus, the procedure applied to both standards and samples consisted of weighing 10 mg of sample and 10 mg of graphite containing internal standards into a pre-formed cup-type electrode, burning to completion in a direct current arc and photographing the resulting spectrum on 35 mm film. After processing the film, various spectrum lines were measured for various elements, with the choice of line being determined by the range of concentration of the element involved. The intensity ratio of sought-for element and internal standard was then determined and a curve established to define the change of intensity with the change of concentration. The percentage of various elements in the sample was then determined from these so-called working curves.

SPECTROCHEMICAL ANALYSES

Spectrochemical analyses were made of every limestone sample for the determination of all elements detectable. The following elements, expressed as oxides, were detected and reported as percentages on a dry weight basis:

	Detection limit (percent)		Detection limit (percent)
Na_2O	0.05	TiO_2	0.0020
K_2O	0.25	V_2O_5	0.0030
Al_2O_3 1/	0.0010	NiO	0.0010
Fe_2O_3 1/	0.0005	ZrO_2	0.0020
SrO	0.0001	Ag_2O	0.0002
MnO	0.0005	PbO	0.0020
CuO	0.0002	BaO	0.1500
Cr_2O_3	0.0005	CoO	0.0010

1/ Al_2O_3 and Fe_2O_3, combined, were reported in regular standard chemical analyses as R_2O_3.

Sodium (Na_2O).—One hundred and forty-four samples contain measurable amounts of Na_2O. The range is from 0.05 to 5.071 percent. The highest values for sodium are usually in the more argillaceous and impure limestones. Eocene limestones of the Olympic Peninsula average 1.06 Na_2O, and the Late Triassic limestones of San Juan Island, 0.76. Strangely, the somewhat argillaceous limestones of Early Pennsylvanian age average only 0.07 Na_2O. Twenty-four samples contain 0.5 percent or more of Na_2O. Unusually large amounts are present in the following samples:

Sample no.	Area	Na_2O (percent)
SJ 50-1	Davison Head, San Juan Island	1.00
Cn 8-1	Entiat	1.23
Cn 8-3	Entiat (green limestone)	1.10
M 1-1 and 1-2	Staircase, Olympic Mountains	1.22 (average)
GH 2	Schofield Creek, Olympic Mountains	5.07
St 17-2	Paystreak	1.13
St 18-3	South Portland claim	1.42
St 20-4	Dock Butte	1.39
St 25-1 and 25-2	Sauk River bridge	3.20 (average)

Potassium (K_2O).—As the detection limit (0.25) is rather high, K_2O was found in only 20 samples. It ranges from 0.25 to 3.00 percent. Seven samples contain 1 percent or more. The Eocene and Late Cretaceous limestones are the only limestones of known geologic age to contain measurable amounts.

Sample no.	Area	K_2O (percent)
SJ 68-1	Langdon, Orcas Island	1.13
SJ 90-1	Stuart Island	1.72
Cn 8-3	Entiat (green limestone)	1.50
St 25-1 and 25-2	Sauk River bridge	1.61 (average)
Pf 1-1	Menlo	1.20
Pf 2-1 and 2-2	Bear River	0.97 (average)

Titanium (TiO_2).—Titanium is present in all but seven samples. It ranges from 0.0020 to 0.70 percent. It is highest in the very impure argillaceous limestones and averages 0.101 percent for the Late Triassic limestones of San Juan Island and 0.117 percent for the Eocene limestones of the Olympic Peninsula. Devonian limestones average only 0.015 percent. Twenty-seven samples from western Washington contain 0.1 percent or more of titanium. The largest amounts are present in the following samples:

Sample no.	Area	TiO_2 (percent)
SJ 90-1	Stuart Island	0.22
W 10-1	Silver Lake tufa mixed with mud	0.18
W 18-3	Sumas Mountain No. 2	0.24
Cn 8-1	Entiat	0.27
Cn 8-3	Entiat (green limestone)	0.35
St 25-1 and 25-2	Sauk River bridge	0.70 (average)
St 20-4	Dock Butte	0.23
St 18-3	South Portland claim	0.18
St 17-2	Paystreak	0.33
M 1-2	Staircase, Olympic Mountains	0.22
GH 2	Schofield Creek, Olympic Mountains	0.62

Aluminum (Al_2O_3).—All samples contain Al_2O_3. The content of Al_2O_3 usually ranges from 0.10 to 9.90 percent, the highest percentage being in the impure argillaceous limestones. Forty-eight samples contain 1.00 percent or more. Most of the San Juan Islands deposits are below 0.10 percent. The argillaceous Eocene limestones of the Olympic Peninsula average 2.80 percent, and the Late Triassic limestones of San Juan Island average 1.83 percent. Late Permian limestones average the lowest, at 0.30 percent, and the Devonian and Early Cretaceous average 0.31 percent. The smallest amounts of Al_2O_3 are in the following samples:

Sample no.	Area	Al_2O_3 (percent)
Cn 4-3	Marble Creek	0.028
SJ 7-5	Cowell	0.023
SJ 29-3	McGraw-Kittinger	0.021
SJ 29-5	McGraw-Kittinger	0.022
SJ 34-2	Cliff Island	0.024
SJ 41-1	Wilson	0.017
St 3-1	Jackman Creek No. 1	0.075
St 13-1	Marble Creek	0.075
Sh 4-3	Galbraith	0.038
Sh 5-3	Boulder Creek	0.012
Sh 12-5	Canyon Creek	0.017
W 5-2	Boulder Creek	0.013

Iron (Fe_2O_3).—All samples contain iron and range from 0.022 to 5.22 percent Fe_2O_3. Forty-six samples contain over 1.00 percent iron. Argillaceous and impure limestones contain the largest amounts of iron, and usually those with a high Al_2O_3 content have a high Fe_2O_3 content. The Late Triassic limestones average 1.83 percent iron, and the Oligocene limestones of southwestern Washington, 1.05 percent. The Devonian limestones have the smallest amount of iron—an average of 0.31 percent. Samples with an unusually low iron content are:

Sample no.	Area	Fe_2O_3 (percent)
Cn 5-5	Dry Creek	0.09
SJ 36-2	West Sound	0.09
SJ 51-3	Wescott Bay, Roche Harbor	0.09
SJ 52-1	Mosquito Pass	0.07
SJ 56-1	Henry Island No. 2	0.055
SJ 59-1	Henry Island No. 4	0.052
SJ 71-2	Newhall	0.09
St 11-9	Sutter Creek	0.11
St 15-1	Webber Creek	0.10
St 17-3	Portland	0.11
Sh 1-1	Blackoak Creek tufa	0.11
W 1-2	Silver Lake No. 1	0.12
W 5-3	Boulder Creek	0.022
W 25-1	Church Mountain tufa	0.11

Manganese (MnO).—All samples contain MnO, which ranges from 0.007 to 6.84 percent. Thirty-three samples contain 0.25 percent or more. Most of these are from the San Juan Islands, where Permian and Triassic limestones appear to contain abnormal amounts of manganese. The largest MnO content average, according to geologic age, is 3.81 percent, in the Eocene limestones of the Olympic Peninsula. Late Triassic limestones average 0.28 percent, and late Permian limestones 0.21 percent. The Oligocene limestones of southwestern Washington have the lowest average amount of manganese—0.064 percent. Limestones with abnormally high MnO content are:

Sample no.	Area	MnO (percent)
SJ 5-2	Lawson, west side	1.00
SJ 30-1	Camp Indralaya	0.80
SJ 27-1	Judd Cove	0.75
SJ 11-1	Rusch No. 2	0.80
SJ 6-1	Smallpox Bay	0.80
M 1-1 and 1-2	Staircase, Olympic Mountains	4.92 (average)
GH 1	Copper Creek, Olympic Mountains	3.70

Chromium (Cr_2O_3).—Chromium is found in over two-thirds of the samples analyzed. It was not detected in 104 samples. It ranges from 0.0005 to 0.0074 percent in true limestones, but is 0.12 percent in a calc-silicate rock near Menzel Lake in Snohomish County that is mentioned in the literature as a limestone deposit, and is 3.20 percent in an argillaceous limestone of the Olympic Mountains. Nine samples contain 0.005 percent or more Cr_2O_3. Most of the higher percentages of chromium are in limestone from the San Juan Islands. The Eocene limestones of the Olympic Peninsula contain the largest amount according to geologic age, an average of 0.0027 percent. The Late Triassic limestones rank next, with an average value of 0.0025 percent Cr_2O_3, and the late Permian next, with 0.0021 percent. The lowest average values according to geologic age are the Early Pennsylvanian limestones, with 0.00118 percent Cr_2O_3. Samples having unusually large amounts of chromium are:

Sample no.	Area	Cr_2O_3 (percent)
SJ 2-1	Bell, San Juan Island	0.0062
SJ 5-2	Lawson West	0.0050
SJ 7-2	Cowell	0.005
SJ 16-1	Double Hill No. 6	0.0065
SJ 67-3	Langdon, north part	0.0067
SJ 68-1	Langdon, south part	0.0074
Cn 8-3	Entiat (green limestone)	0.0064
GH 2	Schofield Creek, Olympic Mountains	3.20
Sh 13-1	Menzel Lake calc-silicate	0.12

Cobalt (CoO).—Cobalt was detected in only 10 samples, most of which are very impure limestones. CoO ranges from 0.001 to 0.006 percent in true limestones. A value of 0.0077 was obtained in sample Sh 13-1, which is a calc-silicate rock often described as a limestone. In deposits of known geologic age, cobalt was detected only in the Eocene limestones of the Olympic Peninsula, where it averages 0.0047 percent. All the cobalt-bearing samples are relatively high in iron, but several samples high in iron do not contain detectable cobalt. Samples containing cobalt are:

Sample no.	Area	CoO (percent)
SJ 67-3	Langdon, north part	0.0014
W 18-3	Sumas Mountain No. 2	0.001
St 25-1 and 25-2	Sauk River bridge	0.0030 (average)
Sh 9-1	Conn Creek No. 2	0.0017
Sh 13-1	Menzel Lake calc-silicate	0.0077
M 1-1 and 1-2	Staircase, Olympic Mountains	0.0056 (average)
GH 1	Copper Creek, Olympic Mountains	0.0028
GH 2	Schofield Creek, Olympic Mountains	0.0053

Nickel (NiO).—About half of the limestones sampled contain nickel. It ranges from 0.001 to 0.06 percent. The impure argillaceous limestones contain the larger amounts. By geologic age, the Eocene limestones of the Olympic Peninsula contain the largest amount, averaging 0.048 percent. Limestones of other geologic ages average between 0.001 and 0.002 percent. Samples with unusually high nickel contents are:

Sample no.	Area	NiO (percent)
SJ 67-3	Langdon, north part	0.007
W 20-2	NW. Black Mountain No. 2	0.0094
St 17-2	Sec. 15, Paystreak	0.0078
St 25-1	Sauk River bridge	0.0052
Sh 9-1	Conn Creek No. 2	0.015
Sh 13-1	Menzel Lake calc-silicate	0.04
M 1-1 and 1-2	Staircase, Olympic Mountains	0.055 (average)
GH 1	Copper Creek, Olympic Mountains	0.033
GH 2	Schofield Creek, Olympic Mountains	0.024

Copper (CuO).—Every sample contains copper. It ranges from 0.005 to 0.037 percent. Twenty samples contain over 0.01 percent CuO, and the greater part of these are from the San Juan Islands; of these, five samples are from the east side of Orcas Island. According to geologic age, the highest average (0.036 percent) is in the impure argillaceous limestones of Eocene age on the Olympic Peninsula. The argillaceous Late Triassic limestones of San Juan Island are next, averaging

0.0016 percent in the Early Cretaceous to 0.0055 percent in the Oligocene of southwestern Washington. Samples containing abnormally large amounts of CuO are:

Sample no.	Area	CuO (percent)
SJ 92-1	Moran State Park, Orcas Island	0.023
SJ 90-1	Stuart Island	0.012
SJ 80-1	Wright, south part, Orcas Island	0.0099
SJ 77-4	Mount Constitution, Orcas Island	0.014
SJ 76-3 and 76-4	Buck Mountain, No. 2, Orcas Island	0.015 (average)
SJ 67-3	Langdon, north part, Orcas Island	0.024
SJ 61-1	Limestone Point	0.013
SJ 59-2	Henry Island No. 4	0.011
SJ 54-1	Rouleau	0.013
SJ 50-1 and 50-2	Davison Head	0.016 (average)
St 17-2	Sec. 15, Paystreak	0.026
St 18-3	South Portland claim	0.012
St 25-1 and 25-2	Sauk River bridge	0.024 (average)
Sh 13-1	Menzel Lake calc-silicate	0.018
M 1-1 and 1-2	Staircase, Olympic Mountains	0.036 (average)
GH 1	Copper Creek, Olympic Mountains	0.035
GH 2	Schofield Creek, Olympic Mountains	0.020

Strontium (SrO). — Strontium was detected in all but five samples, and ranges from 0.0054 to 0.16 percent. Sixteen samples contain over 0.05 percent SrO, and nine of these are from the San Juan Islands. According to geologic age, the highest average SrO content is 0.08 percent, in the Oligocene limestones of southwestern Washington. Limestones of other geologic ages range from a low of 0.012 percent in the Devonian to a high of 0.026 percent in the late Permian. Samples of unusually high strontium content are:

Sample no.	Area	SrO (percent)
SJ 5-1 and 5-2	Lawson	0.061 (average)
SJ 27-1	Judd Cove	0.055
SJ 66-1	Deadman Bay	0.055
SJ 68-1	Langdon, south part	0.05
SJ 70-1	Entrance Mountain	0.052
SJ 75-1	Buck Mountain No. 1	0.16
SJ 78-1	Raccoon Point	0.064
SJ 85-1	Shaw Island, west coast	0.052
Cn 1-1	Soda Springs tufa	0.059
St 11-3	Sutter Creek	0.055
St 11-7	Sutter Creek	0.052
Pf 1-2	Menlo	0.056
Pf 2-1 to 2-3	Bear River	0.108 (average)

Zirconium (ZrO_2). — Zirconium was detected in 39 samples, and ranges from 0.002 to 0.02 percent. The largest average composition according to geologic age is 0.0115 percent, in the Eocene limestones of the Olympic Peninsula. The Oligocene limestones of southwestern Washington average 0.0039 percent. Late Triassic, late Permian, and Early Pennsylvanian limestones each average 0.002 percent. No zirconium was detected in the Devonian and Early Cretaceous limestones. The largest amounts of ZrO_2 are in the very impure argillaceous limestones. Samples with unusually large amounts of ZrO_2 are:

Sample no.	Area	ZrO_2 (percent)
SJ 67-3	Langdon, north part	0.011
SJ 68-1	Langdon, south part	0.0054
SJ 90-1	Stuart Island	0.0084
St 25-1 and 25-2	Sauk River bridge	0.013 (average)
St 20-4	Dock Butte	0.0069
M 1-1 and 1-2	Staircase, Olympic Mountains	0.0125 (average)
GH 2	Schofield Creek, Olympic Mountains	0.020
Pf 1-1 and 1-2	Menlo	0.0067 (average)
Cn 8-1	Entiat	0.0051
Cn 8-3	Entiat (green limestone)	0.0057
W 10-1	Silver Lake tufa (mud)	0.0051
W 18-3	Sumas Mountain No. 2	0.0072
W 20-2	NW. Black Mountain No. 2	0.010
Sh 13-1	Menzel Lake calc-silicate	0.008

Vanadium (V_2O_5). — Vanadium was detected in 104 samples, and ranges from 0.003 to 0.42 percent. Argillaceous limestones of Eocene age from the Olympic Peninsula contain the largest amount, averaging 0.038 percent V_2O_5. Oligocene limestones of southwestern Washington average 0.0039 percent. Limestones of other known geologic ages do not contain detectable amounts of vanadium. There appears to be a relatively high concentration of vanadium in limestones in the Silver Lake valley and adjacent areas of northwestern Whatcom County. Samples analyzed in western Washington that contain unusually large amounts of V_2O_5 are:

Sample no.	Area	V_2O_5 (percent)
SJ 77-1 to 77-3	Mount Constitution	0.0094 (average)
SJ 90-1	Stuart Island	0.009
W 6-3	Red Mountain	0.0098
W 7-2	Black Mountain No. 3	0.012
W 9-1 and 9-2	Silver Lake No. 2	0.008 (average)
W 15-1	Silver Lake No. 2	0.0084
W 10-1	Silver Lake tufa (mud)	0.0092
W 18-3	Sumas Mountain No. 2	0.015
W 20-1 and 20-2	NW. Black Mountain No. 2	0.0064 (average)
Sh 9-1	Conn Creek No. 2	0.0056

Silver (Ag_2O). — Silver was detected in 34 samples and ranged from 0.002 to 0.0023 percent. One sample out of five analyzed from the Oligocene of southwest Washington contains 0.0048 percent Ag_2O, but none was detectable in other samples from these deposits. The impure argillaceous limestones of Eocene age of the Olympic Peninsula contain an average of 0.0015 percent Ag_2O. No silver was detected in limestone deposits of other known geologic ages. There appears to be a concentration of silver in samples from the east side of Orcas Island, in the San Juan Islands. Unusually large amounts of silver were detected in the following samples:

Sample no.	Area	Ag_2O (percent)
SJ 77-1 to 77-4	Mount Constitution, Orcas Island	0.0014 (average)
SJ 78-1	Raccoon Point, Orcas Island	0.0015
SJ 79-2	Payton, Orcas Island	0.001
SJ 79-5	Payton, Orcas Island	0.0018
SJ 80-2	Wright, north part, Orcas Island	0.0023
St 17-2	Sec. 15, Paystreak	0.0018
St 25-2	Sauk River bridge	0.0015
M 1-1 and 1-2	Staircase, Olympic Mountains	0.016 (average)
GH 1	Copper Creek, Olympic Mountains	0.0013
W 18-3	Sumas Mountain No. 2	0.001
Sh 9-1	Conn Creek No. 2	0.0012

Barium (BaO).—Nineteen samples contain BaO, ranging in amount from 0.002 to 0.43 percent. The impure argillaceous limestones of the Eocene of the Olympic Peninsula average 0.0115 percent BaO, and the Oligocene limestones of southwestern Washington average 0.0039 percent BaO. No detectable amounts of barium were found in limestones of other known geologic ages. Unusually large amounts of BaO occur in the following samples of mostly impure limestone:

Sample no.	Area	BaO (percent)
SJ 58-1	Henry Island No. 3	0.15
SJ 88-1	Flaherty No. 2	0.43
SJ 89-1	Flaherty No. 3	0.36
Cn 6-2	Indian Creek	0.14
St 25-1 and 25-2	Sauk River bridge	0.013 (average)
M 1-1 and 1-2	Menlo	0.0125 (average)
J 1-1	Pulali Point	0.010
GH 1	Copper Creek, Olympic Mountains	0.0096
GH 2	Schofield Creek, Olympic Mountains	0.020

Lead (PbO).—Lead was found in only two samples, and these were both from the east side of Orcas Island, San Juan County, in limestones of Paleozoic age.

Sample	Area	PbO (percent)
SJ 77-4	Mount Constitution	0.038
SJ 79-3	Payton	0.023

Remarks on spectrochemical analyses.—

(1) Argillaceous and impure limestones usually contain the largest amounts of minor elements.

(2) All samples contain Al_2O_3, Fe_2O_3, MnO, and CuO, and all but five samples contain SrO.

(3) No element or group of elements seems to be characteristic of any distinctive limestone unit or formation.

(4) There appears to be a concentration of vanadium in the limestones of the northwestern part of Whatcom County and a concentration of copper, silver, and lead in the limestones on the east side of Orcas Island.

(5) San Juan County limestones appear to contain larger amounts of strontium, chromium, and manganese than limestones from other parts of western Washington and appear to be lower than average in amounts of aluminum.

(6) It does not appear possible to use minor element content of limestones of western Washington as an indication of geologic age. This is particularly true of the Paleozoic limestones.

EVALUATION OF DEPOSITS

Four factors—size, quality, amount of overburden, and accessibility—are of prime importance in the evaluation of a limestone deposit in western Washington. The limiting size depends upon a number of factors but mostly on the type of use to which the limestone is to be put and on accessibility to the deposit. Deposits of 100,000 tons or less have been quarried for use as agricultural stone and pulp rock where they were close to market and highway, rail, or water transportation. Many deposits on the San Juan Islands and a few on the mainland were quarried although they contained only a few thousand tons. A limestone deposit of 5,000 tons exposed on the shore of an island in San Juan County would have much greater potential to be quarried than a deposit of 100,000 tons situated at a high altitude in the Cascade Mountains.

Where only a small production tonnage is required per day, a small limestone body may be quite suitable. However, for the manufacture of portland cement a large deposit is necessary to enable a large tonnage to be extracted each day in order to make a profit on an investment of plant and facilities that may run well over $10 million. A reserve of 40 to 50 million tons of limestone would probably be a mimimum requirement for the operation of a small modern cement plant.

Quality, or grade, is next in importance. Details of the requirements for different uses of limestone are given in a later part of this bulletin. In general, chemical uses require high-grade or pure limestone (95 percent $CaCO_3$), whereas agricultural and cement limestone can include up to a certain amount of impurities. Magnesium content is especially critical and, except for agricultural limestone, should generally be less than 3 percent MgO. The presence of objectionable trace elements such as lead, fluorine, and manganese in agricultural stone; phosphorus in stone for carbide manufacture; and iron in limestone to be used for glass manufacture must be determined.

The essential oxides in limestone— lime (CaO) and magnesia (MgO) are reported in this bulletin in the chemical analyses of each deposit. These components are also listed as calculated into their carbonate forms as calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$). Many of the private or published analyses included in this report list one or the other of these compounds. They may be calculated as the carbonates or as oxides, using the following conversion factors (Mathews, 1947):

1 percent CaO is equivalent to 1.78 percent $CaCO_3$
1 percent MgO is equivalent to 2.09 percent $MgCO_3$
1 percent $CaCO_3$ is equivalent to 0.560 percent CaO
1 percent $MgCO_3$ is equivalent to 0.478 percent MgO

The amount and the type of overburden on a western Washington deposit may mean the difference between its being economic or noneconomic. A limestone exposed at the surface without covering or overlying material (overburden) is best, but usually surficial materials such as soil, sand, gravel, clay, or a mixture of these lie over the deposit, or it is capped with bedrock. Removal of more than 10 feet of surficial material is seldom profitable, though in some midwestern quarries the economic limit is about 40 feet. The removal may be accomplished by stripping with a bulldozer, sluicing, or a combination of these methods. Any amount of solid bedrock overburden is expensive to remove, and seldom can a deposit overlain with more than 6 feet of bedrock be surface quarried.

Accessibility includes both the ease with which one may reach the deposit by building road, rail, or tramline facilities and the distance to market for the quarried stone or product. In western Washington the farther east the deposit lies from the industrial center located on Puget Sound, the greater will be the cost of transportation to potential markets; also, since the Cascade Mountains lie to the east, the higher will be the altitude of the deposit and the greater the topographic relief. At the higher altitudes the climate is more severe and operating costs are greater than in the lowlands. The markets for the limestone from deposits on the east side of the Cascade Mountains, in Chelan and Kittitas Counties, are mostly to the east, in towns along the Columbia and Yakima rivers. The cement company at Grotto, King County, on the west side of the Cascade Mountains near the divide, has shipped its products to markets both to the east and to the west, but since it exhausted its limestone quarries near the plant has had to haul limestone from Chelan County over the mountains to the plant.

Deposits composed of millions of tons of limestone at high altitudes in remote areas of the northern Cascade Mountains can not compete under present economic conditions with limestone quarried from near-shore or shoreline sites in British Columbia and southeastern Alaska. Relatively cheap water transportation from these sites allows limestone to be transported profitably to Puget Sound areas and farther south to parts of Oregon and even to California.

It is important that persons owning limestone deposits have a competent geologist or geological engineer examine their property to determine, in as far as surface evidence will permit, the size and quality of the deposit and the amount of overburden and to evaluate the problems of accessibility. It is also important that companies considering the quarrying of limestone bodies have a competent geologist or geological engineer examine the property before development is attempted, to consider what exploratory stripping or diamond drilling or both is necessary in order to determine reserves and the proper method of development. The geologist should continue to work with company engineers after develpment, so as to provide the information necessary for maximum recovery of limestone from the deposits and to investigate any changes in structure and composition. Despite the commonsense approach this procedure provides, there have been many attempts, even in recent years, to develop limestone deposits in western Washington without proper evaluation and exploration. The examples mentioned by McLellan (1927, p. 168), where: "In one instance, after a lime kiln had been completed the whole limestone lens was blown out by one charge of powder," and where (p. 172) the Deer Harbor feldspar deposit was mistaken for limestone, are still just as applicable today, except usually on a somewhat more expensive scale.

During this study an estimate was made, where possible, of the minimum tonnage of limestone available in each of the deposits examined. The estimates are based upon the exposure, shape, and geology of the deposit. This information is included in the description of each deposit and is also incorporated in Table 12 on pages 56 to 60.

ACQUIRING A LIMESTONE DEPOSIT

Persons prospecting for limestone deposits in western Washington or buying or leasing limestone-bearing properties are advised to refer to such publications as:

An Outline of Mining Laws of the State of Washington, (Bulletin No. 41, Washington Division of Mines and Geology, Olympia) compiled by Morton H. Van Nuys, 142 pages, 1953, and supplement 1956.

Mineral Rights and Land Ownership in Washington, (Information Circular No. 36, Washington Division of Mines and Geology, Olympia) by Wayne S. Moen, 23 pages, 1962.

Marketing of Metallic and Nonmetallic Minerals, (Information Circular No. 39, Washington Division of Mines and Geology, Olympia) by Donald L. Anderson, 39 pages, 1963.

In general, limestone deposits on Federal lands open to staking may be located as placer claims. Other Federal lands, such as camp grounds, national parks and monuments, military reservations, and dam sites, are not open to staking. Indian reservations are not open to staking, but under certain conditions mineral deposits on them may be leased. State and County lands may not be staked, but limestone deposits on these lands may be leased for prospecting and mining purposes. Various fees and permits and certain amounts of assessment work are required, and the State charges a royalty of not less than 1 percent of all money received from the sale of material on State lands, less certain deductions for transportation from the quarry to the processing plant and less deductions for the cost of processing. The minimum royalty rate is 1 percent, and the actual royalty rate established in each individual case is determined through negotiation between the applicant and the State.

Private lands are open to prospecting only by permission of the owner, and it should be ascertained who owns both the surface rights and the mineral rights, as the latter may be under different ownership. Private owners usually either sell the land and mineral rights for a stated price or require both a fee for the use of the property and a subsequent royalty per ton of usable limestone produced, the royalty ranging generally from 3 cents to 20 cents per ton, depending upon the value of the limestone and the cost of obtaining it.

PRICE

Prices for limestone depend on many factors; they vary according to location, demand, quantity of sale, quality, subsidies, and degree of preparation or processing. Generally, it is a low-priced material and has relatively high transportation costs. Limestone screenings may be sold for as little as 50¢ per ton, whereas finished ornamental limestone may be valued at more than $90 per ton (Ross, 1964). Final price at destination for such a low-priced commodity is usually much greater than the quarry or plant price.

TAXES AND TARIFFS

There are no specific or special taxes on limestone deposits in the State of Washington imposed by Federal, County, State, or City governments. The County Assessor in each county makes his own appraisal of the value of the real estate containing limestone. As a general rule, he does not increase the value of the real estate because of its limestone content. An operating limestone quarry would make the property of greater value than a deposit that has never been developed or that appears to be unsuitable for development. Property containing an exhausted quarry would be of considerably less value than one with an operating quarry.

Certain depletion allowances are applied by the Federal Government, depending upon the primary use of the limestone quarried. Use of such more or less commercial terms as "flux stone," "cement rock," "marble," "pulp rock," etc. carry certain connotations as far as taxation is concerned. There is need for some clarification of commercial terminology as distinguished from scientific terminology and also of the application of these terms to limestone deposits and their legal and tax implications.

There is a 25 percent ad valorem tariff on the general category of limestone, and other duties for cut and polished limestone slabs, "marble," metamorphosed limestone, etc. entering Canada from the United States. However, there is no tariff on crushed limestone entering Canada under the British preferential, or the most-favored-nation category. (The United States is under the latter category.)

Import tariffs for limestone entering the United States from Canada are as follows (1963):

Crude, broken, or crushed, when imported for use in manufacture of fertilizer	Free.
Not suitable for use as monumental or building stone; crude or crushed, but not pulverized .	20¢ per short ton.
Suitable as monumental or building stone, dressed	21% ad valorem.
Unmanufactured rough	2¢ per cubic foot.

Ornamental stones, such as marble, onyx, and breccia, have a wide variety of tariffs.

MINING AND PROCESSING

Most of the limestone produced in western Washington is obtained from shelf or bench quarries opened in hillsides. In these quarries there are generally no problems of drainage or hoisting, but they may be on such high steep slopes that aerial tram lines, gravity and belt conveyor systems, or other methods must be used to transport the limestone downslope from the quarry or primary crusher. Shelf quarries have one or more benches, each with a vertical or steeply sloping working face. These faces may be from a few feet to as much as 300 feet in height, but where the faces are high it is preferred, if possible, to use several benches ranging from 10 to 50 feet in height. Most of the western Washington limestone deposits occur as mounds, ridges, knobs, or cliff faces, making shelf quarrying (which is usually the cheapest method) possible. The large quarries of the Permanente Cement Company on Red Mountain, Whatcom County; the Lone Star Cement Company at Concrete, Skagit County; and the Ideal Cement Company at Soda Springs, Chelan County, are examples of this type.

Pit quarries are required where the limestone is limited in horizontal extent but is less limited in vertical extent. Several small quarries in western Washington were developed as this type, and many shelf quarries had eventually to be converted into pit quarries, as at Roche Harbor and Mitchell Bay on San Juan Island. Many pit quarries present drainage problems and when idle or exhausted commonly are filled with water, as are some of the pits at Roche Harbor, Mitchell Bay quarry, West Sound quarry, Marble quarry at Grotto, and Granite Falls quarry. Many small pit quarries on the San Juan Islands are filled with water only during the wetter parts of the year. At Roche Harbor, water in the quarries is used to supplement the supplies at the resort, and at Mitchell Bay and West Sound, water-filled quarries provide swimming holes for the local residents.

The glory-hole method, in which a funnel-shaped pit is excavated in the quarry floor and broken limestone drawn down through chutes and loaded below the quarry, was used at one time for a bench quarry near Gold Bar, Snohomish County. An ingenious modification of this method is being used at the Permanente Cement Company quarry on Red Mountain, in Whatcom County. Underground mining (room-and-pillar, shrinkage stope, and block caving) is an acceptable method for mining limestone in many parts of the United States, but none of the limestone deposits in western Washington has required this more expensive type of mining, and very few are large enough to be suitable for it.

FIGURE 11. — Shelf and pit quarry, Marble No. 2 deposit, Grotto, King County. Steeply dipping narrow limestone bodies pose many problems in quarrying.

Drilling and blasting of the limestone in quarries must be guided first by what will result in maximum efficiency for production and second by the size of limestone fragments that is required and the amount of stone that is wanted and can be handled. Detailed studies of the quarry faces and their jointing and bedding are required from time to time in order to plan drilling, blasting, and quarry direction. Solution features such as enlarged joints, caves, and dirt-filled sinkholes, and intrusive features such as igneous rock dikes and clastic dikes also have to be studied and evaluated by a geologist.

Limestone that is to be used for building or monumental stone can be quarried by channeling machines or wire saws. No quarry of this type has been operated in western Washington. For other special uses, close control over chemical composition of the product may require special methods of quarrying to produce suitable rock.

Processing of most limestone involves crushing, grinding, and sizing. Crushing and grinding are done by means of jaw, rotary, and gyratory crushers; and ball, rod, and tube mills. Sizing may be accomplished by various combinations of rotating screens, vibrating screens, wet classification devices, air separators, etc. Coarse products are distributed in bulk, and finely crushed or ground limestone used for agricultural purposes is usually packed in paper sacks.

By the flotation process it is possible to improve the quality of low-grade argillaceous or arenaceous limestones, particularly those used for agricultural purposes or for cement material. The limestone is ground to pass a 20-mesh screen and is floated in a cell using soap reagents. Experiments in this type of beneficiation have been conducted in western Oregon (Clemmer and Clemmons, 1940), and tests to find more effective methods have been conducted by the United States Bureau of Mines (Agey and others, 1963).

Large blocks of limestone of approximately 100 pounds in weight are often termed "man rock," or "pulp rock." Small chunks not processed are referred to in western Washington as "spalls."

Lime, made by calcining ("burning") limestone, is an important processed type of limestone suitable for many industrial purposes. Its manufacture and uses are briefly described in the section of this bulletin on the uses of limestone.

PRODUCTION AND CONSUMPTION

The tonnage of limestone and dolomite produced in the United States exceeds the tonnage of every other mineral product except sand and gravel and fuels (coal and petroleum). According to the U.S. Bureau of Mines, the United States production of carbonate materials from 1960 through 1963 was as shown in Table 2.

TABLE 2.—Amount and value of calcium carbonate and magnesium carbonate sold or used by producers in the United States 1/

Product	Year	Short tons	Value
Limestone and dolomite	1960	451,253,000	$623,437,000
	1961	438,253,000	608,139,000
	1962	461,849,000	649,647,000
	1963	489,243,000	680,000,000
Shell 2/	1960	18,934,000	33,706,000
	1961	18,004,000	30,375,000
	1962	20,054,000	31,241,000
	1963	19,019,000	29,420,000
"Marble"	1960	1,644,000	31,060,000
	1961	1,592,000	30,960,000
	1962	1,769,000	33,117,000
	1963	1,902,000	34,567,000
Calcareous marl 3/	1960	1,283,000	1,353,000
	1961	1,099,000	987,000
	1962	1,182,000	1,011,000
	1963	1,164,000	989,000

1/ Source: U.S. Bureau of Mines Minerals Yearbooks, 1961 - 1963.
2/ Used for concrete and road material, cement, lime, poultry grit, mineral food, agriculture, asphalt filler, whiting, and other uses.
3/ Used for agriculture, mineral food, and cement.

The major uses and tonnage and value of crushed and broken limestone and dolomite are shown in Table 3.

TABLE 3.—Amount and value of limestone and dolomite (crushed and broken stone) sold or used by producers in the United States [1]

Use	1961		1962		1963	
	Short tons	Value	Short tons	Value	Short tons	Value
Concrete and roadstone	258,997,000	$338,798,000	276,878,000	$365,098,000	292,976,000	$380,893,000
Cement, portland and natural	79,779,000	85,883,000	83,318,000	92,886,000	86,842,000	92,646,000
Agriculture	22,196,000	38,478,000	23,029,000	39,348,000	25,956,000	44,195,000
Flux	27,198,000	39,725,000	26,081,000	36,821,000	27,185,000	30,322,000
Lime and dead-burned dolomite	18,124,000	28,283,000	19,356,000	32,959,000	21,450,000	36,024,000
Riprap	9,138,000	10,440,000	10,016,000	12,253,000	10,690,000	13,229,000
Limestone whiting [2]	802,000	9,242,000	838,000	9,639,000	785,000	9,298,000
Filler (not whiting substitute)						
Asphalt	2,130,000	5,408,000	3,208,000	6,955,000	1,994,000	5,012,000
Fertilizer	438,000	1,080,000	448,000	1,132,000	457,000	1,133,000
Other	219,000	873,000	351,000	1,567,000	419,000	1,921,000
Filtration	148,000	221,000	79,000	141,000	62,000	117,000
Railroad ballast	4,260,000	5,376,000	5,065,000	6,578,000	4,923,000	6,410,000
Glass manufacture	1,211,000	3,736,000	1,337,000	4,294,000	1,492,000	4,781,000
Mineral food	695,000	3,723,000	692,000	3,847,000	618,000	3,793,000
Alkali manufacture	2,560,000	2,078,000	2,840,000	3,188,000	2,955,000	3,282,000
Limestone sand	1,693,000	2,596,000	1,706,000	3,103,000	1,759,000	3,234,000
Coal mine dusting	372,000	1,527,000	400,000	1,667,000	539,000	2,268,000
Sugar refining	882,000	2,215,000	623,000	1,506,000	646,000	1,580,000
Poultry grit	153,000	1,185,000	161,000	1,333,000	160,000	1,342,000
Paper manufacture	400,000	1,129,000	271,000	821,000	358,000	1,099,000
Calcium carbide manufacture	764,000	785,000	(included with "Other uses")		(included with "Other uses")	
Refractory (dolomite)	235,000	465,000	322,000	563,000	769,000	1,297,000
Fill material	266,000	277,000	440,000	330,000	383,000	296,000
Other uses [3]	2,838,000	4,603,000	1,741,000	4,253,000	2,125,000	5,472,000
Use unspecified	1,900,000	2,475,000	1,753,000	2,518,000	2,805,000	3,282,000
Total	437,398,000	$591,401,000	460,953,000	$632,800,000	488,348,000	$661,926,000

1/ Source: U.S. Bureau of Mines Minerals Yearbooks, 1962, 1963.

2/ Includes stone for filler for abrasives, calcimine, calking compounds, ceramics, chewing gum, fabrics, floor coverings, insecticides, leather goods, paint, paper, phonograph records, plastics, pottery, putty, roofing, rubber for wire coating, and unspecified uses. Excludes whiting made by companies from purchased stone.

3/ Includes stone for acid neutralization, calcium carbide (1962 and 1963), cast stone, chemicals (unspecified), concrete products, disinfectant and animal sanitation, electrical products, magnesia, magnesite, magnesium, mineral wool, oil-well drilling, patching plaster, rice milling, road base, roofing granules, stucco, terrazzo, and water treatment.

TABLE 4. — Limestone sold or used by producers in Washington, 1917-1963[1]

(In short tons)

Year	Cement manufacture	Lime manufacture	Riprap	Concrete and roadstone	Fluxing stone	Sugar refining	Glass manufacture	Paper manufacture	Agricultural stone	Other uses	Total
1917	--------	--------	--------	--------	44,045	--------	--------	2/	2,764	--------	3/ 46,809
1918	--------	--------	--------	--------	67,418	2/	--------	2/	641	102	3/ 68,161
1919	--------	--------	--------	--------	7,966	2/	2/	2/	2/	2/	23,750
1920	--------	--------	--------	--------	74,780	2/	--------	2/	2/	2/	103,280
1921	--------	--------	--------	--------	3,230	2/	--------	2/	2/	2/	25,480
1922	--------	--------	--------	--------	19,950	--------	--------	17,260	2/	2/	40,380
1923	--------	--------	--------	2/	31,210	--------	--------	10,910	2/	2/	53,540
1924	--------	--------	--------	--------	22,540	2/	--------	2/	2/	2/	46,420
1925	--------	--------	2/	--------	23,490	2/	2/	2/	2/	2/	44,280
1926	--------	--------	--------	2/	28,370	--------	--------	24,990	2/	2/	67,940
1927	--------	--------	--------	--------	24,970	--------	--------	30,540	2/	2/	57,630
1928	--------	--------	2/	--------	18,480	2/	--------	39,320	2/	2/	61,030
1929	--------	--------	--------	--------	18,790	1,000	9,000	44,450	362	1,840	75,440
1930	--------	--------	--------	1,000	21,900	2/	--------	92,210	2,000	970	119,140
1931	--------	--------	40,000	--------	18,770	1,430	--------	68,110	1,320	1,970	131,600
1932	--------	--------	--------	37,200	2/	520	--------	55,750	2/	1,660	112,610
1933	--------	--------	--------	30,820	14,260	2,410	85	39,880	355	1,330	89,150
1934	--------	--------	--------	59,410	2/	--------	2/	75,430	2/	2/	162,040
1935	--------	--------	--------	2/	2/	2/	--------	48,260	1,510	420	123,340
1936	--------	--------	--------	161,660	2/	--------	--------	--------	--------	2/	264,160
1937	--------	--------	310	165,860	67,640	59	--------	120,830	1,799	162	356,660
1938	--------	--------	--------	137,210	45,409	--------	--------	66,086	1,284	121	250,110
1939	--------	--------	--------	--------	23,915	--------	--------	104,155	1,390	200	129,660
1940	--------	--------	--------	--------	20,325	--------	--------	126,575	9,097	1,043	157,040
1941	--------	--------	--------	--------	5,883	--------	--------	153,140	11,650	1,297	171,970
1942	--------	--------	--------	3,260	4,720	--------	40	131,160	13,960	2,747	155,890
1943	--------	--------	--------	--------	7,560	--------	--------	133,946	17,610	4/133,200	292,320
1944	--------	--------	--------	1,760	6,060	--------	1,712	115,855	19,660	2,317	147,360
1945	--------	--------	--------	760	3,020	--------	2,012	121,621	21,630	5,307	154,350
1946	--------	--------	--------	775	938	--------	2,464	99,469	13,595	15,159	132,400
1947	--------	--------	--------	690	3,041	--------	2,325	124,863	29,930	1,146	162,000
1948	--------	--------	--------	60	4,885	--------	2,330	135,600	16,830	2,974	162,680
1949	--------	--------	--------	--------	8,900	--------	2,300	85,395	24,750	16,435	137,780
1950	--------	--------	--------	80	5,225	--------	2,773	109,950	24,260	12,046	154,330
1951	--------	--------	--------	62,513	4,540	--------	3,600	110,519	50,916	20,870	252,958
1952	--------	--------	9,271	153	3,153	--------	3,600	99,005	78,000	4,718	197,900
1953	--------	--------	--------	630	16,500	--------	4,400	81,680	68,155	4,360	175,725
1954	5/1,303,478	5/17,740	--------	21,097	7,739	--------	--------	83,333	33,615	4,640	1,471,642
1955	1,288,437	18,168	--------	10,135	1,727	--------	--------	76,269	25,603	5,175	1,425,514
1956	1,165,346	22,288	--------	--------	402	--------	--------	62,429	9,395	4,688	1,264,548
1957	836,399	--------	--------	46,244	359	--------	--------	10,515	3,026	4,411	900,954
1958	1,002,906	--------	--------	32,569	60,110	--------	--------	10,890	1,900	6,069	1,114,444
1959	1,215,149	--------	--------	117,797	45,171	--------	--------	11,874	862	4,137	1,394,990
1960	6/	--------	--------	--------	6/	--------	--------	6/	6/	6/	1,225,398
1961	1,099,824	--------	--------	--------	6/	--------	--------	11,995	6/	4,865	1,169,771
1962	1,095,896	--------	--------	--------	41,228	--------	--------	14,240	13,751	5,003	1,115,142
1963	1,089,357	--------	--------	--------	6/	--------	--------	6/	15,299	2,408	1,157,575

1/ Data compiled by U.S. Bureau of Mines, Albany, Oregon.

2/ Not available, data missing from microfilm.

3/ Incomplete total.

4/ Includes tonnage of high-magnesium limestone used to manufacture magnesium metal at Mead, Washington.

5/ Data for cement and lime not available for years prior to 1954.

6/ Figures concealed to avoid disclosing individual company data.

Production and consumption details of some of the major uses of limestone are as shown in Tables 5 to 8.

TABLE 5.—Lime production in the United States and apparent consumption in Washington 1/

Year	Lime produced in the United States (short tons)	Imported (short tons)	Exported (short tons)	Average unit value per ton at plant
1959	12,500,000	35,000	53,000	$13.11
1960	12,935,000	32,000	61,000	13.35
1961	13,249,000	37,000	30,000	13.39
1962	13,753,000	78,000	20,000	13.58
1963 (est.)	14,800,000	80,000	20,000	13.60

Apparent consumption of lime (primary and regenerated) sold and used in Washington 2/

Year	Quicklime (short tons)	Hydrated lime (short tons)	Total (short tons)
1961	330,697	120,314	451,011
1962	346,869	127,172	474,041

1/ Source: U.S. Bureau of Mines Minerals Yearbooks.
2/ In 1962, a total of 17,012 tons of lime was imported into Washington from Canada.

TABLE 6.—Portland cement production and capacity 1/

Year	Production in barrels (one barrel = 376 pounds)		Washington and Oregon capacity (barrels)	Washington and Oregon capacity utilized (percent)
	United States	Washington and Oregon		
1959	350,419,000	8,081,000	10,925,000	74.0
1960	328,715,000	8,244,000	11,025,000	74.8
1961	332,558,000	7,413,000	11,025,000	67.2
1962	345,567,000	7,191,000	2/ 11,190,000	64.3
1963	361,235,000	7,799,000	10,750,000	72.5

1/ Source: U.S. Bureau of Mines Minerals Yearbooks.
2/ 7,485,000 barrels for Washington only.

TABLE 7.—Lime materials used (short tons) in Washington for agriculture [1]

Type	1955	1956	1957	1958
Ground limestone ----	12,222	20,745	10,367	5,080
Marl lime ----------	2,028	315	134	------
Dolomitic limestone --	128	242	65	104
Hydrated limestone ---	219	1,300	678	103
Miscellaneous -------	87	------	------	------
Total materials	14,684	22,602	11,244	5,287

1/ Source: Washington State Department of Agriculture.

Table 8, prepared by the Business and Economic Research Division of the Washington State Department of Commerce and Economic Development, shows the consumption of lime and of limestone by major consuming industries in Washington in 1959. The table also shows the proportion of the limestone produced within the State to that consumed within the State.

TABLE 8.—Lime and limestone consumption per industry in Washington in 1959 [1]

Industry	Lime consumption in Washington (all imported in 1959) (short tons)	Limestone consumed in Washington				Total (short tons)
		Imported		Produced in Washington		
		(short tons)	(percent)	(short tons)	(percent)	
Pulp and paper ---	44,014	134,174	84	25,200	16	159,374
Steel alloy and chemical	2,940	42,170	99	87	1	42,257
Portland cement --	------	150,000	11	1,206,000	89	1,356,000
Agriculture ------	7,093	12,138	60	8,000	40	20,138
Other ----------	675	156,100	51	152,015	49	308,115
Total	54,722	494,582	26	1,391,302	74	1,885,884

1/ Source: Washington Department of Commerce and Economic Development.

The figures in Table 8 illustrate to what extent the limestone-consuming industries of the State, except the cement industry, are dependent upon sources of limestone outside the State. Sixty-five percent of all limestone used in Washington, excluding that used in portland cement, is quarried outside the State. The situation is even more critical when we look at the figures for high-calcium limestone, such as is used by the pulp and paper, steel, and chemical industries. Only an average of 13 percent of the limestone used by these industries is produced within the State. When we consider the additional limestone required to make the lime for use in the pulp and paper industry, the State's production contribution to the needs of the high-calcium limestone (and lime) consumers in the State is only 9 percent.

Unfortunately, no large deposits of high-calcium limestone are known in western Washington that are located close enough to industrial users to alleviate the situation for this part of the State. The lime plant established in Tacoma in 1963 uses high-calcium limestone imported from Texada Island, British Columbia, and the Ideal Cement Company's proposed new plant in Seattle will also use limestone from Texada Island.

TABLE 9. — Operating limestone quarries in western Washington in 1964

Name of operation	Product	Quarry location
Everett Lime Company Gordon C. Clauson 1928 Milford Way Seattle, Wash.	Limestone for pulp rock	San Juan County Orcas Island McGraw-Kittinger quarry NW¼ sec. 2, (36-2W) Red Cross quarry SE¼ sec. 20, (35-2W)
Ideal Cement Company Northwestern Division 1320 Washington Bldg. Seattle Wash.	Limestone for portland cement	Chelan County Soda Springs quarry 1/ N½ sec. 10, (27-15E)
Lone Star Cement Corp. Superior Division 3801 E. Marginal Way S. Seattle, Wash.	Limestone for portland cement	Skagit County Concrete quarry Sec. 2, (35-8E)
Miller Lime Company Leslie B. Miller P. O. Box 166 Gold Bar, Wash.	Limestone (ground or crushed), agricultural stone Limestone for flux and landscaping	Snohomish County Goldbar area Haystack quarry SE¼ sec. 15, (27-9E) Canyon Creek quarry NE. of Granite Falls SE¼NE¼ sec. 5, (30-7E)
Mitchell Bay Lime Company Gordon C. Clauson 1928 Milford Way Seattle, Wash.	Limestone for pulp rock	Whatcom County North of Maple Falls Silver Lake quarry SW¼ sec. 7, (40-6E) Doaks Creek quarry W½ sec. 19, (40-6E)
Permanente Cement Company Olympic Division P. O. Box 17 Bellingham, Wash.	Limestone for portland cement	Whatcom County Red Mountain north of Kendall Kendall quarry Secs. 8, 14, 15, 16, 17, 21, 22, 23, 27, (40-5E)
Scheel Stone, Inc. 3314 Harbor Ave. S.W. Seattle, Wash. 98106	"Travertine" (tufa) for landscape rock	Skagit County S½ sec. 4, (35-8E)
Western Lime Company John Koetje 621 W. Division St. Mount Vernon, Wash.	Limestone for agricultural stone (ground or crushed)	Snohomish County Arlington area Bryant quarry NW¼ sec. 7, (32-6E)
Property under current development but not in production:		
Cascade Calcium, Inc. Dr. Glen E. Deer, Pres. 1717 Market St. Seattle, Washington		Chelan County Secs. 21, 22, 27, (26-18E)

1/ Soda Springs quarry closed in 1964.

Table 10 lists some of the principal consumers of limestone in Washington and gives consumption and specifications as of 1958 unless noted otherwise.

TABLE 10. — Limestone consumption in Washington in 1958[1]

Industry	Company	Capacity	Consumption (tons per month)	Specifications
Pulp and paper	Scott Paper Co. Everett		2,100	97% $CaCO_3$
	Crown Zellerbach Corp. Port Angeles		2,170	+90% $CaCO_3$, -8% $MgCO_3$
	Weyerhaeuser Timber Co. Everett		1,710	+96% $CaCO_3$, -1.5% MgO
	Inland Empire Paper Co. Millwood		150	98% $CaCO_3$, 1.2% SiO_2
	Columbia River Paper Mills Vancouver		70	-------------------------
Metallurgy	American Smelting and Refining Co., Tacoma		1,800	minus 5-in. size
Sugar	Utah-Idaho Sugar Co. Toppenish and Soap Lake		12,660	97% $CaCO_3$, $2\frac{1}{2}$-in. to $4\frac{1}{2}$-in. size
Lime	Pacific Lime Inc.[2] Tacoma	250 tons/day		+97.5% $CaCO_3$
Cement	Ideal Cement Co. Grotto	[3] 625,000 bbls./yr.		+90% $CaCO_3$, -2.5% MgO
	Ideal Cement Co. Spokane	[3] 700,000 bbls./yr.		+90% $CaCO_3$, -2.5% MgO
	Permanente Cement Co.[4] Bellingham	[3] 1,900,000 bbls./yr.		85% $CaCO_3$
	Lone Star Cement Corp. Concrete	[3] 1,700,000 bbls./yr.		-------------------------
	Lone Star Cement Corp. Seattle	[3] 1,300,000 bbls./yr.		-------------------------
	Lehigh Portland Cement Co., Metaline Falls	[3] 1,260,000 bbls./yr.		-------------------------
Other	Pacific Northwest Alloys, Inc., Spokane		1,350	+94% $CaCO_3$, -5% SiO_2, -.02% P
	Northwestern Glass Co. Seattle		400	55.5% CaO, -.05% Fe
	Reichhold Chemicals Inc., Tacoma		150	97-98% $CaCO_3$, 5-in. to $\frac{1}{2}$-in. size

[1] Table is incomplete. Data not available for some consumers.
[2] Established 1963.
[3] Capacity data for 1962.
[4] In 1958 was The Olympic Portland Cement Company, Ltd.

List of Washington manufacturers using limestone

Cement

Ideal Cement Co.
Northwestern Division
1320 Washington Bldg.
Seattle, Wash. 98101

Lehigh Portland Cement Co.
Metaline Falls, Wash. 99153

Lone Star Cement Corp.
Superior Division
3801 E. Marginal Way S.
Seattle, Wash. 98134

Permanente Cement Co.
Olympic Division
P. O. Box 17
Bellingham, Wash. 98225

Fertilizer

Agriform Co. of Washington
Bldg. 63, Navy Base
Pasco, Wash. 99301

The Chas. H. Lilly Co.
1900 Alaskan Way
Seattle, Wash. 98101

Northwest Processing Co.
1953 South C St.
Tacoma, Wash. 98402

Oregon-Washington Fertilizer Co.
2218 Airport Way
Seattle, Wash. 98134

Stauffer Chemical Co.
2545 Lincoln Ave. E.
Tacoma, Wash. 98421

Smelters

American Smelting and Refining Co.
Box 1605
Tacoma, Wash. 98401

Sugar (beet)

Utah-Idaho Sugar Co.
Box 126
Moses Lake, Wash. 98837
(Quicklime)

Utah-Idaho Sugar Co.
Box 752
Toppenish, Wash. 98948
(Hydrated lime)

Paper and pulp

Boise Cascade Corp.
Columbia River Paper Co. division
414 W. Fifth
Vancouver, Wash. 98661

Crown Zellerbach Corp.
Camas, Wash. 98607

Crown Zellerbach Corp.
Box 575
Port Townsend, Wash. 98368

Everett Pulp and Paper Co.
Lowell, Wash. 98203

Fibreboard Paper Products Corp.
1313 Marine Drive
Port Angeles, Wash. 98362

Georgia-Pacific Corp.
Puget Sound Pulp Division
Bellingham, Wash. 98225

Inland Empire Paper Co.
Millwood, Wash. 99212

Longview Fibre Co.
Box 1019
Longview, Wash. 98632

Portco Corp.
Paper, Plastics and Pipe Div.
4200 Columbia Way
Vancouver, Wash. 98661

Rayonier, Inc.
Grays Harbor Division
Hoquiam, Wash. 98550

Scott Paper Co.
West Coast Division
2600 Blk. Federal
Everett, Wash. 98201

St. Regis Paper Co.
801 Canal St.
Tacoma, Wash. 98421

Weyerhaeuser Timber Co.
Pulp and Paperboard Div.
Everett, Wash. 98201

Lime

Pacific Lime Co.
1220 Alexander Ave.
Tacoma, Wash. 98106

Limestone (crushed, ground, or powdered)

Manufacturers Mineral Co.
1107 Southwest Idaho St.
Seattle, Wash. 98106

Miller Lime Co.
P. O. Box 166
Gold Bar, Wash. 98251

Western Lime Co.
621 W. Division St.
Mount Vernon, Wash. 98273

Chemicals and alloys

Reichold Chemicals Inc.
2340 Taylor Way
Tacoma, Wash. 98401

Glass

Northwestern Glass Co.
5801 E. Marginal Way S.
Seattle, Wash. 98134

Landscape stone

Scheel Stone Inc.
3314 Harbor Ave. S.W.
Seattle, Wash. 98126

Terrazzo chips

Manufacturers Mineral Co.
1107 Southwest Idaho St.
Seattle, Wash. 98106

North American Non-Metallics, Ltd.
P. O. Box 227
Valley, Wash. 99181

Northwest Marble Products Co.
Ernest Smith
Chewelah, Wash. 99109

Peter Janni & Sons
Box 333
Northport, Wash. 99157

USES

Limestone has a wide variety of uses. It and its calcined products are materials essential to every industrial and agricultural community. No other material is so widely used and so necessary in electrochemical and electrometallurgical industries. In point of tonnage consumed it ranks third only to the mineral fuels and sand and gravel. In many industries only small amounts of it are used, and yet it is essential to their existence.

Much of the information on the uses of limestone given below has been obtained from Lamar (1959, 1961), Bowles (1956, 1958), Hewitt (1960), Bowles and Jensen (1947a and 1947b), Mills (1962), and Mathews and McCammon (1957), but many other sources also have been consulted and are given in the list of references on page 468. Specifications and information on qualities needed for particular industries can best be obtained from the industries concerned, as the requirements often differ in detail. However, the general requirements for different products are described under their uses in the following paragraphs and are listed in Tables 10 and 11 on pages 38 and 55. Descriptions of physical and chemical tests are given in American Society for Testing Materials Standards and other technical publications, such as those of the American Association of State Highway Officials, American Railway Engineers Association, National Lime Association, and the specification lists of the Federal Government.

The uses of limestone may be divided into two classes: those requiring particular physical properties and those requiring a particular chemical composition. However, some uses are dependent upon both physical and chemical properties of various types.

Physical uses include those for which such properties as weather resistance, wear resistance, color, hardness, strength, soundness, density, porosity and permeability, water absorption, coefficient of expansion, and freedom from fractures are involved. Rock with the proper requirements or combination of requirements from the list above might be used for riprap, building stone, decorative stone, aggregate for portland cement concrete, road gravel, filter beds of sewage disposal plants, limestone sands, rock dust for coal mines, poultry grit, filler for asphalt, road base, stucco, terrazzo chips and artificial stone, fill materials, "blacktop" chips and aggregate for bituminous concrete, and railroad ballast. Because of the relative scarcity of limestone and the greater availability of a wide variety of other rock types commonly more suitable and more economical to obtain, limestone is not in much demand for any of the above uses in western Washington. The color and appearance of some limestone may make it attractive for landscaping and for use in rock gardens, where by very slow solution it may be beneficial to the surrounding vegetation.

Chemical uses include those in which the chemical composition is most important, and certain specifications are required regarding the percentages of calcium carbonate, magnesium carbonate, iron oxide, silica, aluminum oxide, alkali, phosphorus, or other elements or compounds. Typical chemical uses are in cement, lime, agricultural limestone, alkali manufacture, calcium carbide manufacture, fertilizer, fluxing stone, glass manufacture, sugar refining, acid neutralization, and carbon dioxide manufacture.

In western Washington the largest amount of limestone is used in the manufacture of portland cement. Pulp rock and agricultural stone are used to a lesser extent, and until 1956 the manufacture of lime was an important use of local limestone. After the shutting down of the Roche Harbor operation, all lime used in western Washington had to be imported until the recent establishment of a lime plant in Tacoma by Pacific Lime Company, Inc., using limestone imported from Blubber Bay, Texada Island, British Columbia. Other uses of limestone in western Washington are minor compared with those listed above.

Much limestone contains deleterious materials, textures, and structures that cause trouble when it is used for specific purposes, and a petrographic examination of commercial stone samples by a competent geologist-petrographer is of primary importance in assessing its value. Among deleterious materials that might be noted (Hewitt, 1960) are clay, shale, shaly limestone, dolomite, iron oxides or other weathering products, chert and other forms of silica, schists, secondary micaceous minerals, coated particles, sulfides, sulfates and water soluble minerals, glauconite, zeolites, and organic matter. Reactive materials, such as montmorillonite clay, the amorphous varieties of silica, opal and opaline chert, and chalcedonic chert, may cause serious swelling and failure of concrete if limestone or dolomite containing them even in small amounts is used as an aggregate material.

REQUIREMENTS FOR PHYSICAL USES

Limestone for concrete aggregate, railroad ballast, chips for blacktop roads, stucco, roofing granules, terrazzo and artificial stone, roadstone, limestone sand, and road base should be sound hard stone. Soft, crumbly, or lightweight stone, or stone containing interbedded sediments such as shale or clay, is not likely to be satisfactory. The size and shape of the particles are also important, and the amount of jointing and the interval between bedding planes often determine the gradation of rock sizes upon crushing.

Roadstone and Aggregate

In concrete aggregate it is undesirable to have flat or elongate particles. Alkalies and organic matter are usually objectionable, and soluble sulfides are prohibitive because they oxidize and the sulfuric acid formed will attack calcareous materials that may be present and form gypsum, which expands during crystallization and disrupts concrete (Bowles, 1956).

The surface texture and porosity of an aggregate are of importance in bituminous construction, because they affect the adhesion of the bituminous coating and the amount of asphalt required. Stripping tests are often necessary.

Stone of various sizes ranging from 3-inch to dust is used in road construction. The principal types of application are waterbound macadam, graded aggregate base course, bituminous macadam, bituminous plant mixes, bituminous surface treatment, and portland cement concrete. Roadstone should break into sharply angular, chunky fragments that, when properly graded for size, will interlock and press firmly into the surface of the road. Limestone, if abundant, makes a good base-course material for roadbuilding. However, exclusive use of limestone dust or limestone aggregates may, for the surfacing of a road, give rise to a low coefficient of friction, as the limestone polishes more easily under tire wear than many other rocks and will result in a slippery road surface.

Abrasion tests such as the Deval and the Los Angeles, in which samples are placed in iron or steel cylinders and rotated with or without steel balls to determine loss by wear, are needed to check on the wearing properties of limestone. Another test is the sodium sulfate test, in which the loss by disintegration of the rock under hydration and expansion of the salt absorbed in the pores is measured. This test usually is repeated five times, or in other words, five cycles are run on a given sample before results are checked. For filter beds for sewage disposal, the test is repeated 20 times.

Stucco, Terrazzo, Roofing Gravel, and Surfacing Chips

A uniform and desirable color such as white, brown, pink, green, or black is preferred for limestone chips used for stucco, terrazzo, and artificial stone. Durability, hardness, ability to take a good polish, and low liquid absorption also are desirable in terrazzo chips (Bowen, 1957). Some of the white limestones of Chelan County may be suitable for this use. The major source in the State of limestone currently used for this purpose is in the vicinity of Valley and Chewelah in Stevens County.

Screened limestone chips are sold as gravel to be used with tar for coating flat roofs. For this purpose color is not too important, and the common gray limestones of western Washington are suitable.

Limestone screenings without a binder afford good surfaces for schoolyards, playgrounds, walkways, tennis courts, etc. Limestone screenings can also be used as aggregate in manufacture of concrete blocks, and limestone chips may be embedded in the surface to make the blocks resemble cut stone.

Veneering, Flagstone, and Dimension Stone

Stone used for building veneering and for flagstones should have a pleasing color and good weather resistance. The type of bedding of the deposit influences the ease of working the stone for these uses. Decorative stone includes crystalline limestone, limestone conglomerate and breccia, and fossiliferous limestone, and is used especially for interior decoration. A thick-bedded stone, commonly in layers 4 or more feet thick, with pleasing color or combinations of color and textural pattern, is most desirable.

Dimension limestone is used principally for building. Blocks that are cut to specified dimensions and surface tooled are known as cut stone. The term "ashlar" is applied to small rectangular blocks. Small rough-surfaced blocks, and strips broken in irregular lengths with unworked surfaces are usually included in a class known as house-stone veneer. Rough building stone consists of faced masses of various shapes and sizes. This stone is commonly used in residential construction for chimneys, basements, walls, bridges, fences, and the more ornamental types of retaining walls.

Requirements for dimension stone may be very exacting. Deposits with irregular or close-spaced joints are unsuitable; large blocks free from cracks or lines of weakness are required. The limestone must be compact, easily workable, uniformly textured, and attractively colored. Purity is not as rigid a requirement as for other uses, but impurities such as silica may make a stone difficult to work, and iron sulfides such as pyrite or marcasite may cause stains on surfaces that have been exposed to weathering.

Fill Stone

Fill material may be waste limestone, usually from a nearby source, and is used to make road fills and the like. Many logging roads in western Washington have had loads of limestone fragments, obtained from abandoned quarries, dumped in muddy or soft places in the roadbed. No particular physical or chemical properties are involved in this use, and it is usually the availability of broken rock nearby that determines what will be used.

Railroad Ballast

Large quantities of limestone are used in other parts of the United States by railroad companies for maintaining roadbeds. A minimum of 3/4 inch and a maximum of $2\frac{1}{2}$ inches for ballast sizes has been widely used, but lately there has been a trend toward the use of smaller sizes. The requirements as to quality are generally the same as for aggregate and roadstone. Limestone has been used for railroad ballast only locally in western Washington, as it is not abundant enough for this purpose.

Asphalt Filler

Limestone dust, approximately 80 percent of which will pass a 200-mesh screen, is used as a filler in road asphalt surface mixtures.

Riprap

Riprap consists of heavy irregular blocks used chiefly for river and harbor work, such as spillways at dams, shore protection, and docks. It is a low-priced product and is usually procured from nearby quarries. Any type of dense, sound limestone can be used; there are no general specifications, except for requirements as to minimum size of stones that will be adequate. The scarcity of limestone in western Washington has prevented its use for this purpose except locally. In the San Juan Islands it has been used for docks and shore protection, and on the mainland it has been placed on river banks to prevent erosion.

Coal-Mine Dusting

Limestone dust is particularly satisfactory for use as a fine incombustible dust for distribution throughout a bituminous coal mine as a means of preventing or checking coal-dust explosions. Rock dusts must contain not more than 5 percent of free and combined silica nor more than 5 percent combustible material, and they must be ground so that 100 percent will pass through a 20-mesh screen and 70 percent or more will pass through a 200-mesh screen. A white dust, readily discernible, is most satisfactory.

Sewage Filter Beds

Crushed limestone, strong and compact, with pore space evenly distributed, either high in calcium or dolomitic, and free from impurities such as pyrite, marcasite, and clay is suitable for this purpose. Siliceous impurities are not objectionable if they are fine grained and evenly distributed. The fragments should be rough to provide anchorage for bacteria, and fines and dirt should be screened out.

Poultry Grit

Almost any type of limestone crushed to granules and screened to uniform sizes is sold for poultry grit. The products may be graded by sizes into turkey grit, chicken grit, pigeon grit, and bird grit. A small amount of western Washington limestone has been used for this purpose and is especially suitable because of the relatively low calcium content of western Washington soils. The fluorine content should not exceed 0.1 percent.

Sand

Limestone crushed to the size of sand grains, when carefully washed and graded, may be substituted for silica sand in mortar, wall plaster, and concrete.

Whiting and Whiting Substitutes

Whiting is a pulverized, purified, and carefully sized chalk. Very little true chalk has been produced in the United States, and none occurs in Washington. Whiting substitutes consist of finely ground limestone or dolomite, ground crystalline limestone, white marl, and chemically precipitated calcium carbonate. True whiting is preferred for calcimine, cold-water paints, and putty. True whiting and substitute materials are used as ceramic raw materials, and as fillers in products such as rubber, paint, paper, oilcloth, window shades, linoleum, and putty. Other products in which whiting or substitutes are used include clacimine, pottery, crayons, dyes, fabrics, plastics, phonograph records, dentifrices, chewing gum, baking powder, tanning compounds, abrasives, shoe dressings, explosives, medicine, foundry compounds, white ink, wire coatings, chemicals, glue, grease, animal nutrients, flooring, cooking compounds, insecticides, cosmetics, flavoring extracts, sealing wax, chocolate, cocoa, fruit juices, and other food products.

The desirable characteristics of high-grade whiting are: good white color, fine particle size, freedom from grit, and chemical purity. Color is of utmost importance for virtually all applications. Limestone suitable for the manufacture of ceramic whiting is limited to a minimum of 96 percent $CaCO_3$, a maximum of 1 percent $MgCO_3$ (0.5 percent MgO), 2 percent SiO_2, 0.25 percent Fe_2O_3, and 0.1 percent SO_3.

Ornamental Stone

Sometimes crystalline, dense, and banded limestones are sculptured into art objects or used for tombstones, tables, mantles, and monuments of various sorts. Many western Washington limestones lend themselves to this use. In recent years, people have used rough limestone and polished limestone blocks for indoor fireplaces and walls. The rapidly growing lapidary hobby has resulted in increasing popularity for ornamental stones. The limestone table and chairs of the McMillan Mausoleum at Roche Harbor, San Juan County, is an interesting example of ornamental use. No large deposits of the highly decorative limestone onyx or travertine are known in western Washington, but occasionally specimens are found and polished by collectors. The porous calcareous tufas found in several places can be used for rock gardens and walls but are not suitable for polishing. It is possible that worked and unworked limestone of this kind for ornamental purposes could become the basis of a profitable business in this area, but at present it is mainly a hobby activity.

Marble

The term "marble" is derived from a Greek word meaning to sparkle or flash, because the calcite crystals in marble sparkle as they reflect light (Bowles 1958). In its geologic sense, the term is often applied to rocks comprising crystallized grains of calcite and (or) dolomite. Commercially, the word has a much wider use. As the ability to take a polish is the chief commercial asset of marble, all calcareous rocks that can be polished are commercially classed as marbles. Furthermore, serpentine rocks that are attractive in color and pattern and can be polished are classed as marbles, although they may contain little calcium or magnesium carbonates.

Commercial marbles may be divided into three groups: The first, which includes most rocks referred to as marble, comprises limestones that have been recrystallized by heat and pressure, accompanied by extensive deformation. Also included are subcrystalline limestones that have been subjected to less extreme metamorphism and that may contain fossils almost intact. Many subcrystalline marbles seem to have been altered from limestone chiefly by circulating water or diagenetic processes, for they show no evidence of deformation or extreme pressure.

The second group comprises the onyx marbles. They may form at the surface from springs, or in caves in the form of stalactites, stalagmites, columns, or flowstone coatings. The cave variety is often referred to as "cave onyx."

True onyx is banded chalcedony—a form of quartz related to agate, flint, and chert. The calcareous rock was called onyx because its banding resembled that of the true onyx. To distinguish the calcareous from the siliceous varieties, the former should be called onyx marble if used in a commercial sense, and probably travertine would be the true geologic term. Near Oaxaca, Mexico, is the most important source of onyx in North America, and bookends, figurines, and decorative objects cut from it are sold all over the United States. In 1962 approximately 5,000 cubic feet of it was imported from Mexico and was valued at $29,428. It comes from cave deposits in volcanic rocks. Onyx in other parts of the world may be referred to as "Brazilian onyx," "Mexican jade," "Egyptian alabaster," "Gibraltar stone," and "Oriental alabaster."

The third type of marble comprises the verd antiques or green serpentines, which in places are associated with impure dolomitic limestone. They are not considered to be carbonate rocks.

Commercial marbles of the first type usually are more cohesive than ordinary limestones and thus resist abrasion better. Their cohesive hardness is therefore an important property, and where slabs of marble are exposed to foot traffic in floors and stairways they must wear evenly and be as resistant as possible. The rate of solubility of marble deserves careful consideration; it varies depending upon the chemical composition, texture, and permeability of the stone. The rate of solubility of a marble usually is extremely slow, but near large cities or industrial plants various acids in smoke are absorbed by rainwater and increase the dissolving rate. Marbles with low water absorption are best for exterior use.

The color of a marble is one of its most important physical properties. Marbles of almost pure calcite or dolomite may be white, black, buff, or bluish gray, whereas verd antique or serpentine marbles are usually green or yellow green. Bands or patterns of color are much sought after in marble and are caused by impurities present originally in the rock or added later during alteration or metamorphism.

Fine-grained marbles that are translucent are sought for ornamental stones. Translucence is the capacity of marble to transmit light, and the waxy appearance of some marbles, particularly the onyx marbles, seems to be related to it. The depth to which light will penetrate the best statuary marbles ranges from $\frac{1}{2}$ to $1\frac{1}{2}$ inches. Texture, rift or grain, porosity, strength, weight, and jointing are other properties of marble that must be examined to determine the value of the stone.

REQUIREMENTS FOR CHEMICAL USES

Lime

The information about lime discussed here is largely taken from Bowles (1952), U.S. Bureau of Mines Information Circular 7651. Lime or quicklime is defined as calcium oxide resulting from the heating of calcium carbonate to a temperature at which carbon dioxide is removed. One hundred pounds of pure calcium carbonate ($CaCO_3$) will yield 56 pounds of lime (CaO). Calcination of rocks rich in magnesium carbonate produces mixed oxides of calcium and magnesium that are also called lime.

Slaked or hydrated lime is calcium hydroxide [$Ca(OH)_2$] , formed by reaction between quicklime and water. Air-slaked lime results when either quicklime or hydrated lime is in contact with air for a considerable time. Moisture and carbon dioxide are absorbed during air-slaking, and a product that will not "set" may result.

Hydraulic lime results from calcination of limestone containing enough argillaceous matter to form a substance that will set under water.

Limes are classified according to their composition as follows:

High-calcium lime, containing not less than 90 percent calcium oxide and from 0 to 5 percent magnesia.

Low-magnesium lime, containing 5 to 25 percent magnesia.

Dolomitic or high-magnesium lime, containing 25 to 45 percent magnesia.

When properly burned and fresh from the kiln, lime should contain virtually no water and less than 0.5 percent carbon dioxide. When limestone is burned, about half the weight of the stone is lost as carbon dioxide. As a result, the proportion of original impurities is nearly doubled. Therefore, a chemical analysis of a limestone is a very good criterion of the grade and commercial utility of the lime it will produce. Commercial limes in the United States are chiefly high-calcium and dolomitic types, with analyses ranging from 0.05 to 2.5 percent magnesium oxide for the high-calcium types to as much as 35 to 40 percent magnesium oxide for the dolomitic varieties. Total impurities generally are under 5 percent.

Lump lime retains after calcination the same form as the lumps of limestone that were put into the kiln, but the porosity is increased greatly. However, some limestones may be so soft that they are broken by abrasion; at the time of burning their pores may be filled with water, which shatters the stone when heated; or their component crystals may be bound together by organic matter that is consumed in the kiln. Sometimes over 50 percent of the output of a kiln is finely divided lime, which is as good as lump lime for most purposes and is easier to handle.

In general, a shorter time and lower temperatures are required to burn a magnesian than a high-calcium stone. The greater the proportion of impurities, the more easily is the lime overburned. Too high a proportion of silica may cause "fire slaking," whereby the lime falls to pieces. If the limestone contains 2 percent or more of silica, it is usually unsuitable for making lime. Fine-grained dense stone can be burned at a lower temperature and for a shorter time than one that is coarsely crystalline and porous. Coarsely crystalline stone, especially if pure, is likely to fall to pieces in the kiln, reducing the size of lumps in the product. The fine-grained crystalline limestones are far better for lime manufacture than the coarser grained varieties.

The reactions of dolomitic lime and of high-calcium lime differ somewhat in the slaking process. A high-calcium quicklime expands greatly when water is added. Dolomitic lime slakes much more slowly, generates less heat, and expands less, which results in a correspondingly smaller volume yield. Other things being equal, the less magnesium oxide in a lime, the more quickly it slakes and the greater is the amount of heat generated.

The rate of hydration depends also on the porosity of the lime. In some limes the porosity seems to be a greater factor than the chemical composition; for instance, a very porous dolomitic lime may slake more quickly than a dense lime that has a much higher content of calcium oxide.

Impurities in the stone have various effects on the properties of lime. Small amounts of silica tend to decrease the plasticity, sand-carrying capacity, and yield of a lime but have no effect on its hardness or strength. The same may be said of iron, except that lime containing large amounts (25 percent iron) is much stronger and harder. Kaolin seems to act in a manner similar to silica and iron. Alumina increases all the factors previously mentioned and also improves the color. Gypsum is detrimental, even when only 1 percent is present.

Since the physical as well as the chemical properties of a stone influence the character of the lime produced, limestones of identical chemical composition may, under the same burning conditions, give limes that differ in character. Thus, to obtain rock for special grades of lime, stone must be carefully selected in the quarry. Where different beds are involved, each may have to be worked as an independent unit. In western Washington, even if the chemical composition is suitable for burning into lime, the actual stone must be burned to see what it will produce in the way of lime before it can be considered to be acceptable.

In the process of converting limestone into lime, the stone is brought into contact with a sufficiently high temperature long enough to dissociate the carbon dioxide and drive it off as gas. The quantity of heat required varies with the chemical and physical properties of the stone; small pieces of stone calcine more quickly than large ones; fine-grained stone conducts heat more readily than stone that is coarsely crystalline and porous. Experimental work (Johnson, 1910) has shown that the temperature of dissociation of calcium carbonate is 898°C (1,648°F) at atmospheric pressure. After the dissociation temperature has been reached, it must be maintained long enough to transfer the required amount of heat to the stone. To obtain a large output per kiln, a temperature of 1,050°C to more than 1,100°C commonly is used. Prompt removal of the carbon dioxide gas is essential to efficient calcination, because if the gas is allowed to accumulate, its pressure may reverse the reaction and

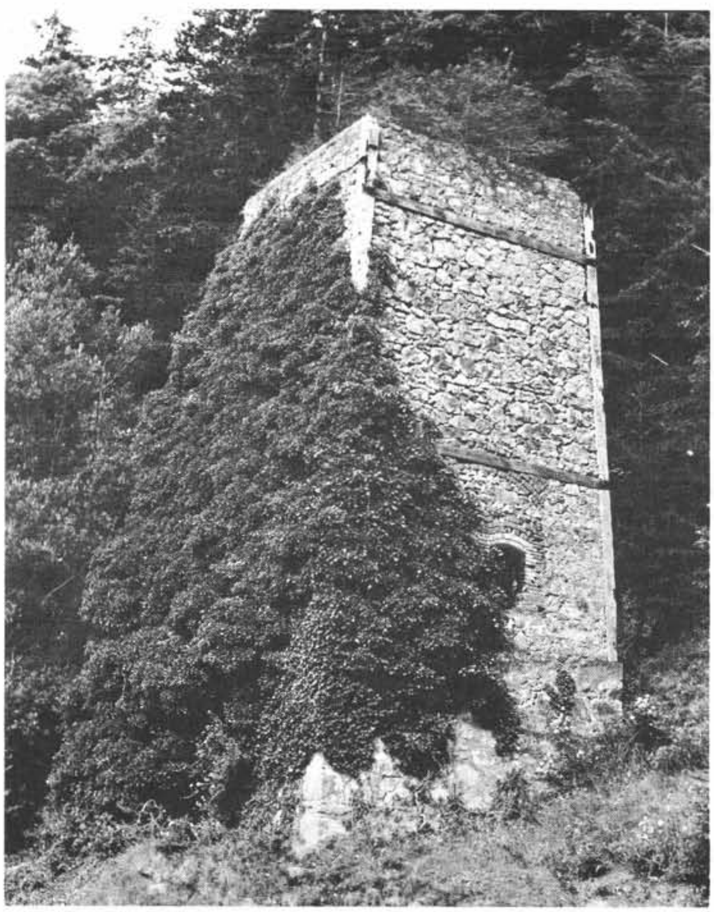

FIGURE 12.—Old limekiln, near shore of East Sound, north of Judd Cove, Orcas Island, San Juan County.

FIGURE 13.—Opening at base of limekiln for removal of lime. Cowell quarry, San Juan Island, San Juan County.

cause the lime to recarbonate. Shaft, or vertical kilns are most generally used for burning limestone, but the use of rotary kilns similar to those used in cement manufacture is increasing. Pot kilns, in which the stone and fuel are added in alternating layers, were used in many places on the San Juan Islands and on the mainland of western Washington, but none are operating at present (1964). The old stone kilns, most of which are in ruins, give evidence to a once small but flourishing lime industry. New types of calcining units such as the Nelson and the Ellernan, sintering machines, and use of the fluo-solids process have been tried in recent years in parts of the United States to improve the manufacture of lime. Recovery of the carbon dioxide gas at lime plants and recovery and reuse of lime in the paper-pulp industry, sugar beet industry, and other manufacturing processes have been attempted with varying degrees of success.

Quicklime, produced by the burning of limestone, is caustic and is unstable when exposed to air, making it difficult to handle. Consequently, most lime is sold in the hydrated form (calcium hydroxide), in which it is more stable and does not require special processing and handling equipment. The hydrated lime is produced by crushing the quicklime to minus 1-inch size and screening out the impurities, then placing it in shallow closed pans and introducing water. As the water is added, the pan is rotated and the bottom is continuously scraped until evolution of steam ceases and the contents become light and dry (Bowen, 1957).

Lime is used in a wide variety of products and industries, including agriculture, construction finishing lime, mason's lime, soil stabilization, masonry mortars, manufacture of alkali compounds, asphalts and other bitumens, sand-lime and slag brick, silica (refractory) brick, calcium carbide and cyanamide, gas purification, explosives, food and food byproducts, glass, glue, lubricating grease, insecticides, fungicides and disinfectants, medicine and drugs, steel and electric furnace flux, flotation, cyanidation of ores, bauxite purification, magnesium manufacture, metallurgical uses, wire drawing, oil drilling, paints, paper making, petrochemicals, petroleum refining, rubber manufacture, salt refining, sewage and waste treatment, soap and fats, sugar refining, leather tanning, water purification, wood distillation, and many more. Patterson (1960, p.463) reports that there are about 7,000 uses for lime. Generally, limestone suitable for making lime must contain at least 95 percent $CaCO_3$, and for most uses it must contain at least 97 percent $CaCO_3$.

In 1956 the Roche Harbor Lime and Cement Company sold out, and their lime plant was shut down due to exhaustion of the limestone quarries supplying it. No lime was produced in western Washington after this until 1963, when a plant of 250 tons per day capacity was erected in Tacoma by Dominion Tar and Chemical Co., Ltd. and its subsidary, Gypsum, Lime, and Alabastine Ltd. This new operation, known as Pacific Lime Company Ltd., cost approximately $3 million and is the second plant in the United States to use a grate kiln. Limestone for the plant is imported from Blubber Bay, Texada Island, British Columbia.

Portland Cement

In 1756 John Smeaton, an English civil engineer, while studying cements for construction of the Eddystone lighthouse, made a series of experiments to find the best cement capable of hardening under water. He later stated that his product would "equal the best merchantable Portland Stone in solidity and durability." This was in reference to a popular building stone quarried from a peninsula on the east coast of England called the "Isle of Portland." His cement was quite different from modern portland cement, but when made into concrete it did resemble Portland Stone in color and properties. In 1824 the Aspdins, at Wakefield and Gateshead, England, were making a product they called "Portland" cement, but true modern portland cement was first made in about 1845 by Mr. I. C. Johnson, manager of White and Son's Works at Swancombe, Kent, England.

The name "portland cement" is now applied to all cement that can meet the rigid specifications of the Federal Government and those established by the American Society for Testing Materials. It is not a brand name but is the name for the main ingredient in the finished product, concrete. Concrete is the most universally used building material of the present day, and its principal uses are in highways, bridges, dams, buildings, sidewalks, military fortifications, walls, and jetties and other protective construction. Concrete is produced when portland cement is mixed with water and allowed to hydrate and become a binding material of sand and crushed stone or gravel.

Two major raw materials are needed for the manufacture of cement. These include the calcareous component, or limestone, and the argillaceous component, or clay. Frequently it is necessary to add iron, silica, or alumina if these are not contained in sufficient amount in the clay or limestone. Gypsum ($CaSO_4 \cdot 2H_2O$) is added in a final stage of cement manufacture to control the setting time.

A variety of limestone, called cement rock, contains the proper proportions of $CaCO_3$ and argillaceous, siliceous, and iron impurities for the manufacture of cement without modification or addition of materials. Much of the argillaceous limestone of the Lehigh Valley of Pennsylvania, where the cement industry of the United States first gained prominence, is rock of this type. Some of the limestones used for cement in western Washington approach a natural cement rock in composition. However, in recent years the specifications for cement have become more rigid, and it is not very likely that any natural rock contains all the necessary ingredients in the proper proportion.

Important to note here is the common misconception that the purer the limestone, the better it is for cement manufacture. In actual fact, the farther the natural composition is from the required composition, the more expensive the manufacturing process becomes. With relatively pure constituents, control of the mix is more difficult, and fine grinding, closer control, and more mixing are required.

The $CaCO_3$ content of limestone used for cement may be as low as 75 percent, but commonly a $CaCO_3$ content of 85 to 95 percent is preferred. The most important impurity is magnesia. If magnesia is uniformly distributed, it is possible to tolerate up to 5 percent $MgCO_3$ in the rock, but the percentage should be less, and 2 to 3 percent is the maximum allowed by most companies. Larger amounts of magnesia require mixing with high-calcium limestone, and even then there is the possibility of producing a product of inferior quality.

Chert is a common impurity in limestone and, although it may furnish part of the silica requirement for cement, it increases costs by wear on drill bits, handling equipment, and crushing and grinding equipment. After burning, it may remain as particles larger in size than the lime and cause a lack of homogeneity in the finished product. Quartz sand grains, if large, have the same effect as chert. Silica content of limestones used for cement should not exceed 20 percent, but some authorities state that 12 to 15 percent is the limit.

The ratio of limestone to the argillaceous component (clay or shale) in the raw mix varies according to the chemical composition of each, but when comparatively pure limestone is used, the mix consists roughly of four parts by weight of limestone to one part of clay or shale. Sandstone may be substituted for some of the clay or shale if the clay or shale is too high in alumina. The content of alumina in limestone used for cement should not exceed 3.7 percent.

The alumina present provides flux for reaction. The argillaceous component may be supplied by use of residual clays, alluvial clays, bedded marine clays, shales, phyllites, argillites, or schists. Alluvial clays are usually the most suitable. The composition of these materials must be examined carefully to determine their proper admixture to the limestone. Sometimes quartz sand, diatomaceous earth, slag, iron ore, or high-alumina clay (bauxite) may be added to make the proper mixture. Other ingredients such as pozzolana (a siliceous material that in finely divided form reacts with calcium hydroxide in the presence of water at ordinary temperatures to form stable insoluble compounds having cementitious properties) may be added for special types of cement. Typical pozzolan materials are montmorillonitic clays, volcanic ash, pumice, tuff, certain shales, obsidian, diatomaceous earth, opal, and chert. Materials have pozzolanic properties only if they are semiconductors of electricty.

The processing of raw materials into finished cement includes four stages (Clausen, 1960, p. 213):

Size reduction (blasting, crushing, grinding) to obtain the fineness and surface that will permit the chemical reactions to take place between the components and permit the formation of the cement compounds during the subsequent pyro-processing.

Blending, correction, and homogenization of the raw mix to obtain the exact desired composition and uniformity.

Liberation of carbon dioxide (calcination) and pyro-processing (burning) to form new compounds.

Fine pulverization of kiln product ("clinker") with addition of gypsum.

Agricultural Limestone

All plants need calcium and magnesium. These two elements improve soil structure, control soil acidity, and increase the population and activity of soil organisms. These effects hasten the decomposition of composts and other organic matter; thus green manure crops and other organics release their fertility faster when lime is supplied in adequate amounts. The benefits of lime applied to the soil are given out slowly over a long period of time. Many of the benefits are indirect, appearing as a better contribution from other soil materials. Phosphates in western Washington soils combine with other soil minerals and convert into mineral combinations that plants cannot use. When lime is applied, more of the phosphate remains available to the plants and the farmer gets more return for his phosphate fertilizer investment. However, too much lime may reverse the process, as on some soils excess lime seems to interfere with the absorption of phosphorus and potassium.

Agricultural limestones (agstone) and dolomite are applied to fields to replace calcium and magnesium cropped and leached from the soils. Small amounts are used in mixed fertilizers to condition the mixture, to reduce chemical attack on bag materials, and to correct any tendency of the fertilizer to increase soil acidity. The heavy rainfall of humid regions of western Washington tends to leach lime from the soil, so that in these regions lime is often an essential soil additive. Lime is especially beneficial to crops such as alfalfa, clover, timothy, rye, spinach, and apples, and to flowers such as iris and delphiniums. Azaleas, hydrangeas, and to a certain extent potatoes, cranberries, blueberries, and strawberries, are typical of plants that do not need much lime and prefer acid soils.

Limestone may contain small quantities of many of the trace elements, such as manganese, copper, zinc, boron, cobalt, and molybdenum, that are essential to plant growth. Though not considered as the main source of these elements, an agricultural limestone containing them would be a more beneficial additive to soils than one that did not contain them. However, an overabundance of trace elements may be harmful. Warren and Delavault (1961, p. 1270) mention an agricultural limestone that was found to contain 45 ppm of lead; this would be a highly undesirable lime to put on agricultural lands. Plants may absorb larger than normal amounts of lead from limestones that are high in lead content, and animals and humans using produce grown in these fields might receive doses of lead that could well be injurious to health (Warren and Delavault, 1961, 1962; Warren, 1962, 1963).

Ground limestone is the leading material for liming soils. Usually it is ground to particles, for the most part smaller than 1/10 inch. The higher the $CaCO_3$ content, the better the stone is, but limestone with a $CaCO_3$ content as low as 75 percent or even lower may be used. Dolomite dissolves more slowly than limestone and is preferred where the soil has a magnesium deficiency. Quicklime and hydrated lime are more expensive, but they give faster results and weigh less than the same volume of limestone rock. Marl is a common form of limestone used for agricultural purposes, and a considerable amount of it is imported into northwestern Washington from the Cheam marl deposit near Chilliwack, British Columbia. Marl also is obtained from several lakes in eastern Washington. Oyster shells and other seashells can be finely ground and used as a source of lime. Some industrial plants, such as paper mills, tanneries, sugar mills, and cement plants, are sources of waste and byproduct limes, which, if available in dry condition, can be used for agricultural lime. Before using these materials it is best to consult the county agricultural agent or other advisers.

Chemically, "lime" means calcium oxide, more commonly called burnt lime or quicklime, but in agriculture it means any calcium-bearing material capable of correcting soil acidity. The term is applied to ground limestone, marl, and other materials. "Liming" means the application of any liming material to the soil for crop-production purposes. For more detailed information on soil "liming" see Whittaker and others (1959).

Recent experimental work (Fowler and Christenson, 1959; Jones and Haghiri, 1962) has shown that the application of lime to soils can restrict the absorption of strontium. Strontium in radioactive debris from atomic explosions deposited on vegetation and soil presents a potential health hazard to man. The radioactive isotope strontium Sr_{90} is of particular concern. It can be readily absorbed by plants, either from the soil or directly through the foliage. Contamination in forage can be carried into the milk of dairy cows and eventually into the calcified bone tissue of man. In acid soils the uptake of Sr_{90} can be significantly reduced (by as much as 60 percent) by liming.

Metallurgical Uses of Limestone and Lime

Limestone, as well as dolomite and lime, is used in the smelting of iron and other metals to supply CaO (and MgO) to combine with the undesirable acid constituents in the ores and fuels to form a slag separable from the molten metal. Most iron ores carry alumina and silica as impurities, and the addition of a basic flux such as limestone is necessary to form a slag with them. Chemically, the ideal flux stone is low in acid constituents, such as silica, alumina, sulfur, phosphorus, and other deleterious elements, and is easily calcined in the furnace. If more than small percentages of these elements are present, the stone is less effective, increases slag volume and fuel consumption, and slows production. Physically, the desirable stone is fine grained and is strong enough to withstand abrasion in handling and shipping, blast furnace stack pressures, and the burden of ore and coke. Limestone acceptable for blast furnaces should contain less than 5 percent and preferably less than 3 percent SiO_2. The MgO content is not critical.

Lime and limestone are used as fluxing agents in the basic open-hearth process, in which they form a basic slag for removing phosphorus, sulfur, and other impurities. The amount of lime used depends upon the quantity and nature of the impurities to be removed. The composition for this flux stone is more critical than that for blast furnace use, as SiO_2 must be less than 2 percent, and less than 1 percent is preferred. Magnesia must be less than 5 percent; it is undesirable, as it does not eliminate phosphorus. Both blast furnace and open-hearth furnace fluxing stone should have low contents of phosphorus and sulfur. The maximum amounts permissible are approximately 0.01 percent P_2O_5 and 0.50 percent S.

Limestone flux is used in copper and lead smelting of ores that are more acidic than basic; high-calcium limestone with a low silica content is desired. Lime may serve several purposes in concentrating ore minerals in flotation. Generally, material is now floated in slightly alkaline pulps, in which lime has advantages over soda ash or caustic soda under certain conditions. Lime is used rather extensively in the cyanide process for gold milling. A high-calcium lime with a CaO content of more than 90 percent and a low phosphorus content is used to neutralize acid leaching solutions from uranium mills. A low phosphorus content is required, because the presence of phosphorus inhibits the precipitation of uranium salts.

Lime is used in three processes for making metallic magnesium: the Dow method from natural brines, the Dow seawater process, and the ferrosilicon (Pidgeon) process. Lime is used to neutralize the "pickling" liquor that removes rust and scale from iron and steel before the liquor can be discharged into streams. Up to 10 percent lime is added to briquettes of ferric oxide to increase their reducibility.

Alkali Manufacture

Lime is added to a solution of sodium carbonate as a causticizing agent in the manufacture of sodium hydroxide, or caustic soda. A high-calcium lime containing not less than 85 percent available CaO must be used. Magnesia should not exceed 3 percent. Lime is added to crude coal gas to concentrate crude ammonia liquors, and it is used also in distilling these liquors to produce aqua ammonia, anhydrous ammonia, or ammonium salts.

The raw materials for the manufacture of soda ash by the ammonia soda process are common salt and high-calcium limestone. Most users insist on limestone with a silica content under 1 percent. About $1\frac{1}{4}$ tons of high-calcium limestone are used for each ton of soda ash produced. Stone ranging in size from 1 to 6 inches in diameter is desired.

Glass Manufacture

Lime is employed as a raw material in plate, sheet, and bottle glass and in a large proportion of the pressed or blown glass. The chemical requirements of the lime depend on the kind of glass to be produced. High-calcium limestone is used in making bottle and window glass; dolomitic stone is used for special glasses. Limestone may constitute as much as 30 percent of some glass batches. Common glass is made from a fused mixture of alkali, lime or limestone, and silica.

For optical glass, the iron oxide content of the limestone should be virtually zero, whereas for some bottle glass 0.5 percent is permissible; the limits for blown or sheet glass are nearly the same. The silica or alumina may run as high as 15 percent for bottle glass, but the percentage should be very much less for the other grades of glass. The sulfur and phosphorus should not exceed 1 percent for bottle glass, should be less for the other kinds, and should be no more than about 0.2 percent for optical glass. The combined CaO and MgO preferably should be at least 89 percent for bottle glass, 91 percent for sheet glass, 93 percent for blown glass, 96 percent for rolled glass, and 99 percent for optical glass. The Northwestern Glass Company, Seattle, specifies a limestone containing more than 98.7 percent $CaCO_3$ and less than 0.05 percent Fe_2O_3.

Sugar Refining

Milk-of-lime is used to clarify and purify beet and cane juices used to manufacture sugar. When added to the juice and heated almost to boiling, it combines with the acids, breaks up and precipitates other organic compounds, and forms insoluble salts. In the Steffen process, ground quicklime is used to precipitate sugar from impure molasses. The lime used in this process must be high in calcium and have less than 1 percent MgO, less than 1 percent SiO_2, and must have a very low iron content. Because carbon dioxide is employed to clarify beet sugar, factories using beets produce their own lime and use the carbon dioxide obtained from the kilns for the carbonation process, which converts the lime back into calcium carbonate. This can be recalcined and used again. Manufacturers of cane sugar usually buy their supplies of lime. This industry requires the purest grade of high-calcium lime that can be obtained. Limestone for this purpose must contain not less than 97 percent $CaCO_3$, and not more than about 2.5 percent MgO, nor more than 1.0 percent SiO_2. It must also be free of impurities that would impart a taste. The effectiveness of any given limestone for sugar refinery use can be determined only by use tests. For every pound of beet sugar produced, a little more than half a pound of limestone is used in the manufacturing process. A large proportion of this can be reused.

Calcium Carbide and Cyanamide

Calcium carbide is made by heating a mixture of lime and carbon (coke, charcoal, or anthracite) to a very high temperature (2,000°C). Approximately 2 tons of limestone or 1 ton of lime is required for each ton of calcium carbide. Calcium cyanamide is made by treating this fused mass with nitrogen. Lime facilitates the reaction of the nitrogen with the carbide. High-calcium quicklime is required. Silica, magnesia, and alumina are undesirable, and the phosphorus and arsenic contents especially should be low to avoid acetylene explosions. Limestone specifications vary with the different users. Oölitic stone is preferred by some users. However, a combination of data from several sources suggests that the limestone should contain not less than 97 percent $CaCO_3$, and not more than 0.50 percent MgO, 1.2 percent SiO_2, 0.75 to 0.5 percent combined Al_2O_3 and Fe_2O_3, 0.01 percent P_2O_5, and a trace of sulfur. The Pacific Carbide and Alloys Company, Portland, Oreg., requires that limestone for their use contain not more than 1 percent MgO, 1 percent SiO_2, 0.5 percent Fe_2O_3, and 0.007 percent P_2O_5.

Lime made into calcium carbide is an essential raw material in the manufacture of chloroprene polymers and butadiene polymers, two types of synthetic rubber.

Pulp and Paper

Both lime and limestone are used in the paper industry in the preparation of cooking-liquors. In the sulfite process, lime is combined with sulfur dioxide to form an acid liquor that at high temperature and pressure dissolves and removes all the constituents of the wood chips except the cellulose. A dolomitic lime (39.6 percent MgO minimum) is preferred, because magnesium bisulfite is more soluble than calcium bisulfite, its decomposition products are more soluble, and it produces a softer, whiter pulp. In the tower system of sulfite pulp production, SO_2 gas is passed up towers packed with lumps of limestone or dolomite down which water flows. The "acid" produced by either method is a solution of calcium or magnesium bisulfite, or both, which also contains dissolved sulfur dioxide. In the tower process, blocks of limestone 8 to 14 inches in diameter are required. A high-calcium limestone is preferred for the tower process and should contain more than 53 percent CaO; less than 1.5 percent MgO; less than 1.5 percent combined SiO_2, Fe_2O_3, and Al_2O_3; and less than 0.5 percent organic matter. If dolomite is used, the $CaCO_3$ content should be between 54 and 59 percent; $MgCO_3$, between 35 and 44 percent; Fe_2O_3 and Al_2O_3, less than 1 percent; and total insoluble not more than 2 percent.

In the Kraft, or sulfate, process for the manufacture of pulp, a high-calcium lime containing less than 2 percent MgO is desired.

Lime is used as a causticizing agent in recovering the caustic soda used in the soda process for digesting wood and other fibers. It serves the same purpose in recovering the sodium sulfate in the sulfate process. Quicklime is preferred and must be low in magnesia, highly reactive chemically, quick settling, quick slaking, and have an available lime content of 85 percent or more. A high-calcium lime containing 92.5 percent CaO, less than 2.5 percent MgO, and less than 3 percent each of silica, iron, and alumina is desired.

Rags for paper manufacture are cooked with lime or lime and soda ash in a digester under steam pressure. Calcium carbonate or precipitated whiting is used as a filler in magazine and book paper.

The specifications placed on limestone for paper manufacture by companies in Washington vary to some extent. Limestone of the following composition probably would suit the requirements of most paper companies: $CaCO_3$ not less than 95 percent, MgO less than 3.0 percent, SiO_2 less than 1.5 percent, and R_2O_3 (Al_2O_3 and Fe_2O_3) less than 0.5 percent. Insoluble matter, carbon, mica, and pyrite are objectionable. In addition, limestone for the tower process must not disintegrate readily into smaller fragments. Tests in the tower are required to satisfy the physical requirements. A considerable quantity of the lime used in the paper industry is recycled. Approximately 300 pounds of limestone is consumed for every ton of pulp produced by the sulfite process.

Refractory Brick and Sand-Lime Brick

Large tonnages of lime are sold for the manufacture of silica brick, which is used chiefly for lining furnaces. A mixture of milk-of-lime and silica is molded in forms, dried, and calcined under carefully controlled conditions. The lime serves as a bonding agent and also acts as an accelerator in the conversion reaction.

Sand-lime brick is made by mixing sand and lime, pressing the admixture into brick form, and treating it with a high steam pressure. The lime, reacting with some of the silica on the surface of the sand grains, forms calcium silicate, which binds the rest of the sand grains together. A high-calcium lime is required to insure proper hydration. The MgO content preferably should be less than 5 percent.

Paint, Bleaching Powder, and Bleach Liquor

Whitewash is prepared by mixing lime and water. Many whitewash formulas are used in preparing water paint for various applications, but the essentials are lime, pigment, and casein. As a protecting agent, soluble lime penetrates wood, then it carbonates, preserving the wood against weathering and increasing its fire resistance. As an alkaline material, lime or carbonate prevents rusting of iron and corrosion of other materials. Hydrated lime serves as a pigment and also functions as a cementing or bonding agent in paints. It also improves the disinfecting properties of paint and makes it more suitable as a sanitary coating.

Bleaching powder, chloride of lime, or chlorinated liquor is formed by the action of chlorine on moist slaked lime. Liquid bleach is made by subjecting a milk-of-lime suspension to the action of chlorine. High-calcium quicklime or hydrated lime is used for these products.

Leather

Lime is used in the leather industry in depilation (dehairing). The skins are soaked in vats containing lime water to which such "sharpening agents" as arsenic sulfide, sodium sulfide, and sodium hydroxide sometimes are added. The lime swells and softens the epidermal cells and dissolves the mucous layer, so loosening the hair from the hide that it can be removed mechanically. Both quicklime and hydrated lime are used, and the available lime content should be at least 85 percent. Magnesia, clay, and iron oxide are harmful in this process. In making morocco leather, however, high-magnesium lime is used.

Water and Waste Treatment

Lime (quicklime or hydrated lime), or a mixture of lime and soda ash, is used extensively for softening water. When an excess of lime is added to hard water, it combines with the bicarbonates present and forms carbonates. As calcium and magnesium carbonates are virtually insoluble, the reaction causes their precipitation, thus removing temporary hardness. Lime is used also as a coagulant for water high in magnesium salts and for its bactericidal action.

Lime is used to abate stream pollution at industrial plants. It is used to neutralize sulfuric and other acids at steel, chemical, explosives, textile, and other factories. It also effects or aids precipitation of various waste products. Specifications require that quicklime for water purification contain at least 85 percent available lime (CaO) and that hydrated lime contain at least 90 percent available calcium hydroxide [$Ca(OH)_2$].

Building Lime

Important physical properties of lime used for building are plasticity, sand-carrying capacity, strength when mixed with sand, time of set, and color. Lime is used for building as mortar, made by mixing lime putty with sand and water. Where high strength is needed, portland cement may be added. Lime plaster is made by mixing lime putty and sand, with or without hair. Coarse sand, often mixed with gravel, is used for exterior walls and ceilings. A highly plastic grade of lime is required for the finishing coat. It must be very nearly white, must work smoothly, and must not expand or shrink too much in setting.

Hydrated lime increases the plasticity, smooth-working quality, and resistance to water absorption of concrete. It is added as the batch goes into the mixer.

Lime added to natural cement increases the strength and plasticity of the mortar. Lime is used as a binder in manufacturing artificial stone made of various sizes and types of aggregates. It produces a whiter and more pleasing product than does ordinary portland cement. Color may be varied by adding appropriate quantities of mineral oxides.

Limestone containing more than about 1 percent iron oxide (FeO) and about 0.03 percent manganese oxide (MnO) produces a lime having an undesirable buff to brown color. Limestone containing more than 1 percent magnesia gives trouble in burning, and the resulting lime plaster tends to blister or "pop." Physical characters of the limestone not only determine the ease or difficulty of burning, but may also affect other properties. The conditions of processing determine or affect final grain size, rate of settling from a suspension, and other characteristics. In general, it is not possible to determine merely from examination of a given limestone sample and from its chemical analysis whether it would be suitable for builder's lime. Burning tests, preferably in a model or full-scale kiln, and laboratory field tests of the resulting lime are essential in indicating the value of a new limestone deposit for this product.

Insecticides, Fungicides, and Disinfectants

Lime, dry or as whitewash, may be used as a mild disinfectant. It is used to make calcium arsenate, and small amounts of calcium arsenate and hydrated lime are usually mixed with commercial lead arsenate. Both are important insecticides. Lime sulfur, an important fungicide and insecticide for fruit trees, is prepared by heating sulfur with milk-of-lime. Bordeaux mixture is made by the reaction of copper sulfate with lime. Lime used in these mixtures should be a high-calcium type with low iron and alumina contents. The lime should contain not more than 1.5 percent magnesium oxide, as magnesium compounds readily decompose, producing hydrogen sulfide and liberating sulfur.

Road Stabilization

Lime is applied to road bases and sub-bases for soil stabilization. This is particularly effective on certain clay or clay-gravel soils, in which the lime appears to react chemically with the silica and alumina in the soil, forming in effect a natural cement. About 3 percent lime, by volume, ordinarily is added to the base-course materials.

Mineral Food

Calcium is important to the success of livestock farming because it serves as a bone builder, is necessary in the proper functioning of the nervous system, and also acts as a neutralizer in the digestive tract. According to the Kansas State Agricultural College, one-tenth pound of limestone should be consumed each day per head of livestock. A satisfactory limestone for stock food should contain at least 95 percent calcium carbonate, no fluorine, and very little magnesium. The stone must be ground almost as fine as wheat flour.

Ground limestone and urea added to chopped corn silage before putting it into silos has been found in experiments in Ohio to spur calf gains by 8 to 10 percent and to cut feed costs $1 per 100 pounds. The limestone holds down the acid content of the silage, so that bacteria keep working longer, which results in silage the animals can use more efficiently. Dolomitic limestone cannot be used for this purpose (Anderson, 1960).

Monocalcium phosphate, a constituent of certain types of baking powders, is made by treating limestone or lime with phosphoric acid.

Rock Wool

Small tonnages of limestone or dolomite are used in making rock wool. These rocks should contain roughly between 20 and 30 percent carbon dioxide, which is equivalent to approximately 45 to 65 percent calcium carbonate, or calcium carbonate and magnesium carbonate. The remainder of the rock should be mainly silica, or silica and alumina. Magnesium carbonate is not necessary in woolrocks, although some operators prefer it. The same applies to alumina. Iron sulfide is undesirable. The noncalcareous constituents should occur in small particles well distributed through the rock, rather than in large masses.

The most common size of rock used is between 2 and 5 inches, but actual size depends upon the equipment and process being used.

Rock wool can be made from mixtures of limestone or dolomite with shale, sandstone, or other siliceous or aluminous rocks, provided the mixture meets the chemical and physical specifications given above.

TABLE 11.—Chemical specifications for limestone used in industry

(Many companies have their own specifications, which may differ slightly from those in this table.)

Industry	Minimum		Maximum						
	$CaCO_3$	CaO	MgO	SiO_2	Al_2O_3	R_2O_3	Fe_2O_3	P_2O_5	S
Glass	98	55.0	1.0	-------	0.10	-------	-.05	-1.0	-1.0
Calcium carbide	97	54.5	0.5	1.2	-------	0.5	0.05	0.01	trace
Chemical and lime	97	54.5	2.5	2.0	1.0	-------	-------	0.02	0.05
Metallurgical	97	54.5	-------	2.0	-------	-------	-------	0.01	0.50
Sugar	97	54.5	2.5	1.0	-------	-------	-------	-------	-------
Whiting (ceramic)	96	54.0	0.5	2.0	-------	-------	0.25	-------	-------
Pulp and paper	95	53.3	3.0	1.5	-------	0.5	-------	-------	-------
Construction (finishing lime)	95	53.3	1.0	-------	-------	-------	1.0	-------	-------
Filler	95	53.3	-------	-------	-------	-------	-------	-------	-------
Cement	75	42.0	3.0	20.0	-------	5.0	-------	0.5	low
Agricultural stone	75	42.0	-------	-------	-------	-------	-------	-------	-------
Rock wool	45	25.2	-------	55.0	-------	-------	-------	-------	low

TABLE 12. — Limestone and tufa deposits of western Washington; uses, potential uses, and reserves[1/]

Deposit	Development	Use	Reserves (tons)	Needs exploration	Potential uses					
					Cement	Pulp	Agri-culture	Chemi-cal	Deco-rative	Land-scape
LIMESTONE DEPOSITS										
SAN JUAN COUNTY										
Roche Harbor	Exhausted	Lime	-100,000	--	--	--	--	--	X	X
Mosquito Pass	Exhausted	Lime	-100	--	--	--	--	--	--	--
English Camp	Quarried	Lime	-1,000	--	--	--	X	--	--	X
Young Hill West	Undeveloped	--	-100	--	--	--	--	--	--	--
Young Hill East	Undeveloped	--	-500	--	--	--	--	--	--	--
Rouleau	Undeveloped	--	-100	--	--	--	--	--	--	--
Wilson	Quarried	Pulp rock	±200	--	--	--	--	--	--	--
Johnson	Quarried	Pulp rock	±100	--	--	--	--	--	--	--
Rocky Bay	Exhausted	Pulp rock	-500	--	--	--	--	--	--	--
Bell	Quarried	Aggregate ?	±500	--	--	--	--	--	--	X
Bell No. 2	Undeveloped	--	±300	--	--	--	--	--	--	--
Eureka	Quarried	Lime	±500	--	--	--	--	--	--	--
Hannah	Undeveloped	--	±500 ?	X	--	X	X	X	--	--
Mount Dallas	Undeveloped	--	-500	--	Unsuitable for most uses					
Cowell	Quarried	Pulp rock, lime, cement	1,000,000	--	--	--	X	--	--	X
Deadman Bay	Undeveloped	--	-500	--	--	--	--	--	--	--
Lawson Cave	Undeveloped	--	+2,500 ?	X	--	X	X	--	--	--
Welch	Undeveloped	--	±100	--	--	--	--	--	--	--
Mitchell Bay	Exhausted	Pulp rock	-500	--	--	--	--	--	--	--
Limestone Point	Exhausted	Lime	-500	--	--	--	--	--	--	--
Davison Head	Undeveloped	--	-500	--	Unsuitable for most uses					
O'Neal Island	Undeveloped	--	-500	--	--	--	--	--	--	--
Henry Island No. 1	Quarried	Lime	-5,000	--	--	--	X	--	--	--
Henry Island No. 2	Quarried	Lime	-1,500	--	--	--	--	--	--	--
Henry Island No. 3	Undeveloped	--	-500	--	--	--	--	--	--	--
Kellett Bluff	Undeveloped	--	±500	--	--	--	--	--	--	--
Open Bay	Undeveloped	--	-100	--	--	--	--	--	--	--
Henry Island No. 4	Exhausted	Lime	-100	--	--	--	--	--	--	--
Jones Island No. 1	Undeveloped	--	±500	--	Unsuitable for most uses					
Jones Island No. 2	Undeveloped	--	-500	--	--	--	--	--	--	--
Jones Island No. 3	Undeveloped	--	-100	--	--	--	--	--	--	--
Cliff Island	Exhausted	Pulp rock	-1,000	--	--	--	--	--	--	--
Crane Island	Quarried	Lime	-10,000	--	--	--	X	--	--	--
Yansen	Undeveloped	--	±5,000	X	--	X	X	--	--	--
Biendle	Undeveloped	--	-100	--	--	--	--	--	--	--
Lutz	Exhausted	Pulp rock	-100	--	--	--	--	--	--	--
West Coast Shaw Island	Undeveloped	--	-500	--	--	--	--	--	--	--
Red Cross	Producing	Pulp rock	+80,000	--	--	X	X	--	--	--
McGraw-Kittinger	Producing	Pulp rock	?	--	--	X	X	--	--	--
West Sound	Quarried	Pulp rock	-5,000	--	--	X	X	--	--	--
Double Hill No. 1	Quarried	Lime	-5,000	--	Unsuitable for most uses					
Double Hill No. 2	Exhausted	Pulp rock	?	--	--	--	--	--	--	--
Double Hill No. 3	Undeveloped ?	--	±6,000	--	--	?	X	--	--	--
Double Hill No. 4	Quarried	Lime	±1,000	--	Unsuitable for most uses					
Double Hill No. 5	Quarried	Pulp rock ?	±6,500	--	--	X	X	--	--	--
Double Hill No. 6	Undeveloped	--	±400	--	Unsuitable for most uses					
Rusch No. 1	Exhausted	Pulp rock	?	--	--	--	--	--	--	--
Rusch No. 2	Undeveloped	--	2,000	--	--	X	X	--	--	--
Langell	Undeveloped	--	±1,000	X	--	--	X	--	--	--
Englehartson	Undeveloped	--	±40,000	--	--	?	X	--	--	--
East Sound	Exhausted	Lime ?	?	--	--	--	--	--	--	--
Fowler No. 1	Undeveloped	--	3,000	--	--	X	X	--	--	--
Fowler No. 2	Undeveloped	--	20,000	X	--	X	X	X	--	--
Fowler No. 3	Undeveloped	--	10,000	X	--	--	X	--	--	--
Judd Cove	Undeveloped	--	-5,000	--	--	--	--	--	--	--
Fowler No. 4	Exhausted	Lime	-100	--	--	--	--	--	--	--
Fowler No. 5	Undeveloped	--	?	X	--	X	X	X	--	--
Camp Indralaya	Undeveloped	--	-5,000	--	--	--	--	--	--	--
Pineo No. 1	Exhausted	Pulp rock	-500	--	--	--	--	--	--	--
Pineo No. 2	Exhausted	Pulp rock	-500	--	--	--	--	--	--	--
Pineo No. 3	Undeveloped	--	? Small	X	--	X	X	X	--	--
Pineo No. 4	Undeveloped	--	? Small	X	--	--	X	--	--	--
Pineo No. 5	Exhausted	Pulp rock	-500	--	--	--	--	--	--	--
Pineo No. 6	Undeveloped	--	-100	--	--	--	--	--	--	--
Orcas Lime	Exhausted	Lime	-5,000	--	--	--	--	--	X	X
Killebrew Lake	Quarried	Lime	-100	--	--	--	--	--	--	--

[1/] Tonnages are estimated on basis of geological information available to the writer and may be more or less than indicated. Potential uses are based on estimates of quantity of limestone in the deposit and quality of limestone in surface outcrops as determined by chemical analyses. Deposits of relatively small size located in areas difficult of access are not indicated as having any potential use. A few small deposits located in advantageous quarry sites are indicated as having a potential use. Some deposits listed as exhausted may still contain scraps of limestone that might possibly be removed for agricultural stone with portable equipment or might be developed as a local source of landscape rock.

TABLE 12.—Limestone and tufa deposits of western Washington; uses, potential uses, and reserves—Continued

Deposit	Development	Use	Reserves (tons)	Needs exploration	Potential uses: Cement	Pulp	Agriculture	Chemical	Decorative	Landscape
LIMESTONE DEPOSITS—Continued										
SAN JUAN COUNTY—Continued										
Moran State Park	Undeveloped	--------	-2,000	--------	Unsuitable for most uses					
Caldwell Point	Quarried	Lime	-1,000	--------	--------	--------	--------	--------	--------	--------
Four Winds	Undeveloped	--------	-100	--------	--------	--------	--------	--------	--------	--------
Deer Harbor	Undeveloped	--------	-500	--------	--------	--------	--------	--------	--------	--------
Soderberg	Exhausted	Pulp rock	-3,000	--------	--------	--------	--------	--------	---X---	---X---
Imperial	Quarried	Lime	±5,000	---X---	--------	---X---	---X---	---X---	--------	--------
Soderberg Beaches	Undeveloped	--------	-5,000	--------	--------	--------	--------	--------	--------	--------
Langdon North	Exhausted	Lime	-1,000	--------	--------	--------	--------	--------	--------	--------
Langdon South	Exhausted	Lime, flux, pulp rock	-10,000	--------	--------	--------	---X---	--------	--------	--------
Entrance Mountain	Undeveloped	--------	-1,000	--------	--------	--------	--------	--------	--------	--------
Olga	Undeveloped	--------	-500	--------	Unsuitable for most uses					
Newhall	Quarried	Lime	-5,000	--------	--------	--------	---X---	--------	--------	--------
Rosario	Undeveloped	--------	-1,000	--------	--------	--------	--------	--------	--------	--------
Buck Mountain No. 1	Undeveloped	--------	-100	--------	Unsuitable for most uses					
Buck Mountain No. 2	Undeveloped	--------	±20,000	--------	---X---	--------	---?---	--------	---X---	--------
Mount Constitution	Undeveloped	--------	±60,000	--------	---X---	--------	---?---	--------	---X---	--------
Raccoon Point	Undeveloped	--------	-500	--------	--------	--------	--------	--------	--------	--------
Payton	Exhausted	Lime?, pulp rock	-1,000	--------	--------	--------	--------	--------	--------	--------
Wright	Undeveloped	--------	-5,000	--------	Unsuitable for most uses					
Flaherty No. 1	Undeveloped	--------	±500	--------	--------	--------	--------	--------	--------	--------
Flaherty No. 2	Exhausted?	?	-1,000	--------	--------	--------	--------	--------	--------	--------
Flaherty No. 3	Undeveloped	--------	-500	--------	--------	--------	--------	--------	--------	--------
Lawrence Point	Undeveloped	--------	500	--------	--------	---?---	---X---	--------	--------	---X---
Chuckanut Lime Company	Exhausted	Lime	-500	--------	--------	--------	--------	--------	--------	--------
		San Juan County total	±1,456,900							
WHATCOM COUNTY										
Boulder Creek	Quarried	Pulp rock	±5,000	--------	--------	---X---	---X---	--------	---X---	--------
Permanente Cement Kendall quarry	Operating	Cement rock	+50,000,000	--------	---X---	---X---	---X---	---?---	---X---	---X---
Red Mountain	Undeveloped	--------	+2,000,000	--------	---X---	---X---	---X---	--------	---X---	---X---
Silver Lake No. 1	Operating	Pulp rock	±4,000,000	--------	---X---	---X---	---X---	--------	---X---	---X---
Silver Lake No. 2	Undeveloped	--------	±200,000	---X---	---X---	---X---	---X---	--------	--------	--------
Balfour No. 1	Exhausted	Cement	±1,000	--------	--------	--------	--------	--------	--------	--------
Balfour No. 2	Exhausted	Cement	±1,000	--------	--------	--------	--------	--------	--------	--------
Balfour No. 3	Exhausted	Cement	±1,000	--------	--------	--------	--------	--------	--------	--------
Balfour No. 4	Exhausted	Cement	±1,000	--------	--------	--------	--------	--------	--------	--------
Balfour No. 5	Undeveloped	--------	-500	--------	---X---	---X---	---X---	--------	--------	--------
Balfour No. 6	Undeveloped	--------	±20,000	---X---	---X---	---X---	---X---	--------	--------	--------
Hilltop	Undeveloped	--------	±1,000	---X---	--------	--------	---X---	--------	--------	--------
Sumas Mountain No. 1	Undeveloped	--------	±1,000	---X---	--------	---?---	---X---	--------	--------	--------
Sumas Mountain No. 2	Undeveloped	--------	±20,000,000?	---X---	---X---	--------	---X---	--------	--------	--------
Northwestern Lime Co. North	Undeveloped	--------	±25,000	---X---	---X---	---X---	---X---	--------	--------	--------
Doaks Creek	Operating	Pulp rock	250,000	--------	---X---	---X---	---X---	--------	--------	--------
German No. 1	Undeveloped	--------	±1,000	--------	---X---	---?---	---X---	--------	--------	--------
German No. 2	Undeveloped	--------	±10,000	---X---	---X---	---?---	---X---	--------	--------	--------
Northwest Black Mountain No. 1	Undeveloped	--------	±1,000	---X---	---X---	---?---	---X---	--------	--------	--------
Northwest Black Mountain No. 2	Undeveloped	--------	±1,000	--------	Unsuitable for most uses					
Vedder Mountain	Undeveloped	--------	0	--------	Trace of limestone					
Frost Creek	Undeveloped	--------	Unknown	---X---	--------	--------	--------	--------	--------	--------
Monument 47	Undeveloped	--------	Unknown	---X---	--------	--------	--------	--------	--------	--------
Monument 48	Undeveloped	--------	Unknown	---X---	--------	--------	--------	--------	--------	--------
Monument 45	Undeveloped	--------	Unknown	---X---	--------	--------	--------	--------	--------	--------
Black Mountain	Undeveloped	--------	+25,000,000	--------	---X---	---?---	---X---	--------	---X---	---X---
Church Mountain	Undeveloped	--------	±5,000	---X---	---X---	---X---	---X---	--------	--------	--------
Baker Lake	Undeveloped	--------	-100	--------	--------	--------	--------	--------	--------	--------
Ridley Creek	Undeveloped	--------	Large	---X---	---X---	---X---	---X---	--------	--------	--------
		Whatcom County total	±101,524,600							
WHATCOM - SKAGIT COUNTY BORDER AREA										
Dock Butte Trail No. 1	Undeveloped	--------	+20,000	---X---	---?---	---?---	---X---	--------	--------	--------
Dock Butte Trail No. 2	Undeveloped	--------	+100,000	---X---	---X---	---X---	---X---	--------	--------	--------
Blue Lake	Undeveloped	--------	-500	--------	--------	--------	--------	--------	--------	--------
Dock Butte	Undeveloped	--------	-100	--------	--------	--------	--------	--------	--------	--------

TABLE 12.—Limestone and tufa deposits of western Washington; uses, potential uses, and reserves—Continued

Deposit	Development	Use	Reserves (tons)	Needs exploration	Potential uses: Cement	Pulp	Agriculture	Chemical	Decorative	Landscape
LIMESTONE DEPOSITS—Continued										
WHATCOM - SKAGIT COUNTY BORDER AREA—Continued										
Washington Monument	Undeveloped	-----------	+10,000,000	---X---	---X---	---X---	---X---	--------	--------	--------
North of Washington Monument[2/]	Undeveloped	-----------	±50,000,000?	---X---	---X---	---X---	---X---	--------	--------	--------
Whatcom - Skagit County border area total			±60,120,600							
SKAGIT COUNTY										
Pilchuck Creek	Undeveloped	-----------	-100	--------	--------	--------	--------	--------	--------	--------
Three Mile Creek	Quarried	Aggregate?	30,000	---X---	--------	---?---	---X---	--------	--------	--------
Concrete	Producing	Cement rock	±500,000,000	--------	---X---	--------	---X---	--------	--------	--------
Jackman Creek No. 1	Undeveloped	-----------	-3,000	--------	--------	---?---	---X---	--------	--------	--------
Jackman Creek No. 2	Undeveloped	-----------	±5,000	--------	--------	---?---	---X---	--------	--------	--------
Jackman Creek No. 3	Undeveloped	-----------	±1,000	--------	--------	---?---	---X---	--------	--------	--------
Jackman Creek No. 4	Undeveloped	-----------	±500	--------	--------	---?---	--------	--------	--------	--------
Jackman Creek No. 5	Undeveloped	-----------	-500	--------	--------	--------	--------	--------	--------	--------
Jackman Creek No. 6	Undeveloped	-----------	-1,000	--------	--------	--------	---X---	--------	--------	--------
Jackman Creek No. 7	Undeveloped	-----------	±100,000	---X---	---X---	---X---	---X---	--------	--------	--------
Webber Creek	Undeveloped	-----------	±2,000,000	---X---	---X---	---X---	---X---	---X---	--------	--------
Jackman Ridge										
Paystreak	Undeveloped	-----------	±1,000,000	---X---	---X---	---X---	---X---	--------	--------	--------
Portland	Undeveloped	-----------	Unknown	---X---	---X---	--------	---X---	--------	--------	--------
Broderick	Undeveloped	-----------	±10,000	---X---	---X---	--------	---X---	--------	--------	--------
Crescent	Undeveloped	-----------	Unknown	---X---	--------	--------	--------	--------	--------	--------
Sauk Mountain	Undeveloped	-----------	Unknown	---X---	--------	--------	--------	--------	--------	--------
North Rockport	Undeveloped	-----------	+400,000	---X---	---X---	---X---	---X---	--------	--------	--------
South Rockport	Undeveloped	-----------	±200,000	---X---	---X---	---X---	---X---	--------	--------	--------
Sutter Creek	Undeveloped	-----------	±100,000	--------	---X---	--------	---?---	--------	--------	--------
Rocky Creek	Undeveloped	-----------	±500	--------	---X---	--------	---?---	--------	--------	--------
Marble Creek	Undeveloped	-----------	Large	---X---	--------	---X---	---X---	--------	---X---	--------
Sutter Mountain	Undeveloped	-----------	+3,500,000	---X---	---X---	---X---	---X---	--------	--------	--------
Sauk River Bridge	Undeveloped	-----------	-500	--------	Unsuitable for most uses					
Suiattle River Bridge	Undeveloped	-----------	Unknown	--------	Unsuitable for most uses					
Damnation Creek	Undeveloped	-----------	-100	--------	--------	--------	--------	--------	--------	--------
Skagit County total			±507,352,200							
SNOHOMISH COUNTY										
Rock Creek	Quarried	Agriculture	+5,000	--------	---X---	---X---	---X---	---X---	--------	--------
Bryant	Quarried	Agriculture	+30,000	--------	---X---	---X---	---X---	---X---	--------	--------
Jack	Exhausted	Agriculture	-500	--------	--------	--------	--------	--------	--------	--------
Skagit Power Line	Undeveloped	-----------	±5,000	---X---	---X---	---X---	---X---	---X---	--------	--------
Paddock (Morcrop)	Exhausted	Agriculture	±1,000	--------	--------	--------	--------	--------	--------	---X---
South Twin Lake	Undeveloped	-----------	±106,500	---X---	---X---	---X---	---X---	---X---	--------	--------
Canyon Creek Lodge	Operating	Agriculture, lime, pulp, landscape	100,000	--------	--------	---X---	---X---	--------	--------	---X---
Shumway	Exhausted	Lime, pulp	±1,000	--------	--------	--------	--------	--------	--------	--------
Granite Falls	Exhausted	Lime	-500	--------	--------	--------	--------	--------	--------	--------
Stillaguamish Canyon	Undeveloped	-----------	Trace	--------	--------	--------	--------	--------	--------	--------
Lake Julia	Undeveloped	-----------	-200	--------	--------	--------	--------	--------	--------	--------
Menzel Lake	Undeveloped	-----------	Unknown	--------	Calc-silicate rock; not limestone					
Kelly Creek	Undeveloped	-----------	Unknown	---X---	--------	--------	--------	--------	--------	--------
Liberty Mountain	Undeveloped	-----------	Unknown	--------	--------	--------	--------	--------	--------	--------
Marble Peak	Undeveloped	-----------	-1,000	--------	--------	--------	--------	--------	--------	--------
Climax and Hi Hi	Undeveloped	-----------	+100,000	---X---	--------	---X---	---X---	--------	---X---	---X---
Galbraith	Undeveloped	-----------	±35,000,000?	---X---	--------	---X---	---X---	--------	--------	--------
Conn Creek No. 1	Undeveloped	-----------	+200,000	---X---	---X---	--------	---X---	--------	--------	--------
Conn Creek No. 2	Undeveloped	-----------	±1,500	---X---	---X---	--------	---X---	--------	--------	--------
Conn Creek No. 3	Undeveloped	-----------	±10,000	---X---	---?---	--------	--------	--------	--------	--------
Whitechuck River	Undeveloped	-----------	±15,000	--------	---?---	--------	---X---	--------	--------	--------
Circle Peak (north part)	Undeveloped	-----------	+750,000	--------	Unsuitable for most uses					
Circle Peak - Meadow Mountain	Undeveloped	-----------	+100,000,000?	---X---	---?---	---?---	---?---	---?---	---?---	--------
Lime Mountain	Undeveloped	-----------	±400,000,000?	---X---	---X---	---X---	---X---	--------	--------	--------
Sultan	Undeveloped	-----------	600,000	--------	---?---	--------	--------	--------	--------	--------
Wallace River	Undeveloped	-----------	±500,000	---X---	---?---	---?---	---X---	---?---	--------	--------

2/ Described in text under Washington Monument deposit, p. 264.

TABLE 12.—Limestone and tufa deposits of western Washington; uses, potential uses, and reserves—Continued

Deposit	Development	Use	Reserves (tons)	Needs exploration	Potential uses					
					Cement	Pulp	Agriculture	Chemical	Decorative	Landscape
LIMESTONE DEPOSITS—Continued										
SNOHOMISH COUNTY—Continued										
Gold Bar deposits										
Haystack	Operating	Agriculture, flux, calcium carbide, landscape	±30,000	-	X	?	X	X	X	X
Marble	Exhausted	Agriculture	±1,000	-	X	?	X	X	X	X
Crystal Creek	Undeveloped	-	±10,000	-	-	-	X	-	X	X
Proctor Creek	Undeveloped	-	±82,000	-	X	?	X	X	X	X
Bonanza Queen	Undeveloped	-	±3,000,000?	X	X	?	X	-	-	-
		Snohomish County total	±540,550,200							
KING COUNTY										
Grotto										
Marble No. 1	Exhausted	Cement rock	-	-	-	-	-	-	-	-
Marble No. 2	Exhausted	Cement rock	-	-	-	-	-	-	-	-
Vulcan	Undeveloped	-	±100,000	-	X	?	X	?	-	-
Annex	-	-	0	-	-	-	-	-	-	-
Tombstone	Undeveloped	-	-100	-	-	-	-	-	-	-
Maloney No. 1	Undeveloped	-	±50,000	-	X	?	X	?	-	-
Maloney No. 2	Undeveloped	-	±20,000	-	X	?	X	?	-	-
Maloney No. 3	Undeveloped	-	±50,000	-	X	?	X	?	-	-
Maloney No. 4	Undeveloped	-	±3,000	-	X	?	X	?	-	-
Maloney No. 5	Undeveloped	-	±8,000	-	X	?	X	?	-	-
Maloney No. 6	Exhausted	Cement rock	-	-	-	-	-	-	-	-
Maloney No. 7	Undeveloped	-	±300	-	-	-	-	-	-	-
Palmer Mountain claims										
Baring Iron Mine	Undeveloped	-	-1,000	-	X	?	X	?	-	-
Calcite Placer	Exhausted	Cement rock	-	-	-	-	-	-	-	-
Carbonate Placer	Undeveloped	-	±3,000	-	-	-	-	-	-	-
Marble Beauty	Undeveloped	-	-500	-	-	-	-	-	-	-
Marble Dale	Undeveloped	-	Unknown	-	-	-	-	-	-	-
Marble Cliff	Undeveloped	-	±20,000	-	X	?	X	?	-	-
Marble Gem	Undeveloped	-	0	-	-	-	-	-	-	-
Marble Gulch	Undeveloped	-	-100	-	-	-	-	-	-	-
Marble Jack	Undeveloped	-	0	-	-	-	-	-	-	-
Marble King	Undeveloped	-	0	-	-	-	-	-	-	-
Marble Mount	Undeveloped	-	-100	-	-	-	-	-	-	-
Marble Quarry	Undeveloped	-	-100	-	-	-	-	-	-	-
Marble Wonder	Undeveloped	-	0	-	-	-	-	-	-	-
Baring (Skyko Camp)	Undeveloped	-	±5,000	-	X	?	X	X	-	-
Denny Mountain	Undeveloped	-	6,000,000	-	-	?	X	-	-	-
Guye Peak	Undeveloped	-	Unknown	X			Unknown			
Chair Peak	Undeveloped	-	Trace	-	-	-	-	-	-	-
		King County total	±6,261,200							
KITTITAS COUNTY										
French Cabin Creek	Undeveloped	-	Unknown	X			Unknown			
Boulder Creek	Undeveloped	-	Unknown	X			Unknown			
Teanaway River	Undeveloped	-	Unknown	X			Unknown			
Taneum-Manastash Creek	Undeveloped	-	Unknown	X			Unknown			
		Kittitas County total	Unknown							
CHELAN COUNTY										
Soda Springs	Operating	Cement rock	±15,000,000	-	X	-	X	-	-	X
Lucky Line	Undeveloped	-	±1,000,000	-	X	-	X	-	-	X
Rainy Creek	Undeveloped	-	+5,000,000	X	X	-	X	-	-	X
Dry Creek	Quarried	Lime	±100,000	-	-	?	X	-	X	X
Marble Creek (Paradise)	Undeveloped	-	±200,000	-	X	?	X	X	X	X
Indian Creek	Undeveloped	-	±1,000	-	X	-	-	-	X	X
Gold Ridge	Quarried	Decorative	±3,000,000	-	X	?	X	X	X	X
Manson (Wapato Lake)	Quarried	Lime	-5,000	-	-	-	X	-	X	X
Entiat	Undeveloped	-	±2,500,000	-	-	-	X	-	X	X
Storme	Quarried	Lime	Small	-	-	-	X	?	X	X
Lake Chelan Area										
Section 29	Quarried	Lime	-1,000	-	-	-	-	-	X	X
Section 13	Quarried	Lime	-5,000	-	-	-	X	-	X	X
Section 14	Quarried	Lime	-1,000	-	-	-	-	-	X	X

TABLE 12.—Limestone and tufa deposits of western Washington; uses, potential uses, and reserves—Continued

Deposit	Development	Use	Reserves (tons)	Needs exploration	Potential uses: Cement	Pulp	Agriculture	Chemical	Decorative	Landscape
LIMESTONE DEPOSITS—Continued										
CHELAN COUNTY—Continued										
Holden Area	Undeveloped	----------	Unknown	---X---			Unknown			
		Chelan County total	±26,813,000							
GRAYS HARBOR COUNTY										
Humptulips East Fork No. 1	Undeveloped	----------	Unknown	---X---			Unknown			
Schofield Creek	Undeveloped	----------	±4,000	--------			Unsuitable for most uses			
Copper Creek	Undeveloped	----------	±40,000	--------			Unsuitable for most uses			
		Grays Harbor County total	±44,000							
JEFFERSON COUNTY										
Pulali Point	Undeveloped	----------	-10	--------			Unsuitable for most uses			
MASON COUNTY										
Staircase	Undeveloped	----------	±50,000	--------			Unsuitable for most uses			
PACIFIC COUNTY										
Bear River	Quarried ---	Agriculture -	-100,000	--------	---X---	--------	---X---	--------	--------	---X---
Menlo	Undeveloped	----------	-1,000	--------	--------	--------	---X---	--------	--------	---X---
		Pacific County total	-101,000							
		Limestone Grand total	±1,244,223,710							
TUFA DEPOSITS										
WHATCOM COUNTY										
Church Mountain	Undeveloped	----------	±1,000	--------	--------	--------	---X---	--------	--------	---X---
Silver Lake No. 2	Undeveloped	----------	-5	--------	--------	--------	---X---	--------	--------	--------
SKAGIT COUNTY										
Strong	Quarried ---	Agriculture -	Unknown	--------	--------	--------	---?---	--------	--------	---X---
Alverson	Undeveloped	----------	Unknown	--------			Unknown			
SNOHOMISH COUNTY										
Reece Ridge Way	Undeveloped	----------	-1	--------			Unknown			
Blackoak Creek	Quarried---	Agriculture -	±10,000	--------	--------	--------	---X---	--------	--------	---X---
PIERCE COUNTY										
McMillin	Exhausted --	Agriculture -	±500	--------	--------	--------	--------	--------	--------	---X---
		Tufa total	±11,506							

STRATIGRAPHY OF WESTERN WASHINGTON LIMESTONE-BEARING ROCKS

A knowledge of the stratigraphic geology of an area is necessary for the proper exploration and development of nonmetallic mineral resources and the search for new deposits. However, except for the Cenozoic rocks, stratigraphic studies have been largely neglected in western Washington and little published information is available. The following brief discussion of the sedimentary sequences of western Washington gives emphasis to the units that contain carbonate rocks.

For purposes of description the stratigraphy of western Washington can be divided into five categories according to geologic age. These are, from oldest to youngest: pre-Devonian, Devonian through Permian, Mesozoic, Cenozoic, and Pleistocene-Recent. Most of the carbonate rocks occur within the second sequence, Devonian through Permian, but small limestone bodies are known in all groups, except possibly the pre-Devonian. Limestone deposits are being formed at the present time as tufa spring deposits and as beds of oyster shells in a few western Washington bays.

Most of the marine Paleozoic and Mesozoic rocks and a large part of the Cenozoic rocks in western Washington belong to the eugeosynclinal suite, which is generally characterized as being composed of pillow lavas, ribbon cherts, graywackes, breccias, siltstones, dark-colored shales, and lenticular bodies of limestone. The Paleozoic eugeosynclinal rocks appear to contain more volcanic rocks, ribbon cherts, and limestones than clastics, whereas the Mesozoic rocks have a preponderance of clastic rocks and fewer volcanic rocks, cherts, and limestones. Cenozoic sequences contain a large volume of volcanic rocks interbedded with clastics. The marine Cenozoic sections are notably lacking in chert but contain small amounts of impure limestone. From Late Cretaceous time onward a high proportion of the sedimentation in western Washington was nonmarine. Units of nonmarine origin have not been identified positively in the older sequences.

PRE-DEVONIAN ROCKS

Pre-Devonian sedimentary rocks in the northern Cascade Mountains were first described from a locality near the town of Skykomish, King County (Smith, 1916), where the brachiopod *Rafinesquina deltoidea* Conrad and a single specimen of the glabella and fixed cheeks of the trilobite *Illanenus americanus* Billings were collected from a "cherty phase of the limestone lens outcropping in Lowe Gulch 2 miles west of Grotto." The sequence including the limestone was named the Maloney Metamorphic Series and was described as including "quartzites, limestone, and schists of sedimentary origin cut by basic igneous rocks, usually best described as greenstones." The fossils were identified by Caroline A. Duror as of Ordovician age.

No other Ordovician fossils have been found in western Washington. The nearest known Ordovician locality is about 200 miles to the northeast, in Stevens County. Smith's fossil locality has never been rediscovered, and the whereabouts of his original collection is unknown (Marshall Kay, written communication, 1954). In 1949 the writer found a float boulder of limestone in a gully on the northeast side of Palmer Mountain near the reported Ordovician fossil locality. This boulder contained numerous specimens of the Permian fusulinids *Neoschwagerina* and *Schwagerina*. Limestone outcrops a short distance to the west contain crinoid columnals as much as two-fifths of an inch in diameter, and what is believed to be a crinoid columnal over an inch in diameter was found in finely crystalline limestone on the west side of Lowe Gulch. Large crinoid columnals are characteristic of the Lower Pennsylvanian limestones of northwestern Washington. Thus, fossil evidence indicates that at least a part of the sequence in this area is of Permian age, and some may be of Pennsylvanian age. The actual occurrence of Ordovician rocks in western Washington is subject to speculation, but if they are present, they are represented by crystalline limestones, metamorphosed ribbon cherts, volcanic rocks, and hornfelsed sedimentary rocks cropping out in the mountains north and south of Grotto.

No other definitely identified pre-Devonian sedimentary rocks have been described in western Washington. However, a metamorphic-igneous complex of amphibolite, gneiss, diorite, and quartz diorite thought to be of pre-Devonian age has been found in the northern Cascade Mountains at several localities (Misch, 1963, 1964; Miller and Misch, 1963; Yeats, 1964). A similar complex occurs on several of the San Juan Islands. In 1958 Joseph Vance, while in company with the writer at the particularly well-exposed section on the west side of Fidalgo Island, first suggested the possibility that these rocks may be "basement" instead of a Mesozoic intrusion. In 1959 the writer found fossiliferous Devonian rocks overlying a similar basement with apparent unconformity on O'Neal Island. No rocks believed to be of sedimentary origin have yet been found in this basement complex below the Devonian in the San Juan Islands except possibly at Bell Point, San Juan Island, where an unfossiliferous conglomerate similar to Devonian conglomerates elsewhere on the islands unconformably overlies a green phyllite. The Devonian conglomerate contains pebbles of limestone and other sedimentary rocks, but no fossils have been found in these materials to indicate their age.

Except for Smith's (1916) unconfirmed Ordovician of the Maloney Metamorphic Series of King County, no limestone is known in outcrops of rocks thought to be of pre-Devonian age in western Washington. However, the age of crystalline limestone in the highly metamorphosed rocks of the central part of the northern Cascade Mountains is unknown.

MIDDLE AND UPPER PALEOZOIC ROCKS

Exposures of middle and upper Paleozoic rocks in western Washington are confined to the northern and central Cascade Mountains and the San Juan Islands. In the western part of the northern Cascade Mountains and on the San Juan Islands they constitute large areas of bedrock outcrop. They are composed of slightly to intensely sheared sedimentary and volcanic rocks of eugeosynclinal type, including ribbon chert, graywacke, graywacke siltstone, lithic sandstone, argillite, breccia, conglomerate, limestone lenses and pods, pillow lavas, volcanic flows, and fragmental volcanic rocks. Throughout much of western Washington they are notably unaffected by any great amount of metamorphism.

Fossils collected mostly from limestones within these Paleozoic rocks indicate a variety of ages, including Middle and Late Devonian, Early Pennsylvanian, and early, middle, and late, but not latest, Permian. Some of the beds are richly fossiliferous locally, but, on the whole, fossils are scarce. Many of those that are found are unknown in other parts of North America and constitute a fauna closely related to the Tethyan faunal province of the Far East and Mediterranean regions. This American Tethyan fauna has never been studied in detail (though several projects are underway) and, except for the Permian fusulinids, it remains undescribed.

Prior to 1949, geologic investigations of the Paleozoic sequences were mostly of reconnaissance nature, so that, for the most part, the rocks were classed only as part of "the old Metamorphic Series." However, Daly (1912) grouped the Paleozoic rocks along the British Columbia-Washington boundary into his Chilliwack "Series." In later years this unit has been referred to as the Chilliwack Group by Canadian and American workers, and recently it has been formally redefined as the Chilliwack Group (Moen, 1962, p. 8). McLellan (1927) called Devonian-Mississippian rocks on the San Juan Islands the Orcas Group, and he correlated Pennsylvanian-Permian rocks with the Leech River Group on Vancouver Island. However, the latter unit contains no fossils at its type locality nor elsewhere on Vancouver Island. Since 1949 much of the physical stratigraphy and petrography of the northern Cascade Mountains has been studied by Peter Misch and students of the University of Washington. Provisional names have been assigned to some of the Paleozoic units in the Cascade Mountain foothills (Danner, 1957), but until more details of the stratigraphy can be worked out, these units cannot be designated formally. Work on this problem is in progress.

Devonian Rocks

Devonian sedimentary and volcanic rocks crop out in the San Juan Islands and in the northern Cascade Mountains of western Whatcom and Skagit Counties. Limestones are widespread in the sequence and, for the most part, are high in calcium, though locally they are argillaceous and partly silicified.

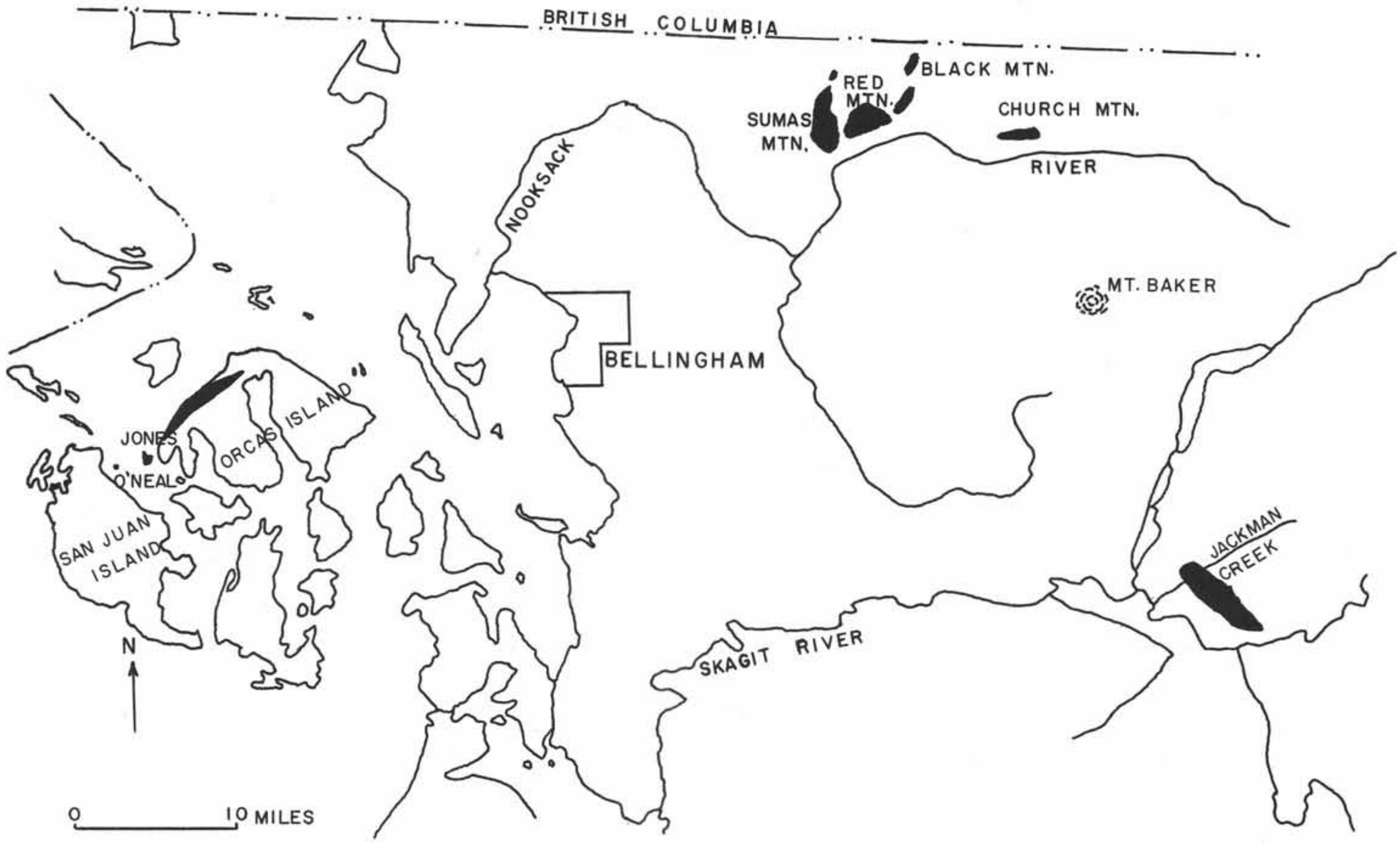

FIGURE 14.—Outcrop area of known Devonian rocks in western Washington.

San Juan Islands

Devonian rocks in the San Juan Islands were first described by McLellan (1924, 1927) and assigned to the Orcas Group, a unit he believed to also contain rocks of Mississippian age. More recent studies of the Orcas Group have failed to disclose any fossils that can be identified as of Mississippian age.

Devonian rocks of the San Juan Islands consist of shale, conglomerate, breccia, graywacke, graywacke siltstone, limestone, ribbon chert, and spilitic volcanic rock. The thickest known section, about 1,500 feet thick, is on the west coast of Orcas Island. The base of the section is not exposed, and the top, although not readily identifiable, is believed to be an erosion surface overlain by volcanic flows and breccias of Early Pennsylvanian or post-Pennsylvanian age. Limestone is scattered through the section and forms pods and lenses ranging in thickness from a few feet to 100 feet or more. Five of the largest limestone bodies have been quarried in the past, and two of the quarries have been reactivated recently.

A conglomerate thought to be near the base of the Devonian sequence on the west coast of Orcas Island consists of scattered pebbles, cobbles, and boulders composed predominantly of amphibolite, dioritic rocks, limestone, and volcanic rocks, all embedded in a graywacke matrix. A similar conglomerate occurs at Bell Point, on the northwest coast of San Juan Island. Angular fragments of amphibolite and diorite are at the base of the Devonian section on O'Neal Island.

No marker beds have been determined, and all the rock types appear to form lenticular bodies that thicken, thin, and pinch out along strike. The limestone bodies are banks or reefoid complexes formed in shallow water in a volcanic archipelago. A variety of limestone types are present and include organic-skeletal, organoclastic, and pelleted textures, algal precipitates, and limestone conglomerates.

Devonian fossils have been found at 11 localities in the San Juan Islands and include the following:

Brachiopods
- Atrypa devoniana, types A and B
- Productella
- Stringocephalus?

Stromatoporoids
- Amphipora
- Idiostroma

Protozoa
- Wetheredella

Gastropod
- Euryzone

Alga
- Rothpletzella

Other corals and brachiopods have been collected but are too poorly preserved for identification. The fauna and flora of these rocks places them in the upper part of the Middle Devonian.

Devonian rocks are known to crop out along the west coast of Orcas Island and to extend northeastward to near the head of East Sound; they also occur on the east side of Jones Island, the south side of O'Neal, and possibly at Bell Point and vicinity on the northwest side of San Juan Island. Rocks with poorly preserved fossils that may be Devonian in age crop out on the northwest side of Mount Constitution, on the east side of Orcas Island.

Northern Cascade Mountains

Devonian rocks of the northern Cascade Mountains consist predominantly of thin-bedded siltstone, shale, and graywacke, along with lesser amounts of limestone, chert, and volcanic rocks. The thickness of the sequence is estimated to be at least 2,000 or 3,000 feet, but the rocks are poorly exposed and neither the top nor the bottom is definitely known. Limestone beds in the form of lenticular reefs, banks, and argillaceous beds are most commonly associated with fine-grained clastic rocks. A few of the limestones are relatively pure, but most of them are argillaceous, and in some areas there has been a considerable amount of secondary silicification. Most of the limestone bodies in western Whatcom County appear, on the basis of fossil evidence, to represent approximately the same stratigraphic horizon. Those in Skagit County appear to represent either a different stratigraphic horizon or a different facies. The fossil evidence of their age is poor; it is possible they may be older than Devonian.

Sheared gray sandstones and siltstones containing carbonized plant fragments are found beneath limestone on the west side of Sumas Mountain, in western Whatcom County. They are believed to have been deposited in a near-shore, shallow-water, marine environment.

The Devonian rocks of the northern Cascade Mountains form the lower part of the Chilliwack Group. They are informally referred to as the American Sumas Mountain sequence. Its base may be exposed west of the Doaks Creek limestone quarry, where outcrops on a hillside south of Doaks Creek contain a coarse conglomerate containing cobbles of granitic rock and limestone.

Fossils are numerous in the Devonian limestones, but many have not as yet been identified. The most common fossil is the coral Scoliopora (Plagiopora), first recognized in specimens identified by Professor M. Lecompte of the Institut Royal des Sciences Naturelles de Belgique. Fossils so far identified include:

Skagit County

Brachiopod
- Atrypa sp.

Scolecodont
- Oenonites?

Whatcom County

Coelenterata	Stromatoporoids	Algae	Protozoa
Scoliopora (Plagiopora)	Amphipora	Rothpletzella	Wetheredella
Thamnopora	Stromatoporella	Calcisphaera	Brachiopod
			Atrypa sp.

The Devonian limestones of Whatcom County are believed to be of Frasnian age, or of the early part of the Late Devonian. Limestones of the Jackman Creek area of Skagit County are probably of the same age, but those cropping out north and east of Rockport may be older.

In Whatcom County the Devonian rocks of the Chilliwack Group are known to occur on the east side of American Sumas Mountain, east of Paradise Valley; to the north on an isolated hill in the NW$\frac{1}{4}$ sec. 9, T. 40 N., R. 5 E., south of Vedder Mountain; on the west side of Red Mountain in the center of sec. 23, T. 40 N., R. 5 E.; on the east side of Red Mountain south of Doaks Creek in sec. 19, T. 40 N., R. 6 E.; on the west side of Black Mountain east and southeast of Silver Lake in secs. 5 and 17, T. 40 N., R. 6 E., and on the southwest side of American Church Mountain along the west Church Mountain logging road, in the E$\frac{1}{2}$ sec. 32, T. 40 N., R. 7 E.

In Skagit County, Devonian rocks crop out along the west side and probably the east side of Jackman Creek in secs. 4 and 5, T. 35 N., R. 9 E., and rocks believed to be of Devonian or older age crop out on the south side of Sauk Mountain along Presentine Creek north of Rockport. A sequence of thin-bedded graywacke siltstone and limestone cropping out north of the Skagit River from Sutter Creek to Rocky Creek, though lacking identifiable fossils, may also be of Devonian age. Volcanic rocks are included in this sequence.

In the past, several Devonian limestone bodies have been quarried as a source of rock for cement and pulp mills. However, in recent years only one small body, at Doaks Creek, has been quarried.

Devonian rocks have not so far been recognized across the border in southwestern British Columbia, but they may occur on Vedder Mountain and in the Liumption Creek area.

Mississippian Rocks

No limestones of Mississippian age are known in western Washington at the present time, and none of the Paleozoic rock sequences contain fossils that are definitely identified as being of this age. It is not know whether rocks of Mississippian age are missing because of non-deposition or removal by erosion or whether they are present but unrecognized because they have so far proved to be unfossiliferous. If they are present, they must be represented by a relatively thin sequence that does not contain limestone.

Pennsylvanian Rocks

Rocks of Pennsylvanian age are widespread in northwestern Washington and have been identified in Whatcom, Skagit, and Snohomish Counties in the northern Cascade Mountains and on Orcas Island and possibly San Juan Island in San Juan County. They may extend northwestward on Vancouver Island, but have not been definitely recognized there, although part of the limestones cropping out at Horne Lake may contain Pennsylvanian fossils. They extend northeastward from Whatcom County into the Skagit Ranges of British Columbia and across the Fraser River valley to at least the southeast side of Harrison Lake. A part of the Chilliwack Series of Daly (1912) (Chilliwack Group of Moen, 1962) is composed of rocks of Pennsylvanian age. These rocks are informally designated the Red Mountain sequence of the Chilliwack Group. The largest limestone deposits of western Washington occur in this sequence, and although they may be argillaceous, siliceous, and in places high in magnesium carbonate, the rock is suitable for cement and for use in pulp mills.

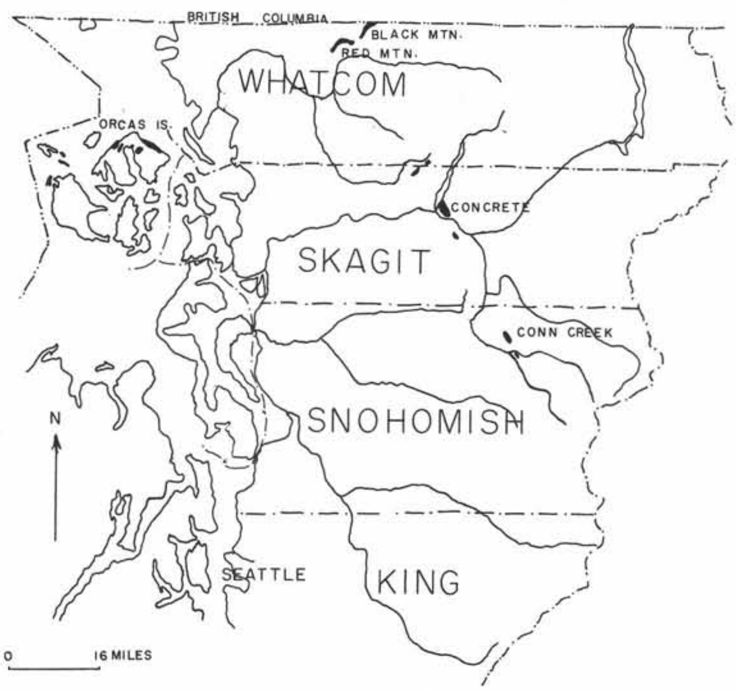

FIGURE 15. — Outcrop area of known Pennsylvanian rocks in western Washington.

San Juan County

Rocks of Pennsylvanian age are known on Orcas Island, in San Juan County, where they crop out on the northwest slopes of Mount Constitution and along the northeast coast of the island. They consist predominantly of thin-bedded shales, siltstones, and graywackes, with small interbedded limestone lenses, and volcanic flows and breccias. Thin seams of very poor quality coal are present in at least one locality on the northeast coast of Orcas Island. The thickness of the Pennsylvanian rocks is not accurately known because of poor exposure, but is estimated to be between 500 and 1,000 feet. Poorly preserved foraminifers found in limestone at Roche Harbor on San Juan Island suggest that the limestones there may be of Pennsylvanian age, but a Permian age is possible.

Fossils in the Pennsylvanian limestones include large crinoid columnals, corals, foraminifers, and bryozoans. A cast of the thorax and pygidium of a trilobite was collected in one outcrop but could not be identified. The fusulinid Eostaffella and one or more species of the foraminifer Tetrataxis are abundant in these limestones and indicate an Early Pennsylvanian age. A fragment of limestone collected from a breccia exposed above the Devonian limestones on Orcas Knob, western Orcas Island, contained part of a large brachiopod shell similar to Gigantoproductus, endothyrid foraminifers, the fusilinids Eostaffella and Ozawainella, and the stromatoporoid? or alga? Komia.

Northern Cascade Mountains

Pennsylvanian rocks crop out at many localities in the foothills of the northern Cascade Mountains. They are predominantly thin-bedded siltstones, and graywackes containing interbedded massive to well-bedded argillaceous limestones. Conglomerate, chert, and volcanic rocks are also present. The thickness is not known accurately, but is estimated to be between 1,000 and 2,000 feet. The lower contact has not been recognized, and the upper part of the sequence is overlain disconformably by coarse- and fine-grained clastics of either Late Pennsylvanian or early Permain age. It is not known whether there is more than one stratigraphic horizon of limestone beds, but most of the Pennsylvanian limestone appears to be near the top of the sequence and is characterized by distinctive large crinoid columnals. Other fossils include corals, a stromatoporoid?, bryozoans, brachiopods, gastropods, pelecypods, worm tubes, and foraminifers. Tetrataxis, endothyrid foraminifers, and the fusulinids Eostaffella and Ozawainella are especially abundant in oölitic limestones. At several localities in feldspathic sandstones underlying the limestone, conical shells (?), preserved as thin films of black carbonaceous material, are abundant and commonly associated with macerated plant remains and the molds of pelecypods and gastropods. The dating of the limestones is somewhat doubtful, as they contain brachiopods strongly resembling those of the Visean (Mississippian) of Asia and Europe, a few foraminfers and a stromatoporoid? that seem to be characteristic of the Early Pennsylvanian in many parts of the world, and a coral fauna of distinctive Asiatic type, which appears to have strong affinities with the Permian.

The following fossils have been identified[1] from the supposed Lower Pennsylvanian limestones on Black and Red Mountains, Whatcom County:

Protozoa
- Eostaffella (Paramillerella)
- Ozawainella
- Plectogyra
- Tetrataxis
- Cribrogenerina

Coelenterata
- Iranophyllum aff. I. spongifolium Smith
- Pseudoromingeria?
- Lophophyllidium
- Carruthersella? sp.
- Heritschioides (Waagenophyllum)
- Cyathaxonia?

Echinodermata
- Platycrinid columnals, indet.
- Large crinoid columnals, indet.
- Echinoid spines

Brachiopoda
- Gigantoproductus?
- Spiriferid brachiopod, indet.

Stromatoporoid?
- Komia

Bryozoa
- Archimedes communis
- Fenestrate and cyclostomatan bryozoa, indet.

Mollusca
- Pelecypods, indet.
- Gastropods, indet.

Miscellaneous
- Calcareous worm tubes
- Conical shells of unknown affinity

Limestones form large lenticular beds that are at least 400 feet thick on Red Mountain and may be thicker on the northeast side of Black Mountain and at Concrete, Skagit County. Locally the limestones appear to be internally deformed, but in most places where they are well bedded they show a homoclinal dip. Limestone that is more argillaceous in composition usually shows good bedding.

The limestone is overlain by argillite, graywacke, and volcanic rocks on Red Mountain and by a thick basalt-andesite-chert cobble conglomerate and graywacke on Black Mountain and farther north in the Liumption and Church Mountain areas of British Columbia. Clastic sedimentary and volcanic rocks overlie the limestone to the southeast, in Skagit and Snohomish Counties. On Black Mountain and Red Mountain these overlying clastics locally contain poorly preserved plant remains, some of which have been identified as Calamites and Lepidodendron (Glenn Rouse, oral communication, 1963).

In Whatcom County, Pennsylvanian limestone crops out at the east base of American Sumas Mountain in sec. 21, T. 40 N., R. 5 E.; it forms a discontinuous series of lenses striking across Red Mountain from the southeast corner of sec. 15 northeastward through secs. 14 and 13, T. 40 N., R. 5 E.; it continues in secs. 7 and 4, T. 40 N., R. 6 E., and on northeastward into British Columbia. In Skagit County similar limestone is found forming two northwest-trending ridges northeast of the town of Concrete. It crops out again near the northern boundary of the county at Washington Monument, as well as over a mile to the northeast just over the border in Whatcom County, on the ridge west of Blue Lake. Limestone exposures southeast of Concrete on Sutter Mountain and on the high ridges west of Sauk Mountain and east of Jackman Creek may also be of Pennsylvanian age, but no fossils diagnostic of age have been found in these areas. Pennsylvanian limestone in Snohomish County crops out 6 miles southeast of Darrington, in the Conn Creek area.

The cement plants at Bellingham and Concrete obtain limestone from quarries in the Pennsylvanian sequence. The Silver Lake quarry, in Whatcom County north of Maple Falls, also in Pennsylvanian limestone, is used as a source of pulp rock. Relatively large undeveloped limestone bodies of Pennsylvanian age occur in Whatcom and Skagit Counties, but because of the mountainous terrain, they are, for the most part, not easily accessible.

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[1] Fossils identified by Smith (1961), W. R. Danner, J. Thomas Dutro, Jr., Helen Duncan, and John W. Skinner.

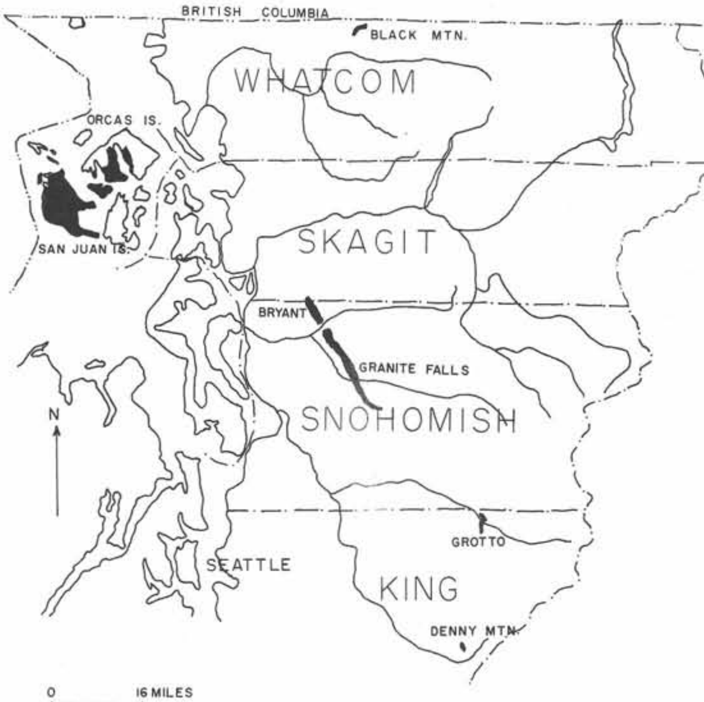


FIGURE 16. — Outcrop area of limestone-bearing rocks of Permian age in western Washington.

Permian Rocks

Rocks of Permian age (Danner, 1950, 1957) are known to occur in three areas of western Washington: San Juan Islands, Black Mountain in northern Whatcom County, and in a narrow southeast-trending belt of outcrops extending from Pilchuck Creek in southern Skagit County southeastward to the Grotto area of King County. In addition, outcrops at Denny Mountain, near Snoqualmie Pass in King County, may also be of Permian age.

The rocks can be divided into two units differing in age, fauna, and lithology. The older is referred to informally in this report as the Black Mountain sequence of the Chilliwack Group and is found in Whatcom County on Black Mountain and extending northeastward into British Columbia. The younger is referred to informally in this report as the Trafton sequence;[1] it comprises the sequence in San Juan, Skagit, Snohomish, and King Counties. At one locality on Double Hill, Orcas Island, in San Juan County, a limestone containing a fauna similar to that of the Chilliwack Group appears to be overlain by limestones with a fauna typical of the Trafton sequence, but nowhere else are the two sequences known to be in juxtaposition. This Orcas Island section may contain a greater Permian age range than any of the other localities in western Washington.

Limestones of Permian age are mostly lenticular in shape and range in thickness from a few inches to 400 feet. All that have been mapped are less than 5,000 feet in length, but similar limestone bodies in the Chilliwack Valley of British Columbia are larger in size.

The Black Mountain sequence of the Chilliwack Group contains relatively large lenticular beds of argillaceous, cherty, and magnesian limestone, argillite, cherty argillite, volcanic rocks, quartzitic chert, graywacke, and conglomerate. Black chert is common in the limestone.

The younger Trafton sequence contains many small high-calcium limestone lenses and partially dolomitized limestone lenses, spilitic greenstone flows, ribbon chert, argillite, graywacke, and sedimentary and volcanic breccias.

Most of the fossils are found in the limestone and consist of abundant faunas of fusulinid foraminifers usually associated with calcareous algae. Bryozoa are fairly abundant in the Chilliwack Group. Fusulinid faunas, especially those from the upper part of the western Washington Permian (Trafton sequence) are similar in many respects to those of the Eastern Hemisphere, particularly from the Permian of Japan, China, Indo-China, Sumatra, and New Zealand, and similar to the Mediterranean faunas of Crimea, Yugoslavia, and Tunisia. Middle and upper Permian rocks of the Eastern Hemisphere are commonly believed to have been deposited in a seaway called by geologists "The Tethys," extending from the Mediterranean region to New Zealand and Japan and apparently connected across the Pacific Ocean to Yukon, British Columbia, Washington, and Oregon. The most notable features of the deposits containing the Tethyan fauna in North America are the lack of abundant fossils other than crinoid debris, fusulinids, and calcareous algae, and the predominance of volcanic rocks, ribbon cherts, and clastic rocks typical of a eugeosynclinal environment. The limestones are also distinctive, being mostly high in calcium (where not locally dolomitized) and relatively free of argillaceous matter. They appear to have been deposited in shallow open water on banks in a volcanic archipelago.

1/ This sequence was formerly referred to as the Stillaguamish Group (Danner, 1957).

It is possible that the differences between the Tethyan faunas and the other Permian faunas of North America may be more that of an environmental facies difference than that of an isolated seaway with a distinctive isolated fauna. The pure limestones of the Trafton sequence with spilitic flows and ribbon cherts contain the Tethyan fauna, and the more argillaceous limestones of the Chilliwack Group contain typical Cordilleran faunas.

Correlations have not yet been satisfactorily established between Permian rocks of China and Japan, Washington-Oregon-British Columbia, and the American central and southern Cordillera. Correlations of North American Permian sections are given by Dunbar and others (1960).

San Juan Islands

Permian rocks in the San Juan Islands compose a section that is estimated to be 5,000 feet or more in thickness and that is divisible into the following three parts:

Part III	1,000-5,000 feet	Mainly argillite with minor amounts of graywacke, tuff, and a few thin volcanic flows; rare small lenses of limestone.
Part II	800-1,000 feet	Mainly ribbon chert with minor amounts of tuff, limestone, argillite, and thin volcanic flows.
Part I	500-3,000 feet	Mainly submarine volcanic flows and breccias, tuff, ribbon chert, limestone, argillite, and graywacke.

Identifiable fossils have been found only in Part I, and range from Wolfcampian to Late Guadalupian in age. Part II is probably Guadalupian in age. Part III may extend into the Early Mesozoic.

Part I.—Rocks assigned to Part I are exposed along the west coast of San Juan Island between Deadman Bay and Smallpox Bay. They consist of massive to ellipsoidal spilitic flows and breccias containing lenticular bodies of ribbon chert and partly dolomitized limestone. A small area of similar rocks is exposed to the north along the island shore between Mitchell Bay and Smugglers Cove.

The base of the sequence has not been found exposed, but it is possible that Part I rocks thin northward and are either overlapped by rocks of Part II or interfinger and pinch out within them. Part II rocks appear to rest either in fault contact or unconformably on rocks of questionable Pennsylvanian or Devonian age and on "basement rocks" in the Roche Harbor area. South of Roche Harbor, along the west side of San Juan Island, Part II rocks rest conformably on top of the volcanic sequence of Part I.

Limestones of the Cowell quarry and Deadman Bay area on the west coast of San Juan Island contain the following fossils:

Foraminifera (Cowell quarry)	Algae (Deadman Bay)
Neoschwagerina	Oligoporella expansa
Schwagerina	Mizzia velebitana
Pachyphloia	Gyroporella igoi

No fossils have been identified in the limestone exposed in the walls of the abandoned limestone quarry at Mitchell Bay, but a small outcrop less than 200 feet to the south of the quarry contains Neoschwagerina (M. Nestell, written communication, 1964), and less than 500 feet to the south of the quarry a limestone bed exposed at the head of a small cove contains a large Schwagerina and algae tentatively identified as Mizzia and Gyroporella.

Fossiliferous limestones of Part I crop out on Orcas Island at the northwest side of East Sound, north and south of Judd Cove, and on the hillside above known as Double Hill. The sequence is composed mostly of volcanic flows and breccias but also contains ribbon cherts, argillites, siltstones, and volcanic arenites. The sequence either rests unconformably on or is in fault contact with gneissic amphibolites, serpentines, and dioritic rocks of the pre-Devonian basement complex. The following fossils have been collected from limestone in this area:

North and south of Judd Cove
- Neoschwagerina
- Schwagerina

Double Hill No. 4 limestone
- Misellina
- Calcareous algae

Field near East Sound-West Sound-Orcas Landing road junction (Fowler farm).
- ?Yabeina or Neoschwagerina

Double Hill No. 1 limestone
- Schwagerina
- ?Pseudofusulinella
- ?Parafusulina
- Rhomboporella

Part II.—Part II rocks crop out on San Juan, Orcas, and Shaw Islands, and are composed of ribbon cherts, predominantly, and lesser amounts of clastic sediments and volcanic rocks. On San Juan Island the sequence is well exposed along the south and west coasts from Deadman Bay south to Cattle Point. North and east of Deadman Bay it constitutes the high ridge of Mount Dallas and is exposed again along the shore from Smallpox Bay to Smugglers Cove and probably comprises all the rocks of Henry and Battleship Islands. It forms a belt of outcrops across the north part of San Juan Island and south along the east coast to the vicinity of the Eureka limestone deposit, north of Friday Harbor. Several small limestone bodies are interbedded with the ribbon chert throughout these rocks. No fusulinids have been found in place in these limestones, but fusulinid-bearing limestone float has been found near outcrops on the west side of Young Hill and at the Eureka deposit. Several limestones in this group of rocks contain masses of thin filamentous-appearing shells believed to be similar to the thin shells of the pelagic pelecypod Pseudomonotis. At Limestone Point, well-bedded limestone contains fragments of bryozoans, foraminifers, and algae. Of these, the foraminifer Pachyphloia Lange has been recognized. Small spherical bodies, which may be foraminifers or calcite-replaced radiolarians, are abundant in the limestones at Limestone Point and Rocky Bay.

Ribbon cherts crop out in a northeast-striking belt across Orcas Island from Deer Harbor to Mount Constitution and appear to lie directly on or to be in fault contact with pre-Devonian basement rocks. No fossils have been found in limestones within the Orcas Island part of Part II. The large limestone deposit known as the McGraw-Kittinger ledge was reported by McLellan (1927) to be composed of the coral Lithostrotian, but no specimens could be found during the present investigation.

Part III.—Ribbon cherts of Part II appear to grade upward into a sequence of fine-grained clastic rocks that, on western San Juan Island, include thick massive green lithic or volcanic graywackes. Minor amounts of ribbon chert and pillow-structure volcanic flows occur within the sequence, and limestone is rare. No fossils have been identified from this part. It occupies the trough of a large syncline forming the bulk of the interior of San Juan Island and also crops out on Shaw Island and the southern part of Orcas Island east and west of East Sound.

Northern Cascade Mountains

CHILLIWACK GROUP

Rocks of early Permian age (Black Mountain sequence of the Chilliwack Group) crop out on the northern end of Black Mountain, in western Whatcom County. The lowest limestone bed containing a definitely identified Permian fauna is separated from Early Pennsylvanian limestone by 150 to 400 feet of pebble and cobble conglomerate and sandstone containing plant fragments. This clastic sequence may be either Late Pennsylvanian or early Permian.

Above the clastic sequence is a lenticular body of gray, partly silicified and dolomitized limestone as much as 400 feet thick. It contains thin beds of black chert. Parts of the limestone are made up of a fusulinid coquina containing species of the following genera:

Schwagerina
Pseudofusulinella
Paraschwagerina

and other foraminifers including:

Textularia

and the bryozoans:

Rhomboporella, Stenopora, Fenestella, and Polypora.

Above the limestone are shales and graywackes containing two additional lenticular limestone beds, the lower of which appears to be less than 20 feet thick, and the upper of which is at least 50 feet thick. The thicker limestone contains rare fusulinids and brachiopods. Overlying the limestone is a sequence of quartzitic and cherty argillites and graywackes.

The Permian sequence extends northeastward across the Canadian border in the vicinity of Lihumitson Creek, where partially recrystallized limestones containing Permian fusulinids were discovered by Hillhouse (1956). The Permian sequence continues northeastward across the Chilliwack Valley to the south side of the Fraser Valley (James Monger, personal communication, 1963). Fusulinids similar to those found in the Chilliwack Group have been described in the Kettle Falls area of Stevens County, Washington, by Mills and Davis (1962).

No early Permian limestones similar to those of the Chilliwack Group have been identified south of Black Mountain, in the northern Cascade Mountains, but volcanic rocks and clastic sediments believed to lie above the Early Pennsylvanian part of the Chilliwack Group crop out to the southeast on Washington Monument peak and probably occur elsewhere.

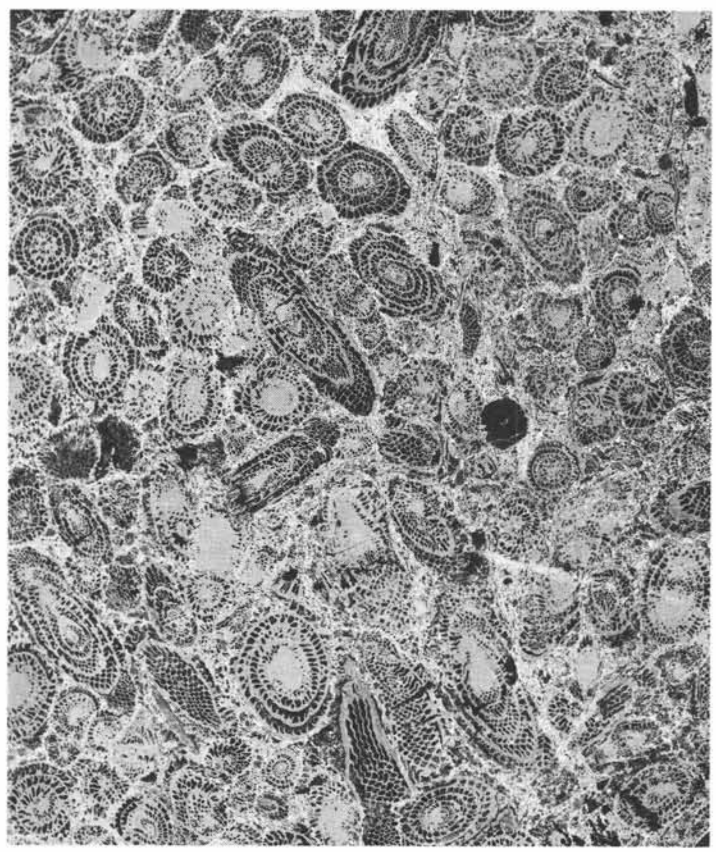


FIGURE 17.—Permian fusulinids, Chilliwack Group. Schwagerina and Pseudofusulinella. Acetate peel negative print. Black Mountain sequence of the Chilliwack Group, Black Mountain, Whatcom County. X 2.

TRAFTON SEQUENCE [1/]

The middle-upper Permian Trafton sequence crops out in a continuous belt extending from Pilchuck Creek, Skagit County, to Pilchuck River, Snohomish County, and reappears again to the southeast on Palmer Mountain, in the Grotto area of King County. Similar-appearing but unfossiliferous rocks on Denny Mountain near Snoqualmie Pass, King County, also are believed to be a correlative of the Trafton sequence.

Volcanic rocks, ribbon cherts, limestone, graywacke, and graywacke siltstone compose the common rock types. They are isoclinally folded and are cut by numerous small faults, but they may attain a maximum thickness of 5,000 to 10,000 feet. The base of the sequence has not been seen. The top is overlain with pronounced angular unconformity by Upper Jurassic-Lower Cretaceous rocks of the Nooksack Group.

Limestone forms only a very minor part of the Trafton sequence. Almost all known occurrences are lenticular bodies less than 200 feet thick and only a few hundred feet long. Despite their small size, these limestones have been important economically because of their high purity. Many of them are high in calcium and range from 95 to 99 percent calcium carbonate. The larger bodies have been quarried for many years for agricultural stone, flux, lime, pulp rock, and cement manufacture. Most of these deposits are now exhausted, and only one, near Bryant, Snohomish County, is still being quarried (for agricultural stone). Parts of some of the limestone bodies have been dolomitized, and limestones in the Grotto area and on Denny Mountain have been intruded by Mesozoic and Cenozoic plutonic rocks resulting in their recrystallization.

At least three fusulinid zones are known in the Trafton limestones. These include the Cancellina subzone of the Parafusulina zone, the Neoschwagerina-Verbeekina zone, and the Yabeina zone.

The following faunas have been collected in various limestones of the Trafton sequence:

Skagit Power Line limestone, Snohomish County
- Neoschwagerina brevis
- Pseudodoliolina oliviformis

South Twin Lakes, Snohomish County
- Pseudodoliolina
- Schwagerina caurus
- Small gastropods, indet.

Canyon Creek quarry, Snohomish County
- Yabeina cascadensis
- Schwagerina royandersoni
- Codonofusiella duffelli (?)
- Algae

Shumway quarry, Snohomish County
- Yabeina cascadensis
- Schwagerina royandersoni

FIGURE 18.—Permian fusulinids, Trafton sequence. Yabeina. Acetate peel negative print of limestone exposed in Canyon Creek quarry near Granite Falls, Snohomish County. Limestone fractured and recemented with calcite. X 2.

[1/] This sequence was formerly referred to as the Stillaguamish Group (Danner, 1957).

Paddock (Morcrop) limestone quarries, Snohomish County

Neoschwagerina brevis
Neoschwagerina morcropensis
Pseudodoliolina oliviformis
Verbeekina americana
Boultonia cascadensis
Cancellina
Yabeina
Climacammina
Schwagerina
Pachyphloia
Nigriporella minima (Rigby)
Small gastropods, indet.
Foraminifers, indet.
Crinoid debris
Algal fragments

Kelly Creek, Snohomish County

Cancellina
Schubertella
Gyroporella igoi
Mizzia velebitana

Palmer Mountain, King County

Neoschwagerina sp. indet.
Schwagerina sp. indet.

It is possible that the Trafton sequence is represented by metamorphic rocks exposed in Kittitas County, but no fossils have been found in these rocks to indicate their age. The Granite Falls Limestone (Anderson, 1941), exposed in the Canyon Creek and Shumway quarries of Snohomish County, appears to most closely correlate faunally with the Marble Canyon Limestone of southwestern British Columbia and an unnamed limestone in eastern Oregon discovered by Dr. David Bostwick, of Oregon State College (written communication, 1962). Other limestone lenses of the Trafton sequence correlate faunally with a limestone bed exposed on Kloch and Copley Mountains north of Trembleur Lake in north central British Columbia (Armstrong, 1949).

Correlation of Permian Formations, Western Washington and Southern British Columbia 1/

Age	Fusulinid zones 2/		Western Washington			Southern British Columbia		
Ochoan	*Palaeofusulina*							
	Codonofusiella							
Guadalupian	*Yabeina*		TRAFTON SEQUENCE	Limestones at Granite Falls			CACHE CREEK GROUP	Limestone at Marble Canyon
	Neoschwagerina-*Verbeekina*			Limestones at Morcrop quarry area, South Twin Lake, and Orcas and San Juan Islands				Faunas of this interval so far not recognized in southern British Columbia
Leonardian	*Parafusulina*	*Cancellina* Subzone		Limestones on south side of Mount Pilchuck				
		Misellina Subzone		Limestone at Double Hill	Chilliwack Group Black Mountain limestones	Chilliwack Group Chilliwack Valley		Limestone at Bonaparte River and Kamloops areas
Wolfcampian	*Pseudoschwagerina*-*Pseudofusulinella*							

1/ Based on fusulinid faunas in limestones.

2/ Modified from Sheng (1963).

Paleozoic Sequences Recognized in Western Washington [1]

Geologic time		San Juan Islands southeast to Snohomish County and King County	Northern Cascade Mountains, Whatcom and Skagit Counties, and eastern Snohomish County
PERMIAN	Ochoan		
	Guadalupian	Trafton sequence	
	Leonardian	Trafton sequence	Black Mountain sequence
	Wolfcampian	Double Hill limestone	Black Mountain sequence ? ? ? ?
PENNSYLVANIAN	Virgilian		Chilliwack Group: Plant-bearing clastic sedimentary rocks
	Missourian		Chilliwack Group: Plant-bearing clastic sedimentary rocks
	Desmoinesian		Chilliwack Group
	Lampasan	Raccoon Point beds	Chilliwack Group: Red Mountain sequence
	Morrowan	Raccoon Point beds	Chilliwack Group: Red Mountain sequence
MISSISSIPPIAN	Chesterian	NOT RECOGNIZED	Chilliwack Group; NOT RECOGNIZED
	Meramecian	NOT RECOGNIZED	Chilliwack Group; NOT RECOGNIZED
	Osagian	NOT RECOGNIZED	Chilliwack Group; NOT RECOGNIZED
	Kinderhookian	NOT RECOGNIZED	Chilliwack Group; NOT RECOGNIZED
DEVONIAN	Famennian		Chilliwack Group
	Frasnian		Chilliwack Group: American Sumas Mountain sequence
	Givetian	President Channel sequence	Chilliwack Group: American Sumas Mountain sequence ? ? ?
	Eifelian	President Channel sequence	Chilliwack Group ?
	Coblenzian		?
	Gedinian		
SILURIAN		NOT RECOGNIZED	
ORDOVICIAN		NOT RECOGNIZED	
CAMBRIAN		NOT RECOGNIZED	
PRECAMBRIAN		NOT RECOGNIZED	Pre-Devonian gneissic amphibolites, mylonitized amphibolites, dioritic rocks, age unknown

[1] Provisional names.

MESOZOIC ROCKS

Mesozoic rocks crop out in the San Juan Islands and in the northern Cascade Mountains. Probably they also occur in the central part of the Olympic Mountains, but their occurrence there has not yet been proven. In all these areas, clastic sedimentary rocks predominate and consist largely of graywackes, feldspathic subgraywackes, subarkoses, arkoses, conglomerates, slates, argillites, shales, volcanic flows and breccias, ribbon chert, and rare small lenses of limestone. The limestone is mostly argillaceous or cherty, and in only a few places does it occur in bodies more than a few feet thick. Except for the deposits of supposed Mesozoic age in the Skykomish River valley near Gold Bar, the Mesozoic rocks do not contain limestone of commercial value.

Mesozoic sequences fall into three general groupings according to age and composition:

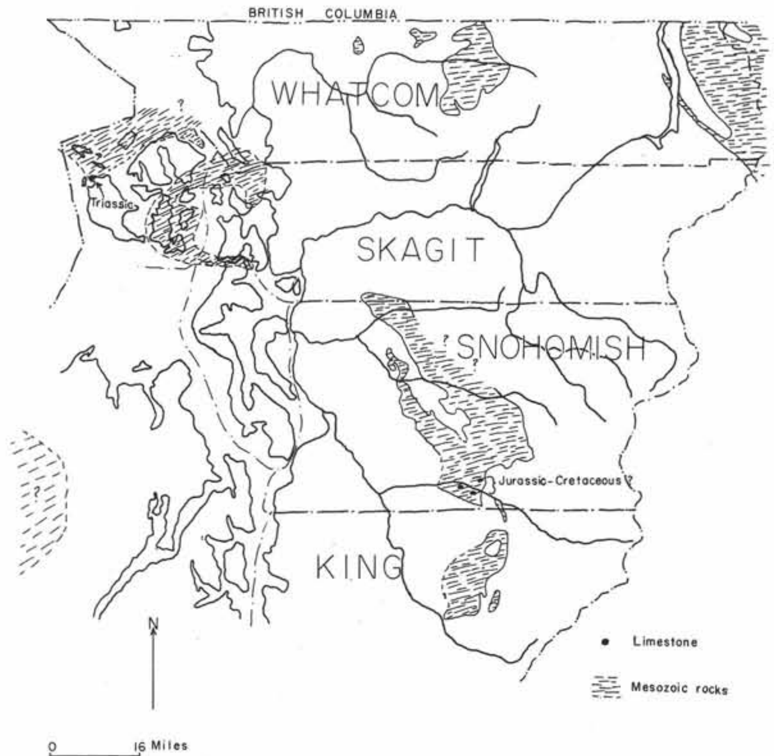


FIGURE 19.—Outcrop area of known Mesozoic rocks in western Washington.

Late Cretaceous: Arkosic and subarkosic sandstones, graywackes, shales, argillites, slates, pillow lavas, coarse conglomerates, and small lenses of argillaceous buff-weathering limestone.

Late Jurassic-Early Cretaceous: Feldspathic graywackes, slate-fragment breccias, argillites, slates, siltstones, volcanic flows and breccias, ribbon chert, and oölitic, dense, and fragmental limestone.

Late Triassic: Conglomerates, breccias, grits, lithic sandstones, calcareous graywackes, and black argillaceous to light bluish gray limestones.

Late Triassic Rocks

San Juan Islands

The only definitely identified Triassic rocks known in western Washington are those described by McLellan (1927) as the Haro Formation at the northwestern end of San Juan Island. It crops out on Davison Head, a narrow west-trending ridge connected to the main island by a low gravel bar, and on the main island coast south of the Head.

The rocks of the Haro Formation consist mainly of coarse conglomerates and breccias, grits, lithic sandstones, calcareous graywackes, siltstones, argillites, and limestones. A high percentage of the material making up the clastics is of volcanic origin. A bed of coarse breccia with a limestone matrix crops out along the south side of Davison Head. In places a dense gray porcelaneous-appearing limestone bed as much as 1 foot thick is present between breccia layers. Fragments of a similar-appearing limestone are scattered throughout the breccia. Thin layers of argillaceous limestone crop out on the north side of the Head.

On the shore of the main part of San Juan Island south of Davison Head is a steep southward-dipping sequence of thin-bedded grits, conglomerates, and red-weathering argillites that contains a section almost 50 feet thick of calcareous shales and black argillaceous and pyritiferous limestones. Thin interbeds of gray chert occur in the purer layers of this limestone. In thin section, the limestone is seen to be composed mostly of thin layers of shells of the pelagic pelecypod Halobia. An occasional echinoid spine, ostracod shell, or globular foraminifer is associated with the Halobia shells.

The sequence exposed on Davison Head and the mainland is approximately 1,400 feet thick. However, part of the section, at least, is broken by faulting and part or all may be overturned.

Limestone of the Haro Formation has never been quarried and is too impure and thin to have any economic value. No other rocks of Triassic age have been definitely identified in the San Juan Islands.

Northern Cascade Mountains

No Triassic rocks have been identified on the mainland of western Washington. Thin-bedded argillites and siltstones of the Cultus Formation of Early Jurassic age probably extend south from British Columbia into northern Whatcom County at the northern ends of Black and Red Mountains, but no fossils have been discovered in these rocks on the American side of the border, and therefore it has not been possible to differentiate these rocks from similar-appearing thin-bedded rocks of the associated Chilliwack Group of Paleozoic age.

Late Jurassic-Early Cretaceous Rocks

Northern Cascade Mountains

NOOKSACK GROUP

Most of the rocks of Late Jurassic-Early Cretaceous age in northwestern Washington have been assigned to the Nooksack Group (Peter Misch, oral communication, 1954). This group is composed of a thick sequence of marine graywackes, slates, siltstones, dark-greenish hard fine-grained sandstones and graywackes with interbedded coarse-grained sandstone, and local conglomerates containing rare and thin limy beds. In its type area the group crops out on both sides of the North Fork of the Nooksack River, and it was named by Peter Misch (McKee and others, 1956). It is underlain by volcanic rocks correlated with the Middle Jurassic Harrison Lake Formation of Crickmay (1930) and is overlain unconformably by rocks of the Cretaceous and younger Chuckanut Formation. Pre-Nooksack Wells Creek volcanics contain, in a slate interbed, belemnites identified by J. A. Jeletzky as not older than Middle Jurassic (Peter Misch, written communication, 1965). Fossils found in the Nooksack Group range in age from Oxfordian to Valanginian.

Fossils identified from Nooksack Group rocks that crop out at several different localities in the Nooksack Valley include the following, identified by McLellan (1927), Imlay (1960), J. A. Jeletzky (written communication to Peter Misch, 1954, and to W. R. Danner, 1963, 1964), and G. E. Rouse (oral communication, 1964):

- Homolsomites stantoni (McLellan)
- Olcostephanus cf. O. pecki Imlay
- Cylindroteuthis sp. indet.
- Pecten (Entolium)
- Pleuromya
- Pteria
- Buchia crassicollis (Keyserling)
- Buchia blanfordiana
- Buchia ex gr. mosquensis (Buch) non Lahusen nec Sokolov
- Buchia ex gr. bronni Lahusen
- Cupressinoxylon sp.

Age: Late Jurassic-Early Cretaceous

Rocks similar to those of the Nooksack Group crop out in western Snohomish County and adjacent parts of Skagit and King Counties (Danner, 1957). They also include volcanic rocks, radiolarian ribbon cherts, and a few small lenses of limestone that are considered by the writer to be part of the Nooksack Group but that are not typical of the Nooksack Group in its type area.

In this southern area, Nooksack rocks are intruded by granitic bodies in several places and have been thermally metamorphosed along the contacts with the intrusive rocks. The sequence becomes more indurated and metamorphosed as it is traced eastward.

Several small lenticular limestone bodies are found in the Nooksack Group in the Skykomish River valley east of Gold Bar, Snohomish County. They usually form lenses associated with chert, in graywackes and argillites. The limestone is dense or oölitic in texture, but locally it includes beds of limestone breccia composed of fragments of the typical dense-textured limestone in an oölitic matrix. The larger limestone bodies appear to be predominantly oölitic in texture, whereas the smaller bodies are dense and usually contain a high proportion of chert. In outcrops near Gold Bar the limestone bodies are larger and contain the least amount of chert of any in the eastern part of the area, but become smaller and more cherty to the west.

No fossils diagnostic of geologic age have been found in these limestones. However, a few miles to the north, in rocks similar to those enclosing the limestones, two collections of pelecypods have been obtained from shales and slates exposed in logging road cuts on the south side of the ridge between Sultan River and Pilchuck River. These have been identified by J. A. Jeletzky as follows:

NE¼ sec. 26, T. 29 N., R. 8 E.
Strongly sheared and deformed Buchia apparently belonging to:
Buchia ex gr. piochii (Gabb)
Buchia ex gr. fischeri (d'Orbigny) B. trigonoides (Lahusen)
Age: Tithonian stage of the latest Jurassic.

South-central part of sec. 22, T. 29 N., R. 8 E.
Strongly sheared and deformed:
Buchia ex gr. B. volgensis (Lahusen) or Buchia ex gr. okensis (Pavlow)
Age: Earliest Early Cretaceous (lowermost Neocomian, or Infravalanginian)

Pelecypods were also collected from a calcareous argillite in the Jordan Uplands north of Granite Falls, approximately in the SW¼ sec. 30, T. 31 N., R. 6 E., and identified by Dr. Jeletzky as:

Buchia piochii (Gabb) emend. Anderson
Buchia cf. stantoni Anderson
Buchia cf. trigonoides Lahusen
Age: Tithonian stage of the latest Jurassic.

Long tapering agglutinated tubes are found at several localities in Nooksack Group rocks in the Skykomish River valley area, particularly near Wallace Falls, along Proctor Creek, and in exposures on the south side of the Skykomish River valley between Gold Bar and Sultan. They are very similar, if not identical, to specimens first found in Alaska in 1895 by Dall (1896) and identified as worm tubes. In 1899, Ulrich (1904) collected other specimens in Alaska and assigned to them the name Terebellina palachei. Similar tubes have been found in the Olympic Mountains (Danner, 1948, 1955a, 1955b; Brown, Snavely, and Gower, 1956). Terebellina palachei closely resembles descriptions of the internal form of the foraminifer Bathysiphon.

The value of this fossil as an age indicator is not definitely known, but it is probably not diagnostic. In Alaska the tubes are found associated with *Buchia* similar to those found in the Nooksack Group (Reed and Coats, 1941). In the Olympic Mountains, forms apparently similar are found in undated rocks closely resembling those of the Nooksack Group and also in rocks of late Eocene or Oligocene age (R. D. Brown, Jr., written communication, 1956).

Rocks bearing a resemblance in lithology to those of the Nooksack Group also crop out in a southeast-trending belt from Frailey Mountain and Lake Cavanaugh in Skagit County south to Mount Pilchuck, Bald Mountain, and Marble Peak in Snohomish County, but they may be part of a Paleozoic sequence. A few small lenticular bodies of limestone are found within this sequence, but none are known to be large enough in outcrop to have commercial value. Ribbon chert is more common in these rocks than in typical Nooksack Group rocks, but no fossils have been found to establish the age.

DEWDNEY CREEK-PASAYTEN GROUPS

Along the crest of the northern Cascade Mountains on the east side of the upper Skagit Valley south to the Methow Valley and beyond are shales, graywackes, subgraywackes, and conglomerates similar in many respects to those of the Nooksack Group. Pelecypods, ammonites, belemnites, fucoids, fragments of wood, and plant remains are found within this sequence and indicate an age of Late Jurassic to at least Early Cretaceous. Part of the section may be as young as Late Cretaceous (Barksdale, 1948). Continental beds of possible Paleocene age occur in the Methow Valley (Royse, 1965). Calcareous concretions are abundant in some outcrops, and thin limy beds are found that are similar to those of the Nooksack. These rocks extend north to the Canadian border into Manning Provincial Park, where they are intruded by many dikes of volcanic rock and also show numerous examples of intricate internal crumpling.

San Juan Islands

SPIEDEN FORMATION

Spieden Island, in the San Juan Islands, is composed almost entirely of conglomerate underlain by about 35 feet of massive to well-bedded sandstone, calcareous shales, and thin lenticular argillaceous limestones assigned to the Spieden Formation (McLellan, 1927). The sequence dips steeply to the south. It includes finer grained clastics under the conglomerate at Spieden Bluff, on the north shore of the island. The base of the sequence is not exposed. Shales, sandstones, and calcareous beds contain a well-preserved fauna including pelecypods, ammonites, belemnites, and worm tubes, among which the following have been identified by McLellan (1927), Imlay (1959), and J. A. Jeletzky (written communication, 1964):

Homolsomites stantoni (McLellan)
Phylloceras
Acroteuthis sp. indet.
Pleuromya
Lima
Pinna
Gryphaea
Buchia crassicolis (Keyserling) s. str., and var. *solida* (Lahusen)
Buchia n. sp. aff. *inflata* (Toula, 1881) (= *Aucella sublaevis* Imlay, 1959 non Keyserling, 1846; single well-preserved spec.)
Inoceramus aff. *quatsinoensis* Whiteaves, 1882
Serpula

Age: Late Valanginian (Early Cretaceous)

Graywackes, slates, and volcanic rocks similar to those of the Nooksack Group crop out on Lummi, Eliza, and Samish Islands and on southern Fidalgo Island and northern Whidbey Island at Deception Pass. It is not known whether they are a part of the Nooksack Group or belong to a similar-appearing but younger sequence of Cretaceous rocks exposed to the southwest on Lopez Island.

Olympic Mountains

Rocks lithologically similar to those of the Nooksack Group crop out in the central part of the Olympic Mountains and are usually referred to as the Soleduck Formation. They consist of graywackes, feldspathic sandstones, slates, phyllites, black-slate-fragment breccias, conglomerates, and rare flows of greenstone. Spilitic pillow flows and associated small lenses of argillaceous limestone occur interbedded with graywacke and argillites around the border of the core area of the Olympic Mountains. Foraminifera from some of the limestone beds indicate a middle Eocene age, whereas others may be as old as Paleocene. Foraminifera have been found in limestones on Mount Claywood and vicinity, at the head of the Dosewallips River (Danner, 1948), but so far none of the specimens have been well enough preserved to be identified. The supposed fossil worm tube *Terebellina palachei* (Danner, 1955) is abundant in fine-grained sandstones at a few localities within this sequence.

Rocks in the core of the Olympic Mountains are isoclinally folded and in places are cut by large veins of milky quartz. Clastic dikes have been found cutting the sequence east of Low Divide, and an intrusive rock of gabbroic composition crops out on Chimney Peak, above Enchanted Valley. Only traces of limestone are known in the sequence exposed in the core of the Olympic Mountains.

Late Cretaceous Rocks

San Juan Islands

NANAIMO GROUP

The northern part of the San Juan Islands contains a thick sequence of coarse conglomerates, sandstones, graywackes, and shales correlated with part of the Nanaimo Group of Vancouver Island and the Gulf Islands. These rocks are highly folded and faulted, and their thickness and stratigraphic succession in Washington have not been accurately determined. Some parts are overturned. The shales contain calcareous concretions and at a few localities are highly fossiliferous.

Marine fossils predominate, but leaf imprints and chunks of calcified wood occur in some shale sections. The wood has been identified as *Cedroxylon* (Glenn Rouse, oral communication, 1964). The marine fauna consists chiefly of pelecypods, gastropods, and ammonites. The pelecypod *Inoceramus* is one of the most abundant fossils. Fish teeth and *Dentalium* shells compose a minor part of the fauna. Large oyster shells occur in outcrops on Waldron and Orcas Islands.

Much of the sandstone part of the sequence is crossbedded and contains molds and casts of logs and fragments of wood. Pebble and cobble conglomerates form thick and, in places, lenticular beds. A conglomerate, composed mostly of milky white quartz pebbles and cobbles and angular to subangular fragments of phyllite, crops out on the south coast of Sucia Island. The clasts closely resemble rock in outcrops of the Leech River Formation on Vancouver Island to the west.

Nanaimo Group rocks have not been found on the mainland of western Washington, but their continental equivalent may be present in the lower part of the sequence of rocks assigned to the Chuckanut Formation in Whatcom and Skagit Counties (Miller and Misch, 1963). Rocks assigned to the Nanaimo Group crop out on Stewart and associated islands; Waldron, Flattop, Skipjack, Patos, Matia, Sucia, Clark, and Barnes Islands and associated reefs; and also at several places along the north and northwest coasts of Orcas Island.

LOPEZ ISLAND CRETACEOUS ROCKS

A sequence of graywackes, argillites, slates, conglomerates, and pillow lavas cropping out on Lopez Island was correlated, with reservations, by McLellan (1927) with the supposed Paleozoic age Leech River Formation of Vancouver Island. On the south side of Lopez Island this sequence contains fossiliferous red calcareous argillites interbedded with pillow lavas. In these argillites the writer found Foraminifera that indicate an age of Late Cretaceous or younger. Globigerina, ?Globorotalia, or ?Globotruncana and ?lagenid Foraminifera have been tentatively identified from the collection by V. S. Mallory (written communication, 1959). No limestone has been found in these rocks, but they do contain calcareous clastic sediments.

Similar clastic and volcanic rocks crop out along the strike of this sequence north of Lopez Island on southern Orcas Island, northern Cypress Island, and on several small islands in the vicinity. No limestone has been found in these areas. There is a close similarity between these rocks and those exposed in the central part of the Olympic Mountains.

CENOZOIC ROCKS

Cenozoic rocks in western Washington are less likely than older rocks to contain good-quality limestone deposits. Only one deposit, of Oligocene age, has been quarried. Cenozoic rocks crop out over much of western Washington and make up all the outcrops in the southwestern part of the State. Sedimentary and volcanic rocks of continental origin were deposited in the present area of the Cascade Mountains during Cenozoic time; they interfinger with marine-deposited sequences in the area of the present-day western foothills of the Cascade Mountains. Most of the Cenozoic rocks lying west of the foothills are marine and are well exposed around the Olympic Peninsula and in parts of southwestern Washington.

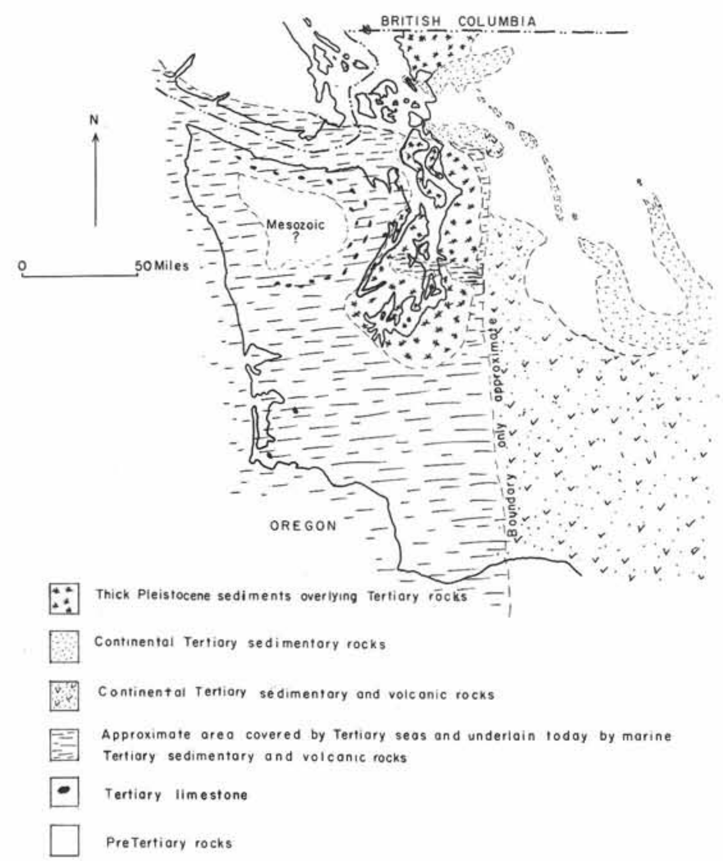


FIGURE 20. — Outcrop area of known Tertiary rocks in western Washington.

Rocks representing the interval of time from Late Cretaceous to Early Eocene are not definitely known in most of western Washington. No Cretaceous rocks have been definitely identified in the southern part of western Washington, and the oldest outcrops appear to be of Eocene age. The Paleocene is not very well established anywhere in western Washington but may be represented by sedimentary and volcanic rocks exposed near the base of the Metchosin Formation[1] in the eastern Olympic Mountains. Rocks of this age are thought to be represented in the northern part of western Washington by continental sedimentation in the Chuckanut Formation of Whatcom and Skagit Counties (Miller and Misch, 1963).

During Eocene time, western Washington south of Vancouver Island was a subsiding basin open to the west. On southern Vancouver Island, in the area of the Olympic Mountains, and farther south, submarine pillow lavas were extruded on the sea floor. Lenticular bodies

[1] The Metchosin Formation in Washington has been referred to as the Crescent Formation in recent reports by the U.S. Geological Survey, but the more commonly used and generally more familiar name, Metchosin, is used in this report.

of argillaceous limestone were deposited with the flows, due in part to precipitation of calcium carbonate from the warmed sea water and in part to the accumulation of the tests of foraminifers. The more impure of these limestones are red to maroon in color, whereas the purer varieties are gray, blue gray, green, and varicolored. None of the purer types form deposits large enough or of such easy accessibility as to be of economic value. They compose part of the Metchosin Formation, and their enclosed foraminifers indicate ages from doubtful Paleocene to middle Eocene or later. Impure, gray- and buff-weathering argillaceous limestones are interbedded with breccias and volcanic flows near the top of the formation. They are generally of shallower water origin than the older limestones of the formation.

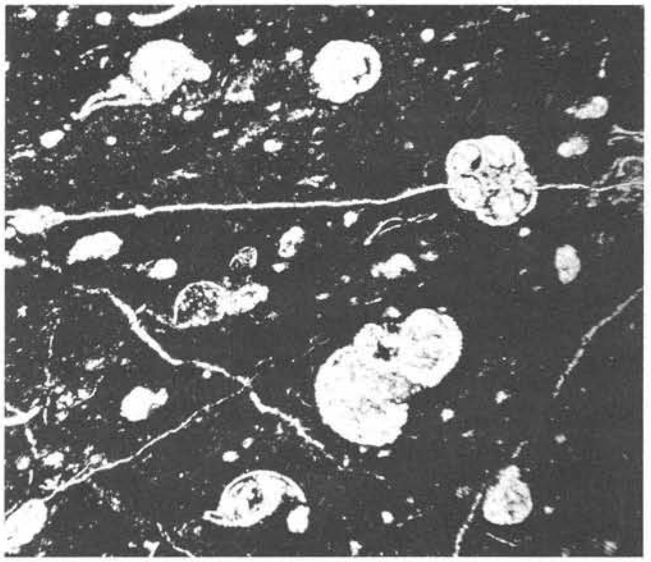


FIGURE 21.—Foraminiferal limestone in Metchosin Formation at headwaters of Big Quilcene River, Jefferson County. X 33. Eocene.

Limestones of the lower part of the sequence contain abundant Globigerina and Globorotalia, and at a few outcrops north of the headwaters of the Big Quilcene River they contain species of orbitoid and other types of foraminifers.

Eocene and Oligocene rocks deposited on top of the Metchosin Formation in the northern part of the Olympic Peninsula are mainly clastic, and limestone is found in the Twin River Formation only in the form of impure cream-colored calcareous concretions.

In southwestern Washington, Oligocene rocks assigned to the Lincoln Creek Formation contain lenticular beds and concretionary masses of argillaceous limestone. These are well exposed in the bed and banks of the Willapa River near Menlo in Pacific County. An alga-pelecypod limestone bank is exposed in the same formation on Bear River, in southern Pacific County, and has been quarried as a source of agricultural limestone.

During Oligocene time the area of marine sedimentation in western Washington decreased from that of the Eocene, and still more decrease was apparent in the early Miocene. By Pliocene time, only a few small marine embayments persisted along the west coast of the Olympic Peninsula. Calcareous concretions have been found in many of the rocks of Oligocene age in western Washington.

The northern part of western Washington appears to have been above sea level after Late Cretaceous time, and arkosic clastic sediments were deposited in a basin extending from south of Bellingham north to the Coast Mountains of British Columbia and east up the present Fraser River valley at least as far as Chilliwack. Probably other valleys extended east and southeast of Bellingham across the present site of the Cascade Mountains to at least the vicinity of Wenatchee. Deposition in the Bellingham-Fraser basin area probably has persisted with only slight interruption up to the present day. Deposition in the valleys to the east and southeast probably ceased by the end of Eocene time. Miller and Misch (1963) pointed out that the continental rocks northeast of Bellingham consist of two distinct sequences separated by a major angular unconformity.

The farthest northward exposures of Cenozoic marine rocks known in western Washington are the outcrops in the bed and canyon walls of Pilchuck Creek, in southern Skagit County, where fossiliferous calcareous sandstones and conglomerates lie unconformably on Paleozoic and Mesozoic sedimentary and plutonic rocks.

Cenozoic rocks in western Washington do not contain commercial quantities of limestone (with the exception of the Bear River deposit) and probably are not worth prospecting for this material.

The reader is referred to a paper by Snavely and Wagner (1963) for a more detailed account of the Tertiary geologic history of western Washington and to Youngquist (1961) for an excellent description of the stratigraphic nomenclature of the Cenozoic formations west of the Cascade Mountains.

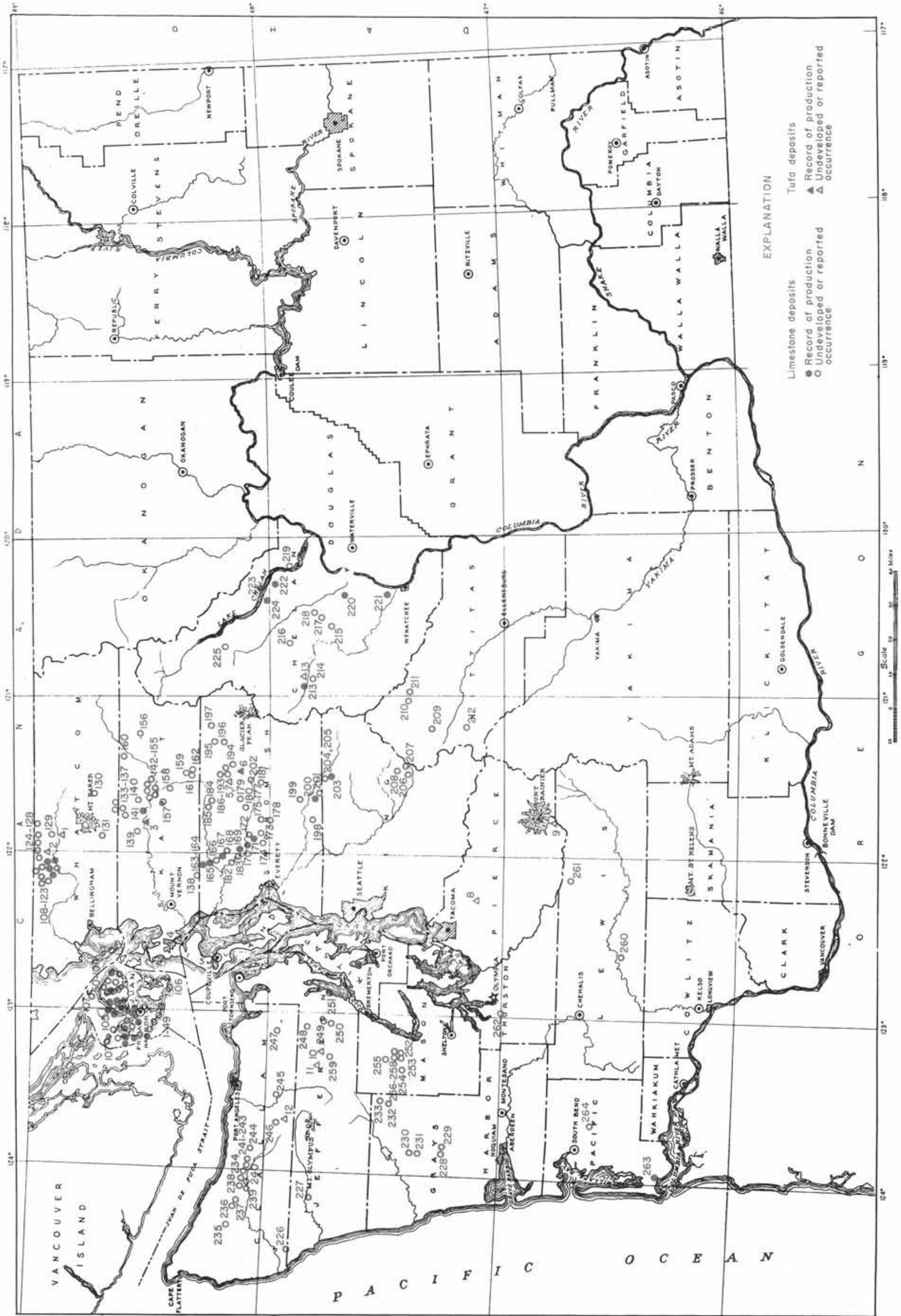


FIGURE 22.—Limestone deposits of western Washington and Chelan County.

LIMESTONE DEPOSITS

(Listed in the order they appear in the text)

SAN JUAN COUNTY

1. Roche Harbor
2. Mosquito Pass
3. English Camp
4. Young Hill West
5. Young Hill East
6. Rouleau
7. "Rulo"
8. Wilson
9. Johnson
10. Rocky Bay
11. Bell
12. Bell No. 2
13. Small outcrops, NE. San Juan Island
14. Krumdick
15. Eureka
16. Cattle Point
17. Eagle Point
18. False Bay
19. Hannah
20. Mount Dallas
21. Cowell
22. Deadman Bay
23. North of Cowell quarries
24. Bellevue Point
25. Smallpox Bay
26. Lawson Cave
27. Welch
28. Mitchell Bay
29. Limestone Point
30. Davison Head
31. O'Neal Island
32. Henry Island No. 1
33. Henry Island No. 2
34. Henry Island No. 3
35. Kellett Bluff
36. Open Bay
37. Henry Island No. 4
38. Nelson Bay
39. Pole Island
40. Battleship Island
41. Jones Island No. 1
42. Jones Island No. 2
43. Jones Island No. 3
44. Cliff Island
45. Crane Island
46. Yansen
47. Biendle
48. Lutz
49. West Coast Shaw Island
50. Red Cross
51. McGraw-Kittinger
52. West Sound
53. Double Hill No. 1
54. Double Hill No. 2
55. Double Hill No. 3
56. Double Hill No. 4
57. Double Hill No. 5
58. Double Hill No. 6
59. Rusch No. 1
60. Rusch No. 2
61. Langell
62. Englehartson

SAN JUAN COUNTY—Cont.

63. East Sound
64. Fowler No. 1
65. Fowler No. 2 and No. 3
66. Judd Cove
67. Fowler No. 4
68. Fowler No. 5
69. Camp Indralaya
70. Pineo No. 1 and No. 2
71. Pineo No. 3
72. Pineo No. 4
73. Pineo No. 5
74. Pineo No. 6
75. Orcas Lime Company
76. Killebrew Lake
77. Moran State Park
78. Ryman
79. Crow Valley
80. Lehman
81. Caldwell Point
82. Four Winds
83. Deer Harbor
84. Soderberg
85. Imperial
86. Soderberg Beach
87. Langdon (north part)
88. Langdon (south part)
89. Entrance Mountain
90. Olga
91. Newhall
92. Rosario
93. Buck Mountain No. 1
94. Buck Mountain No. 2
95. Mount Constitution
96. Raccoon Point
97. Northeast Coast Orcas Island
98. Payton
99. Wright
100. Flaherty No. 1
101. Flaherty No. 2
102. Flaherty No. 3
103. Lawrence Point
104. Chuckanut Lime Company
105. Spieden Island
106. Lopez Island
107. Stuart-Sucia-Orcas Islands (Nanaimo Group)

WHATCOM COUNTY

108. Boulder Creek
109. Permanente Cement Company
110. Red Mountain
111. Silver Lake No. 1
112. Silver Lake No. 2
113. Balfour deposits
114. Hilltop
115. Sumas Mountain No. 1
116. Sumas Mountain No. 2
117. Northwestern Lime Company
118. Doaks Creek
119. German No. 1
120. German No. 2
121. Northwest Black Mountain No. 1

WHATCOM COUNTY—Cont.

122. Northwest Black Mountain No. 2
123. Vedder Mountain
124. Frost Creek
125. Monument 47
126. Monument 48
127. Monument 45
128. Black Mountain
129. Church Mountain
130. Baker Lake
131. Ridley Creek
132. Lummi Island
133. Dock Butte Trail No. 1
134. Dock Butte Trail No. 2
135. Blue Lake
136. Dock Butte
137. Washington Monument

SKAGIT COUNTY

138. Pilchuck Creek
139. Goat Mountain
140. Three Mile Creek
141. Concrete
142. Jackman Creek No. 1
143. Jackman Creek No. 2
144. Jackman Creek No. 3
145. Jackman Creek No. 4
146. Jackman Creek No. 5
147. Jackman Creek No. 6
148. Jackman Creek No. 7
149. Webber Creek
150. Jackman Ridge deposits
151. Sauk Mountain
152. North Rockport
153. South Rockport
154. Sutter Creek
155. Rocky Creek
156. Marble Creek
157. Sutter Mountain
158. Sauk River Bridge
159. Suiattle River Bridge
160. Damnation Creek
161. $NW\frac{1}{4}$ sec. 15, T. 33 N., R. 10 E.
162. $NE\frac{1}{4}$ sec. 15, T. 33 N., R. 10 E.

SNOHOMISH COUNTY

163. Rock Creek
164. Bryant
165. Jack
166. Skagit Power Line
167. Paddock
168. South Twin Lake
169. Canyon Creek Lodge
170. Shumway
171. Granite Falls
172. Stillaguamish Canyon
173. Lake Julia
174. Menzel Lake
175. Mount Pilchuck area

SNOHOMISH COUNTY—Cont.

176. Worthy Creek
177. Heather Lake
178. Kelly Creek
179. Liberty Mountain
180. Green Mountain
181. Marble Peak
182. King Lake
183. Lost Lake
184. Climax and Hi Hi
185. Galbraith
186. Conn Creek No. 1
187. Conn Creek No. 2
188. Conn Creek No. 3
189. Gravel Creek
190. $W\frac{1}{2}$ sec. 35, T. 32 N., R. 10 E.
191. Sec. 13, T. 32 N., R. 10 E.
192. Sec. 14, T. 32 N., R. 10 E.
193. Sec. 24, T. 32 N., R. 10 E.
194. Whitechuck River
195. Circle Peak (north part)
196. Circle Peak-Meadow Mountain
197. Lime Mountain
198. Sultan
199. Wallace River
200. Gold Bar deposits
201. Proctor Creek deposits
202. Bonanza Queen

KING COUNTY

203. Grotto deposits
204. Palmer Mountain claims
205. Baring (Skyko Camp)
206. Denny Mountain
207. Guye Peak
208. Chair Peak

KITTITAS COUNTY

209. French Cabin Creek
210. Boulder Creek
211. Teanaway River headwaters area
212. Taneum-Manastash Creek area

CHELAN COUNTY

213. Soda Springs and Lucky Line
214. Rainy Creek
215. Dry Creek
216. Marble Creek
217. Indian Creek
218. Gold Ridge
219. Manson
220. Entiat
221. Storme
222. Section 29
223. Section 13
224. Section 14
225. Holden area

OLYMPIC PENINSULA

226. Bogachiel State Park
227. Hoh River
228. Humptulips River
229. Humptulips East Fork No. 1
230. Quinault area
231. Stevens Creek
232. Schofield Creek
233. Copper Creek
234. Helen Mine
235. Lake Pleasant area
236. State Lease
237. Victory Lode
238. Clallam No. 1, No. 2, and No. 3
239. Blue Eyes claim
240. Ed B group
241. June group
242. Sunshine group
243. Crescent Mine
244. Thomson group
245. Skookum and Hurricane claims
246. Bertha
247. Dungeness-Forks area
248. Tubal Cain
249. Tunnel Creek
250. Elkhorn
251. Pulali Point
252. Triple Trip
253. Apex Mine
254. Bosnia
255. Black and White Mine
256. Four Stream
257. Red Reef Pool
258. Staircase
259. Mount Claywood

SOUTHWEST WASHINGTON

260. Newaukum
261. Mineral Creek
262. Perry Creek
263. Bear River
264. Menlo

TUFA DEPOSITS

1. Church Mountain
2. Silver Lake No. 2
3. Strong
4. Alverson
5. Reece Ridge Way
6. Blackoak Creek
7. Paddock
8. McMillin
9. Longmire Mineral Springs
10. Dosewallips
11. West Creek
12. Olympic Hot Springs
13. Soda Springs

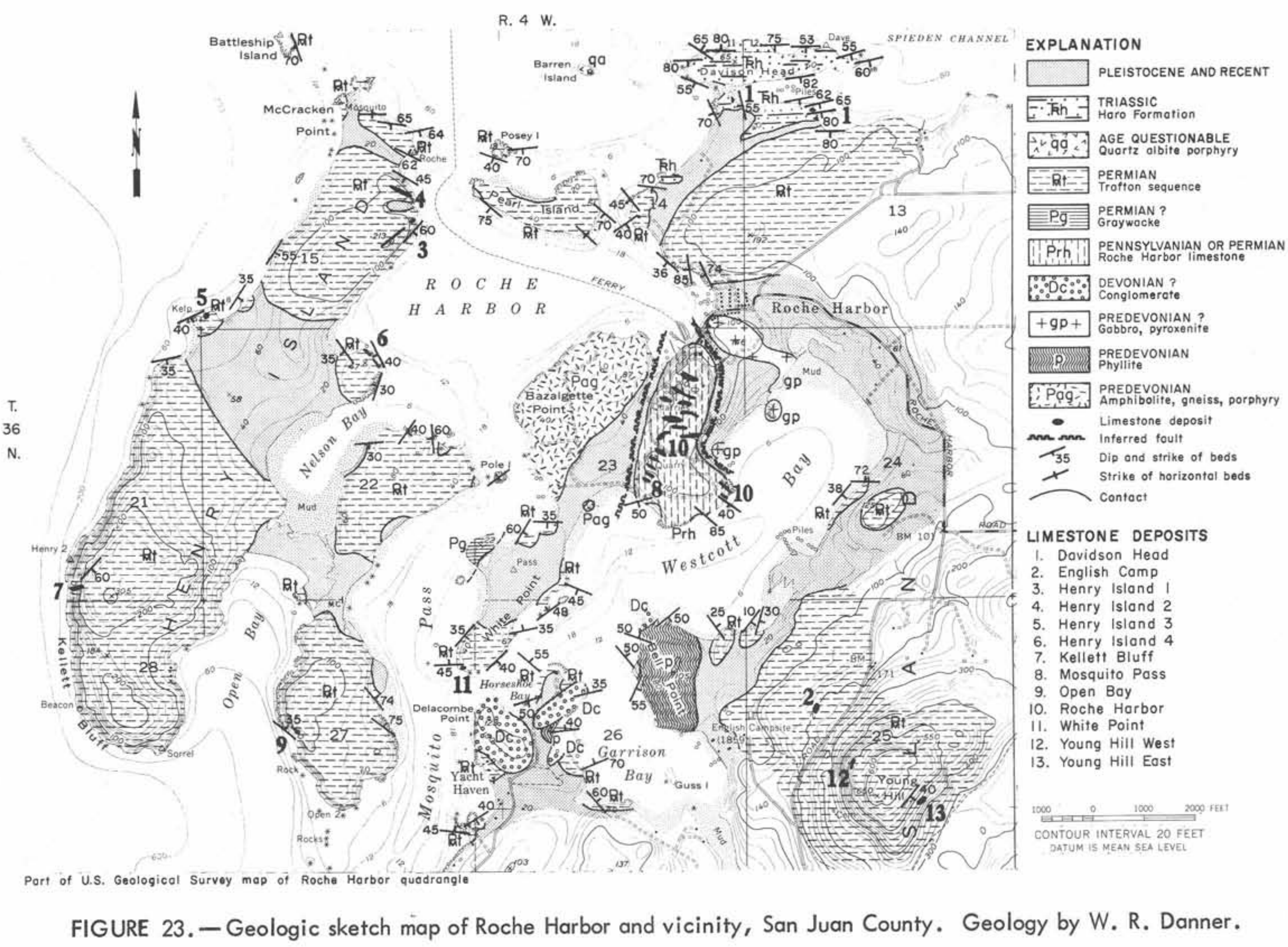
LIMESTONE DEPOSITS

SAN JUAN COUNTY

San Juan County consists entirely of islands lying between the mainland of northwestern Washington on the east and Vancouver Island, Canada, on the west. More limestone deposits have been developed on these islands than in other parts of western Washington. Though most of the limestone bodies are small, they have proved to be of economic value because of ease of accessibility, cheap water transportation, and generally high quality.

Most of the limestone is of Paleozoic age, and fossils of the Devonian, Pennsylvanian, and Permian periods have been found in various outcrops. The majority of the limestone occurrences appear to be lenticular bodies formed as bank or reef complexes and organoclastic accumulations in volcanic rocks, cherts, and graywackes.

The Paleozoic rocks form the central part of the island belt that makes up San Juan County. They compose the older core of an ancient mountain system that once extended across the Pacific Northwest from Vancouver Island into central Washington. As a result of the earth movements that produced this mountain system and of previous deformation, the Paleozoic rocks are intensely folded and faulted. In some areas this deformation has increased the amounts of limestone by repetition



Part of U.S. Geological Survey map of Roche Harbor quadrangle

FIGURE 23.—Geologic sketch map of Roche Harbor and vicinity, San Juan County. Geology by W. R. Danner.

of beds, but in others it has cut off the limestone, resulting in smaller limestone bodies than if there had been no earth movement.

Mesozoic limestones occur mainly in small beds or lenses a few feet in length and thickness interbedded in clastic sedimentary rocks of Triassic and Early and Late Cretaceous age. None of these deposits is of economic size or quality. The Mesozoic rocks, though also strongly deformed, were less affected by the earth movements than were those of Paleozoic age.

Intrusions that accompanied the mountain building and periods of volcanic activity appear to have had no appreciable effect on the limestone. Intrusive contacts and dikes are rare in the San Juan County deposits.

Most of the Paleozoic limestones occur in the central part of the county, on Orcas and San Juan Islands, but a few bodies are known on Henry, Shaw, Jones, O'Neil, Cliff, and Crane Islands. Thin-bedded impure limestones of Mesozoic age occur in the northern part of the county, on Spieden, Stuart, Sucia, and on the north coasts of San Juan and Orcas Islands. To a lesser extent they occur to the south along the southern coast of Lopez Island.

San Juan Island

San Juan Island, approximately 55.4 square miles in area, is the second largest island of the San Juan group. It is composed almost entirely of sedimentary and volcanic rocks thought to be of Permian age. However, small areas of pre-Devonian metamorphic and igneous rocks, Devonian sedimentary rocks, Pennsylvanian sedimentary and volcanic rocks, and Triassic sedimentary rocks are known. Several limestone bodies occur on the island, but only two of them, Roche Harbor and Cowell, were large enough to produce over one million tons each. Eight other, smaller limestone occurrences have been quarried, but there are no quarries in operation at the present time (1964). Small tonnages of limestone remain in a few of the abandoned quarries, but there are no known limestone deposits of commercial size, developed or undeveloped, remaining on the island.

Roche Harbor Quarries

Location, size, and accessibility. — The Roche Harbor limestone deposits are near the northwest corner of San Juan Island, on the peninsula separating Roche Harbor and Wescott Bay. This occurrence was the largest in San Juan County. Today (1964) less than 100,000 tons of limestone remains on the walls and floors of 15 abandoned quarries and in small undeveloped outcrops. Most of the quarries and outcrops are in the NE$\frac{1}{4}$ sec. 23, T. 36 N., R. 4 W. They are accessible by road from the resort of Roche Harbor and are adjacent to harbor facilities. None of the limestone outcrops is more than 1 mile by road from the harbor. These outcrops extend from sea level to a height of 200 feet. Where not cleared, the peninsula is covered with a dense second growth of trees and brush.

Geology and description. — The geology of the Roche Harbor limestone deposits is very complex. There is at least one and may be several more beds of high-grade limestone interbedded with graywacke siltstone, argillite, ribbon chert, and volcanic rocks. Ribbon chert is the dominant rock type. The whole sequence has been folded into a series of northwest-trending, intensely sheared anticlines and synclines plunging to the northwest. McLellan (1927, p. 165) recognized the duplication of strata and stated: "The large accumulation of limestone at this locality is not due to the thickness of individual strata. As a result of the intensity of folding in this area, the folds have been locally overturned, and as a consequence, each limestone layer is repeated at least three times in the quarries." Individual layers of limestone pinch and swell along their strike and in many places are cut by faults of small displacement. The beds range in thickness from a few feet to more than 50 feet, but appear thicker where repeated by folding. Judging from the position of the quarries, some 12 major outcrop areas originally must have existed in an area 1,000 feet wide east-west and 1,900 feet long. At a distance of 1,200 feet to the southeast on the shore of Wescott Bay are other exposures, and to the southwest are small quarries formerly worked by the Orcas Lime Company.

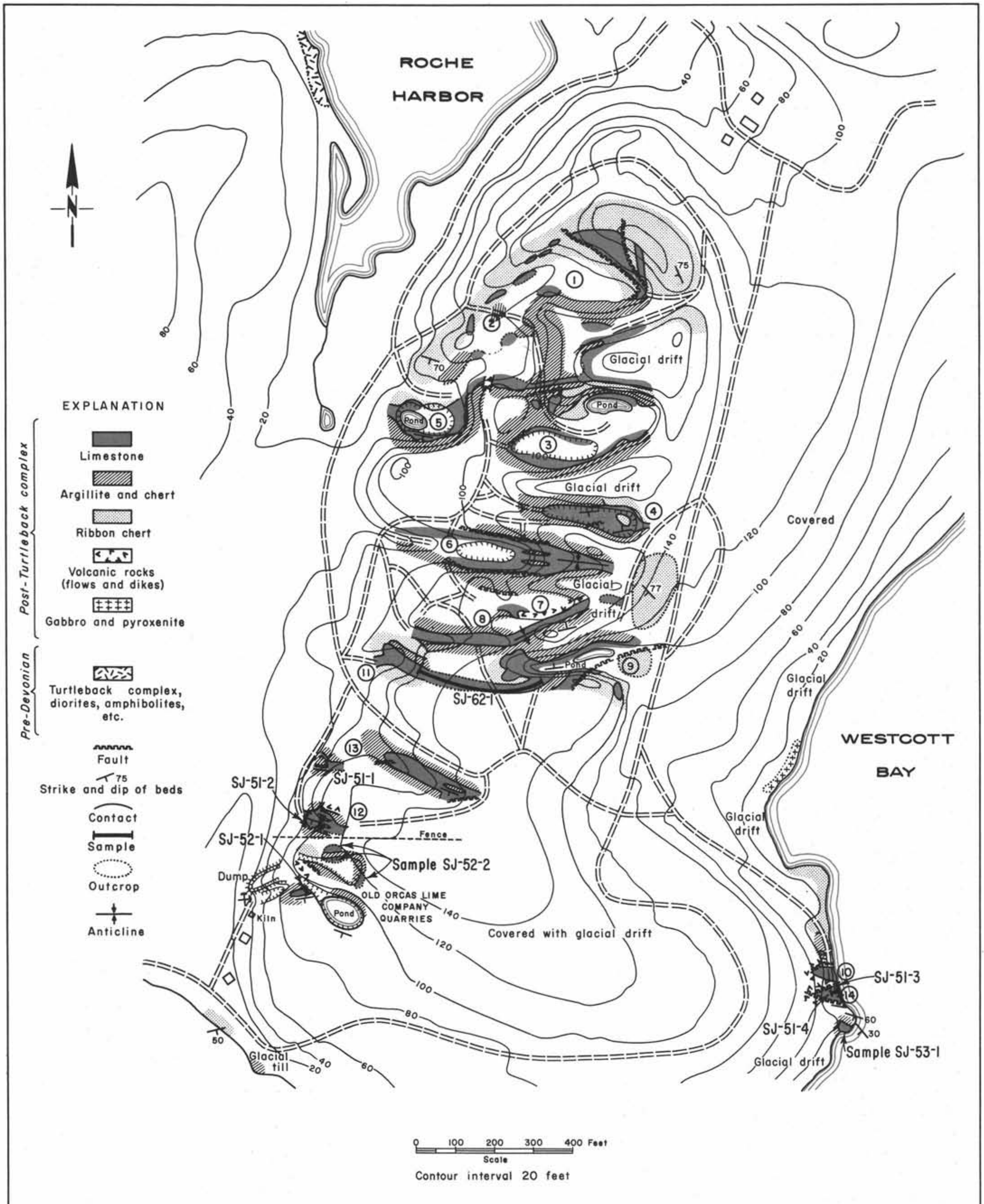


FIGURE 24. — Geologic map, Roche Harbor limestone deposit. Geology by W. R. Danner and C. L. Smith. Base map from U.S. Geological Survey Roche Harbor $7\frac{1}{2}$-minute quadrangle.

Glacial deposits as much as 30 feet thick cover bedrock between some of the quarries. Throughout most of the quarries only remnant slabs and pockets of limestone remain. Debris on the quarry floors conceals possible extension of limestone to depth. In many of these quarries the boundaries between the limestone and wall rock are planes of shearing.

Most of the limestone is dense to organoclastic in texture and bluish gray in color. In some of the quarries it is crystalline and fine to medium grained. There appears to be more crystalline limestone in the southern quarries than in the northern ones. Fossil remains are extremely rare, and the only fossil material visible on weathered surfaces is a few calcite plates believed to be of echinoderm origin. In thin section, much of the dense-apppearing rock is seen to have a clastic texture. Pseudo-oölites or pellets, oölites, and fossil fragments are abundant. Echinoid spines and plates, some of which are encrusted with algae, and various shell fragments give evidence of abundant marine life in the seas in which this limestone was laid down. The only fossil that has been found is the fusulinid ?Eostafella, seen in thin section. This fossil indicates a Late Mississippian or Early Pennsylvanian age, but its state of preservation in this limestone is so poor that its identification is uncertain. It may actually be a Permian fossil.

The peninsula containing the limestone beds is bordered by water on the east, northwest, and south. To the west the limestone-bearing rocks disappear beneath a swampy alluvium-filled valley, and to the west of this is a hill composed of a metamorphic and igneous complex believed to be pre-Devonian in age. The concealed contact between these rocks and the limestone-bearing sequence may be a fault. To the northeast of the limestone-bearing rocks is an outcrop of amphibole, pyroxene, and gabbro.

Quality.—The limestone in the Roche Harbor deposits is mostly of a high-calcium type, and a company brochure issued in 1917 emphasized this fact: "Our lime usually commands a premium in price over other limes of from 10% to 20%, from the fact that it is almost absolutely pure and free from foreign and deleterious matter."

Chemical analyses of Roche Harbor limestone

Sample no.	Location	Sample length (feet)	$CaCO_3$	$MgCO_3$	Loss on ignition	CaO	MgO	SiO_2	R_2O_3	P_2O_5
			Analyses of samples collected for this report (Mark Adams, analyst)							
SJ 51-1*	Quarry 12, upper level --	25	98.43	0.35	43.57 43.55	55.19 55.42	0.18 0.16	0.30 0.26	0.16 0.18	0.039
SJ 51-2	Quarry 12, lower level --	25	98.18	0.50	43.20	55.16	0.24	0.22	0.19	0.036
SJ 51-3*	Wescott Bay quarry, north-south chips --	30	98.64	0.46	43.77 43.57	55.53 55.31	0.21 0.23	0.27 0.35	0.10 0.18	0.018
SJ 51-4*	Wescott Bay quarry, east-west chips ---	20	98.56	0.65	43.68	55.37	0.31	0.13	0.35	0.032 0.031
SJ 53-1	Wescott Bay south outcrop -	50	98.04	0.54	43.52	55.08	0.26	0.65	0.27	0.021
SJ 62-1	Outcrop between Quarries 9 and 11 ------	320	97.75	0.60	43.28	54.92	0.29	1.11	0.33	0.032

* Duplicate analyses.

(Chemical analyses continued on page 88)

Chemical analyses of Roche Harbor limestone—Continued

Sample no.	Location	Sample length (feet)	$CaCO_3$	$MgCO_3$	Loss on ignition	CaO	MgO	SiO_2	R_2O_3	P_2O_5
	Analyses from other sources									
	Unknown[1] ----		98.21					0.44	1.13	
	Unknown[1] ----		99.06	0.46				0.27	0.21	
	Unknown[1] ----		98.57	1.02				0.20	0.30	
	Quarry 10[2] ---		98.8		43.64	55.32	0.13	0.62	[5] 0.31	
	Unknown[3] ----		99.63				0.17	0.20		
	Unknown[3] ----		98.32					0.44	[6] 0.13	0.11
	Unknown[4] ----		98.85					0.25	0.80	0.10

[1] Eckel (1913, p. 360).
[2] Dolmage (1948, p. 6).
[3] Hodge (1938, p. 15).
[4] Landes (1902, p. 186).
[5] Fe_2O_3 = 0.11, Al_2O_3 = 0.20.
[6] Fe_2O_3 = 0.13.

Ownership and development. — These quarries have been operated since 1882 by the Roche Harbor Lime and Cement Company. Small-scale quarrying activities were carried on before this; possibly some lime from this occurrence was burned as early as 1857. The major period of operation started in 1886, when John S. McMillin bought the company. Lime was shipped to destinations as far away as the Hawaiian Islands and South America. From 1901 to 1917, nominal capacity was listed as 1,500 barrels of lime per day. Lime was sent from Roche Harbor to help rebuild San Francisco after the earthquake and fire of 1906. In 1923 a fire paralyzed the Roche Harbor operations for a time, but the plant was rebuilt. Mathews (1947, p. 51) gives the annual capacity as 150,000 tons of crushed limestone, 45,000 tons of burned lime, and 12,000 tons of dehydrated lime. Operating 13 kilns, Roche Harbor was the largest producer of lime in the Pacific Northwest and in recent years the only producer in western Washington. Gradually, however, it became more difficult to obtain limestone in sufficient quantity and of the right quality. During the summer of 1951, six kilns were running, burning 3½ cords of wood per kiln every 24 hours. Four kilns were not running. The kilns processed 120 tons of limestone per day to produce 54 tons of quicklime, or 9 tons per kiln. Operations were discontinued in 1956, when the company was sold to R. J. Tarte, Neil Tarte, and Byron Halverson. They have converted the property into a large resort. In 1960, two of the quarries containing springs were in use as water reservoirs.

FIGURE 25. — Limestone exposed in quarry wall, north end of Roche Harbor deposit. View looking south. Dark rock above and below limestone is composed of ribbon chert and argillite.

An early report by Professor William B. Newberry, or J. S. Newberry, of Cleveland, Ohio, (private report,

1906) stated that the Roche Harbor and vicinity deposits contained a minimum of 20,800,000 tons of limestone. Before production ceased, 15 different quarries were operated. The deposits are largely depleted now; probably not much more than 100,000 tons of limestone still remains scattered among the different workings, and much of this is in scraps and pieces on the walls and floors of the quarries. Most of the quarries are long and narrow with steep walls and would be expensive and dangerous to operate further. At one time it was thought that the outcrops on the shore of Wescott Bay might extend under the glacial drift and vegetative cover to the northwest and connect with exposures being quarried 1,200 to 1,500 feet distant, but work in the Wescott Bay quarries indicated that the limestone there thinned to the northwest and plunged beneath an overburden of volcanic rock. However, stripping of the cover between the quarries in this area probably would reveal additional tonnage. Small tonnages remain in Quarry 12 and south of the quarries at Wescott Bay. Some additional tonnage is present in quarry floors and under cover of glacial drift to the west of Quarry 5.

Annual sales of Roche Harbor lime 1890-1913

Year	Barrels	Year	Barrels
1890	146,203	1902	217,597
1891	139,574	1903	260,023
1892	135,394	1904	275,698
1893	74,151	1905	204,385
1894	40,639	1906	234,837
1895	70,906	1907	220,983
1896	79,069	1908	186,123
1897	94,109	1909	212,213
1898	93,717	1910	228,097.5
1899	129,909	1911	242,895
1900	131,845	1912	170,812
1901	176,446	1913	155,699

Roche Harbor lime and limestone production, 1919-1956

Year	Lime (tons)	Limestone (tons)	Year	Lime (tons)	Limestone (tons)
1919	4,807	7,230	1938	12,088	38,736
1920	6,741	7,500	1939	20,645	42,541
1921	6,308	8,831	1940	24,177	61,919
1922	11,794	8,290	1941	27,172	58,352
1923	13,414	-----	1942	23,877	49,871
1924	12,600	7,430	1943	13,460	66,566
1925	-----	-----	1944	9,501	38,711
1926	11,945	13,161	1945	4,754	44,585
1927	11,239	18,055	1946	7,100	21,053
1928	10,155	20,603	1947	12,073	20,761
1929	12,962	44,000	1948	18,662	13,842
1930	10,892	15,524	1949	14,363	12,305
1931	7,031	15,130	1950	14,313	5,000
1932	5,167	8,074	1951	16,843	14,320
1933	2,939	10,177	1952	14,747	2,202
1934	6,144	10,349	1953	13,768	17,100
1935	12,313	11,010	1954	17,740	17,740
1936	15,726	15,591	1955	18,168	33,223
1937	41,650	72,734	1956	12,543	22,288

References.—Landes (1902, p. 184-187), Shedd (1913, p. 201-203), McLellan (1927, p. 164-166), Glover (1936, p. 56), Mathews (1947, p. 51). Private reports: W. B. or J. S. Newberry (1906), Victor Dolmage (1948), W. H. Mathews and H. C. Gunning (1950), Harry Townsend (1951), W. R. Danner (1951).

Mosquito Pass Quarries

Location, size, and accessibility. — The Mosquito Pass limestone deposits are on the peninsula between Mosquito Pass and Wescott Bay in the NW¼SE¼ sec. 23, T. 36 N., R. 4 W. They are on property that adjoins the Roche Harbor quarries on the southwest and lie between 250 and 600 feet north of the shore of Wescott Bay and about 1,800 feet east of Mosquito Pass. Only a few tons of limestone remains in irregular masses on the quarry walls. The quarries are accessible by a gravel road about a mile in length from Roche Harbor and lie just north of the Houde farmhouse. They are also accessible by hiking through the brush a short distance due south of Quarry 12 of Roche Harbor. Outcrops are at altitudes of between 80 and 120 feet above sea level at the west side and crest of a steep west-sloping hillside. The area is covered with a dense second growth of trees and brush, and the quarries are so overgrown that one may approach the rims without realizing that there is a quarry in the vicinity.

Geology and description. — The Mosquito Pass deposits form the southwestern part of the northwest-striking folded beds of the Roche Harbor deposit. Limestone is exposed in only a few places on the quarry faces and appears to consist of lenses in argillite, ribbon chert, and volcanic rocks. The rock is similar in appearance to that at Roche Harbor but is more coarsely crystalline. At the west end (entrance) of the most northerly quarry is an intrusion of light-gray porphyritic rock that has a malachite stain along its contact with the sedimentary rocks. The sequence exposed in these quarries appears to dip gently to the south. All the rocks are extensively sheared, and where shearing is most intense on steep or overhanging quarry walls there is usually a drusy coating of gypsum crystals.

Quality. — The limestone remaining in these quarries is similar in quality to that of Roche Harbor.

Chemical analyses of Mosquito Pass limestone

(Mark Adams, analyst)

Sample no.	Location	Sample length (feet)	$CaCO_3$	$MgCO_3$	Loss on ignition	CaO	MgO	SiO_2	R_2O_3	P_2O_5
SJ 52-1	SW. side, middle quarry ---------	10	98.75	0.42	43.53	55.48	0.20	0.50	0.22	0.023
SJ 52-2	Composite of limestone in walls of north quarry ----	—	98.92	0.21	43.58	55.59	0.10	0.32	0.17	0.024

Ownership and development. — The land on which this limestone is located was acquired in 1889 by Robert Scurr, who had started lime operations at Roche Harbor. The limestone was not developed. After he died in 1913 his widow sold the property to the Orcas Lime Company, which opened up the first quarry in 1923 and built a kiln and wharf to the west on the shore of Mosquito Pass. It is not known when that company stopped operations, but the small size of the quarries indicates that they were operated for only a short time. Since 1937 the property has been owned by Mrs. Delilah Houde, whose home is about halfway between the quarries and Wescott Bay.

The quarry area is heavily overgrown with brush and second-growth trees. The development consists of three pits, the largest of which is about 75 feet long, 50 to 65 feet wide at the widest point, and 25 to 30 feet deep at its eastern end. In the largest quarry is a pond of unknown depth. A few tons of limestone is still present on the southeast side of the largest quarry, but drilling and surface stripping would be required to determine the quantity.

Reference.— McDonald (1959, 1960, p. 4-5; 9).

Other Deposits in the Vicinity of Roche Harbor

Several small pods of limestone a few feet in length and width are exposed along the shores of Roche Harbor and Wescott Bay, but none are considered to be of economic value. They are in a sequence of ribbon chert and clastic and volcanic rocks similar to that of the Roche Harbor limestone; ribbon chert is the dominant rock type.

Two small limestone pods crop out on the beach a few hundred feet north of the Roche Harbor resort. They are enclosed in chert and other sedimentary rocks and are less than 3 feet in length. Still farther north, on the beach east of Pearl Island, is a crystalline limestone lens about 6 feet in maximum width and 15 feet long. A few feet to the north of this is another, smaller limestone body. They both contain a few thin argillaceous interbeds.

On the west side of White Point is a lens of limestone about 10 feet in maximum width and 40 feet long. It dips about 30° to the north and is enclosed in ribbon chert. At high tide it may be covered by water.

Another small pod of limestone is exposed on the beach on the west side of Wescott Bay, directly east of the Wescott Bay quarries of Roche Harbor. It is gray to greenish gray and reddish gray in color, dense in texture, and thin bedded. The exposure is approximately 8 feet long north-south and 3½ feet wide. It disappears under beach gravels.

English Camp Deposit

Location, size, and accessibility.—The English Camp deposit is about 400 feet west of the Mitchell Bay road in the SE¼NW¼ sec. 25, T. 36 N., R. 4 W. It is about ½ mile northwest of the old blockhouse at English Camp, on a gently west-sloping wooded hillside at an altitude of approximately 200 feet. It contains less than 1,000 tons of limestone. It can be reached by hiking old abandoned roads from English Camp but is difficult to locate.

Geology and description.—The limestone at English Camp consists of an outcrop about 100 feet long northeast-southwest and 35 to 40 feet in maximum width. A small quarry exposes limestone to a depth of about 10 feet. The limestone narrows to 10 feet at its southern end. It is interbedded in a sequence of chert, cherty argillite, and volcanic rocks. Glacial drift borders it to the east, and cherty argillite forms the contact to the west. The outcrop pinches out to the north and south. The rocks in the vicinity strike northeast-southwest and dip at a low angle to the southeast. Topographically, the deposit forms a low mound.

The limestone is light gray in color and dense to finely crystalline in texture. Partially recrystallized oölites were seen in thin section. No fossils were found. The age is unknown but is thought to be Permian.

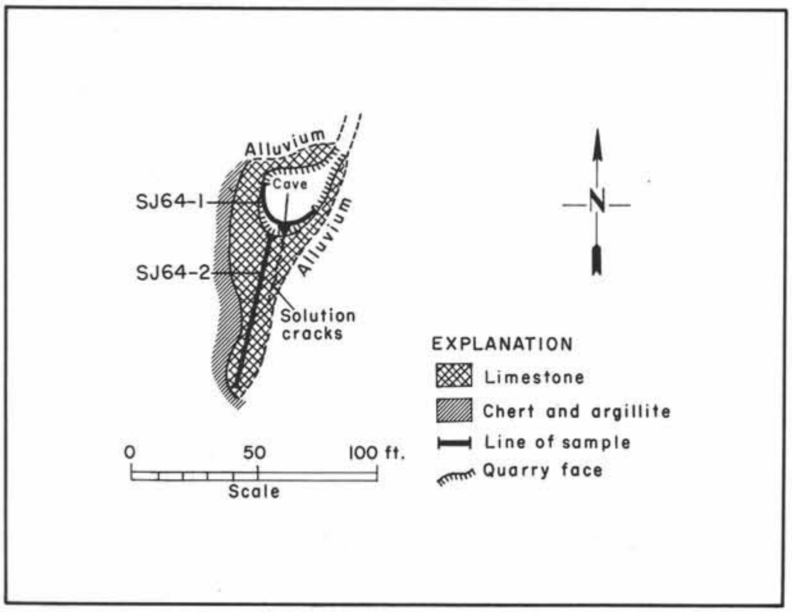


FIGURE 26.—English Camp deposit. NW¼ sec. 25, T. 36 N., R. 4 W. Geology, base, and topography surveyed by compass and tape by W. R. Danner, C. L. Smith, and C. F. Royce, Jr.

The limestone contains a small cave. Its entrance is at the south side of a small quarry that is at the north end of the outcrop. The cave is about 3½ to 4 feet high and 5 to 6 feet wide. At the entrance is a water-filled pit about 4 feet deep. The cave walls are smooth, and the floor is dirt covered. A line of solution tubes admit light through the ceiling of the cave for about the first 40 feet, then the passage narrows and changes direction sharply to the west.

Six small pods of limestone are in cherty argillite and chert to the west and southwest of the quarry. They are not more than 2 or 3 square feet in area in surface outcrop.

Quality. — The samples analyzed from this limestone are high in calcium, though slightly siliceous.

Chemical analyses of English Camp limestone

(Mark Adams, analyst)

Sample no.	Location	Sample length (feet)	$CaCO_3$	$MgCO_3$	Loss on ignition	CaO	MgO	SiO_2	R_2O_3	P_2O_5
SJ 64-1*	Quarry face, east-west ------	35	96.86	0.83	42.96	54.42	0.38 0.40	1.13	0.79	0.015
SJ 64-2	Outcrop, north-south ----	63	96.43	0.71	42.94	54.19	0.34	1.51	0.90	0.030

* Duplicate analyses.

Ownership and development. — The limestone is owned by James Crook, of English Camp (1960). A small quarry about 30 feet square and 9 feet in maximum depth is on the north end of the outcrop. A small limekiln was operated at this property many years ago. A pile of lime is still to be seen north of the quarry, but there is no trace of the kiln. In later years some limestone was taken to Roche Harbor but reportedly did not burn into good lime, so operations were abandoned. The deposit was explored by drilling, but the results are unknown. Remains of dug test pits surround the main limestone outcrop, and small limestone outcrops in the vicinity have been stripped by bulldozer.

The depth of the deposit is unknown. The present outcrop contains less than 1,000 tons.

Reference. — Halliday (1963, p. 58-60).

Young Hill West Deposit

Location, size, and accessibility. — The Young Hill West limestone deposit is in the NE¼SW¼ sec. 25, T. 36 N., R. 4 W., on the steep west face of Young Hill at an altitude of approximately 500 feet. The slope is rocky or brush covered. Only a few tons of limestone is exposed. The deposit can be reached by hiking up a rough bulldozed logging road leading north from the English Camp cemetery.

Geology and description. — The limestone forms a lens in chert and volcanic rocks exposed about 150 feet above an old bulldozed logging road on a cliff face on the west side of Young Hill. The lens is about 150 feet long and reaches a maximum width of 15 feet. It averages 3 to 5 feet in thickness for most of its length. It dips gently east into the hillside and is overlain by a bed of argillite containing limestone fragments. The limestone is medium crystalline in texture and light gray in color. No fossils were found in the outcrop, but limestone float, a short distance below on the steep hillside, contains Permian fusulinids of the genus Schwagerina. It is thought that the limestone is of middle Permian age. Other small pods of limestone crop out at various places on the hillside but are smaller than the one described above.

Quality. — The deposit was not sampled because of its small size.

Ownership and development. — This limestone outcrop is believed to be on the property of James Crook, of English Camp. There has been no development. The limestone body is believed to be too small to be of economic value, and because it dips under bedrock overburden it would be expensive to quarry.

Young Hill East Deposit

Location, size, and accessibility. — The Young Hill East limestone body is in the NW¼SW¼ sec. 25, T. 36 N., R. 4 W., on the east side of Young Hill at an altitude of about 450 feet. It contains only a few tons of limestone. It can be reached by hiking about a third of a mile from the English Camp cemetery over the top of Young Hill or by hiking 600 feet up the east side of Young Hill from an old logging road, starting approximately 1 mile from its junction with the Mitchell Bay road at the entrance to English Camp. The terrain is rocky and partly covered with brush and forest.

Geology and description. — The limestone forms two major outcrops and several minor ones on an east-sloping hillside. The regional dip is easterly, and it is believed that these outcrops are thin slablike beds of limestone exposed on a hillside that is approximately a dip slope.

The largest outcrop, which is at the south end of the occurrence, is about 100 feet long east-west and 60 feet wide at its maximum north-south extent. It is in contact with chert on the south and east and with glacial drift and soil to the north and west. Limestone is exposed over a vertical distance of about 9 feet. The outcrop contains a prominent east-west vertical joint system, which has been enlarged by solution action.

The northern outcrop lies 175 feet to the northeast and is about 60 feet long north-south and 30 feet wide. It is lenticular in shape and is interbedded with ribbon chert. It is exposed for a 3-foot vertical distance. The limestone is light gray in color and has a finely crystalline texture. It is cut at its east end by numerous calcite veinlets. No fossils have been found. The age is unknown but may be Permian.

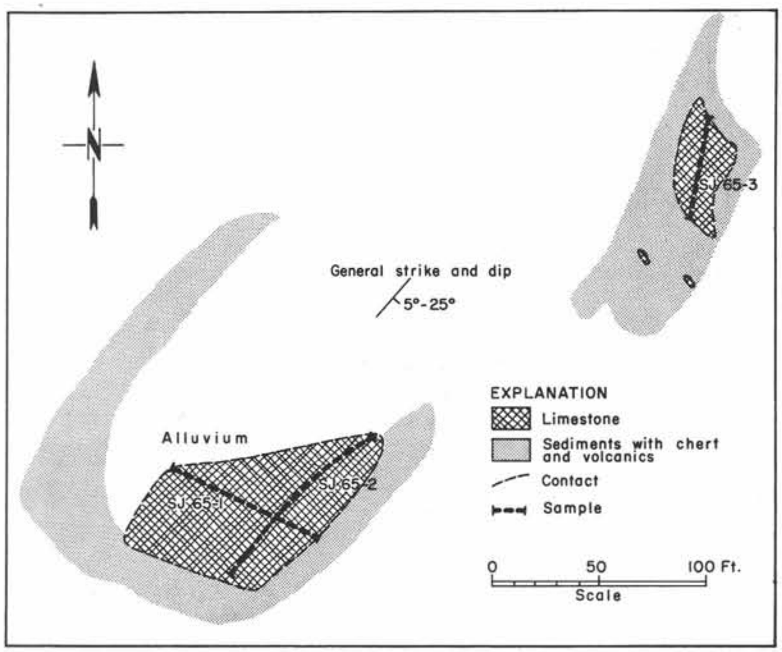


FIGURE 27. — Young Hill East deposit. SE¼ sec. 25, T. 36 N., R. 4 W. Geology and base by W. R. Danner and C. L. Smith. Compass and tape survey.

Quality. — This is a siliceous calcium limestone, the quality of which is not as good as that of other deposits on the northwestern side of San Juan Island.

Chemical analyses of Young Hill East limestone

(Mark Adams, analyst)

Sample no.	Location	Sample length (feet)	$CaCO_3$	$MgCO_3$	Loss on ignition	CaO	MgO	SiO_2	R_2O_3	P_2O_5
SJ 65-1	South outcrop, east-west ------	75	96.45	0.56	41.53	54.19	0.27	2.65	1.00	0.160
SJ 65-2	South outcrop, north-south ----	90	96.00	0.54	42.45	53.93	0.26	1.91	1.04	0.071
SJ 65-3	North outcrop, north-south ----	100	95.35	0.52	42.01	53.57	0.25	3.03	0.95	0.070

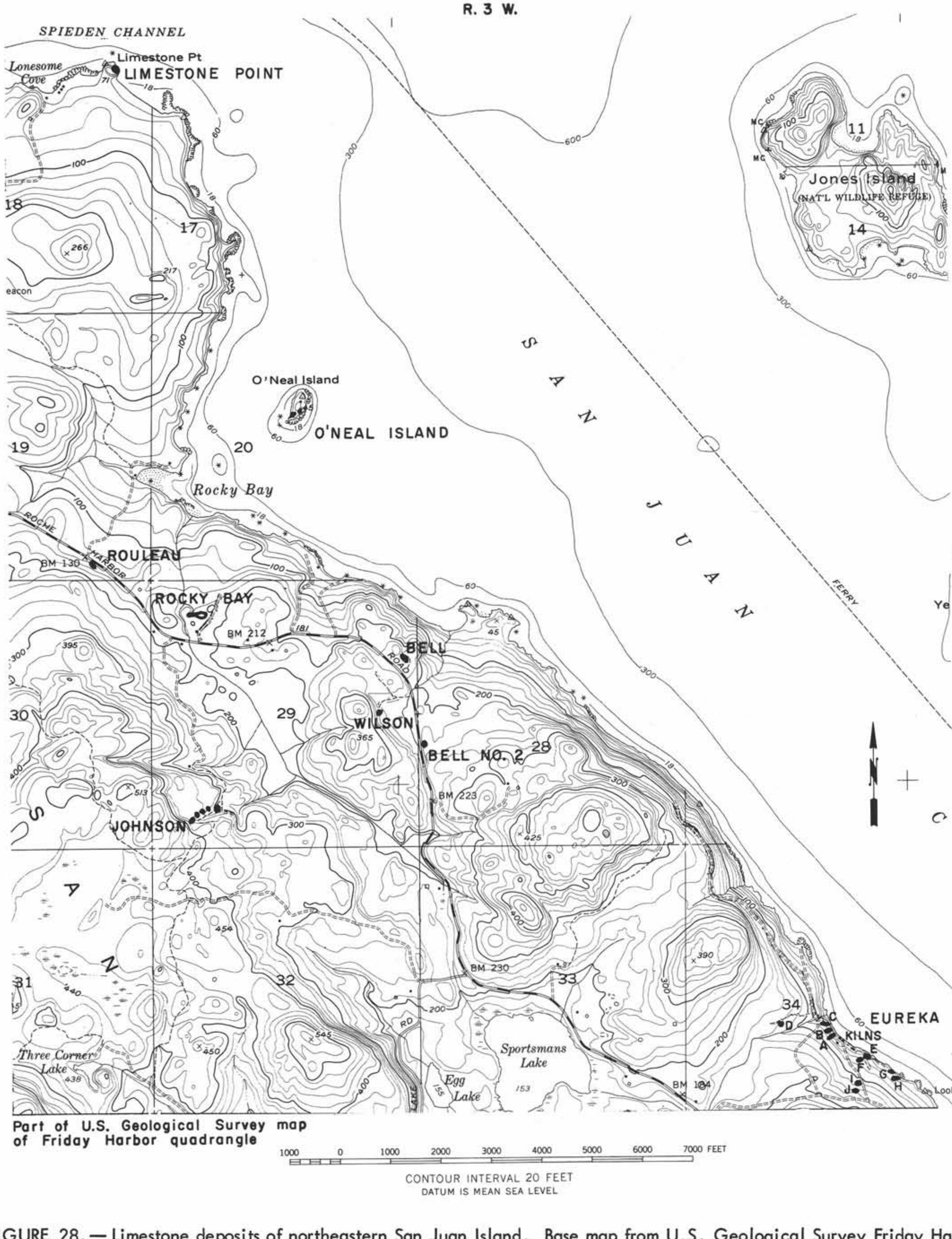


FIGURE 28. — Limestone deposits of northeastern San Juan Island. Base map from U.S. Geological Survey Friday Harbor 7½-minute quadrangle.

Ownership and development. — This limestone is owned by the Roche Harbor Lime and Cement Company. There has been no development. The deposit is too small to be of any economic value; however, it is considered by some local residents to be a large deposit and to connect with small outcrops on the west side of Young Hill to form a large concealed limestone body under the hill. The two sides of Young Hill represent different parts of the geologic section, and therefore the western limestone (Young Hill West) is over 100 feet below the eastern, stratigraphically.

Rouleau Deposit

Location, size, and accessibility. — The Rouleau limestone body is in the SE¼SE¼ sec. 19, T. 36 N., R. 4 W., on the south side of the black-topped road leading from Roche Harbor to Friday Harbor. Only a few tons of limestone is exposed. The outcrop is 215 feet east along the highway from the junction with the highway of Stan Rouleau's private gravel road leading to Rocky Bay.

Geology and description. — The outcrop is 20 feet long east-west and 5 to 6 feet wide. It is exposed along the edge of the highway and might extend north underneath it. The exposure is very poor. Chert and argillite crop out to the south up the hillside and north below the highway. The limestone is light gray in color and is cut by numerous calcite veinlets. It is very similar in appearance to the Young Hill East limestone. Thin layers of argillaceous material interbedded with the limestone are common. The age is unknown but may be Permian. No fossils were found.

Quality. — Argillaceous material interbedded with the limestone gives it a high silica content.

Chemical analysis of Rouleau limestone

(Mark Adams, analyst)

Sample no.	Location	Sample length (feet)	$CaCO_3$	$MgCO_3$	Loss on ignition	CaO	MgO	SiO_2	R_2O_3	P_2O_5
SJ 54-1	East-west along strike ---------	20	54.70	0.98	24.58	30.73	0.47	41.75	2.47	0.082

Ownership and development. — The limestone is on the highway right-of-way, so is owned by San Juan County. There has been no development. The limestone body is too small and impure to be of economic value.

"Rulo" Deposit

Location and accessibility. — The Rulo limestone occurrence is described as being in sec. 30, T. 36 N., R. 3 W. It could not be found by the writer and is not known to local residents. It may actually be the deposit described above as the Rouleau, but it is in a different location.

Geology and description. — The limestone is described as a lens in argillite containing a few thousand tons.

Quality. —Unknown.

Ownership and development. — The owner is unknown. The deposit is described as being able to supply a small tonnage.

Reference. — Northern Pacific Railway Co. (1941, unpublished notes, p. 13).

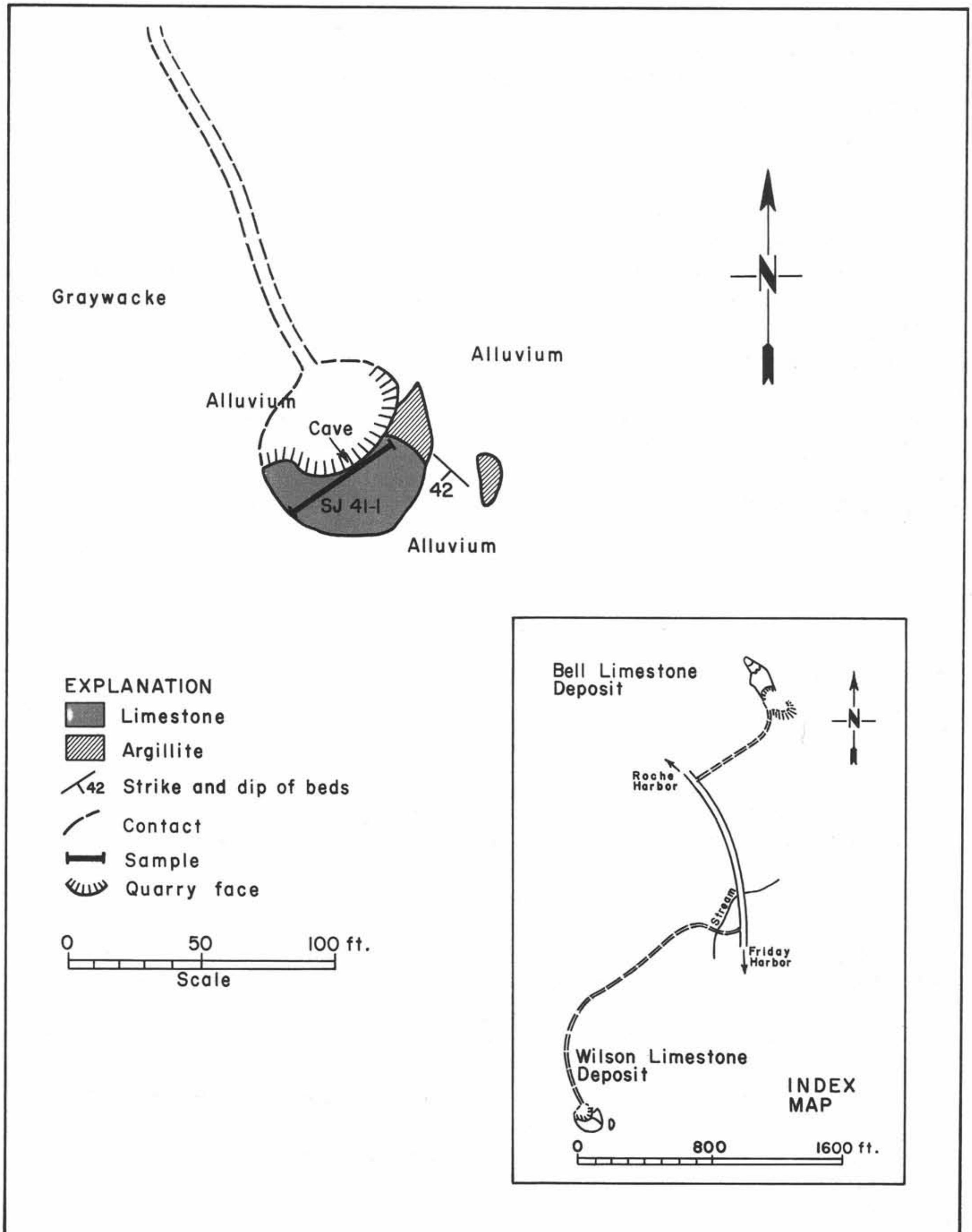


FIGURE 29.—Wilson deposit. NE¼ sec. 29, T. 36 N., R. 3 W. Geology by W. R. Danner, C. F. McKillop, and A. M. Rivisto. Base map by compass and tape survey.

Wilson Quarry

Location, size, and accessibility.—The Wilson limestone deposit is in the east-central part of sec. 29, T. 36 N., R. 3 W., at an altitude of about 220 feet at the northwest edge of a meadow area and at the east base of a northwest-southeast-trending bedrock ridge. The limestone outcrop forming the deposit is approximately 60 feet long east-west and 30 feet at its widest point north-south. The maximum exposed vertical distance is 17 feet.

The limestone can be reached by following 850 feet of old logging road extending west from the Roche Harbor road in the SE¼ sec. 29. The terrain is rocky and partly covered with thick second-growth trees and brush and also small patches of grass.

Geology and description.—The Wilson deposit is a lens of crystalline limestone in argillite. It was exposed as an erosional knob, most of which has been removed by quarrying. The remaining limestone forms a roughly crescent-shaped ridge 60 feet long and 30 feet in maximum width. The highest point on the ridge is 17 feet above the quarry floor. Crumbly weathered argillites crop out to the northeast and east of the limestone. Other parts of the limestone are bordered by glacial drift and soil. The plane of contact between limestone and argillite on the northeast side of the deposit strikes approximately N. 50° W. and dips 42° SW. The limestone is light gray in color and crystalline in texture. No fossils were found. The geologic age is unknown but may be Permian.

The limestone is strongly jointed, and there has been some solution activity along joint planes. A remnant of the limestone knob contains a small cave, the largest entrance of which is at the north side of the quarry. The entrance is 4 feet high and 3 to 8 feet wide. The cave can be followed south through the limestone for a distance of at least 24 feet. A wide but low-ceilinged branch room extends more than 15 feet to the east. Small inaccessible passages extend off this room An entrance to a smaller and lower level cave is just west of the entrance to the main cave. The cave has a dirt floor. The walls are smooth, and there were no stalactites or stalagmites visible in the accessible parts of the cave.

No other limestone outcrops were found in the immediate vicinity of this deposit. Ribbon chert crops out to the east along the road, and argillite and graywacke form a ridge to the west.

Quality.—Because of the small size of this deposit, only one sample was taken, consisting of a series of chips along the north face. Small amounts of chert or jasperoid were the only visible impurities.

Chemical analysis of Wilson limestone

(Mark Adams, analyst)

Sample no.	Location	Sample length (feet)	$CaCO_3$	$MgCO_3$	Loss on ignition	CaO	MgO	SiO_2	R_2O_3	P_2O_5
SJ 41-1	North side of outcrop along strike ---------	50	98.84	0.25	43.43	55.53	0.12	0.72	0.19	0.080

Ownership and development.—The Wilson deposit is on the property (1959) of Ben Haffner, who lives a little less than a mile to the south on the west side of the highway. The limestone was formerly owned by George E. Wilson, from whom it gets its name. It was quarried by the Everett Lime Company some time prior to 1941. The limestone was to be used as pulp rock and shipped to Bellingham, but how much was actually shipped is unknown. It is believed that from 500 to 800 tons was extracted from the quarry and that less than 200 tons remains in the knob. The depth of the deposit is unknown.

References.—Northern Pacific Railway Co. (1941, unpublished notes, p. 13), Guard (1943, unpublished field notes), Halliday (1963, p. 60-61).

Johnson Quarries

Location, size, and accessibility.—The Johnson deposit consists of at least five small pods of limestone, mostly less than 50 feet in length, exposed over a northeast-southwest distance of approximately 750 feet. The limestone pods are in the SW$\frac{1}{4}$SW$\frac{1}{4}$ sec. 29, T. 36 N., R. 3 W., in a narrow valley at the base of a north-facing scarp. They lie at altitudes of 300 to 350 feet above sea level. Much of the terrain is covered with a dense growth of brush and small second-growth trees. The limestone can be reached by following about 0.8 mile of abandoned logging road starting from the Roche Harbor road near the northwest corner of sec. 29. At about the 0.8-mile position the logging road forks; the right, or west, fork leads to the limestone. Abundant fragments of limestone are found along the road at the fork.

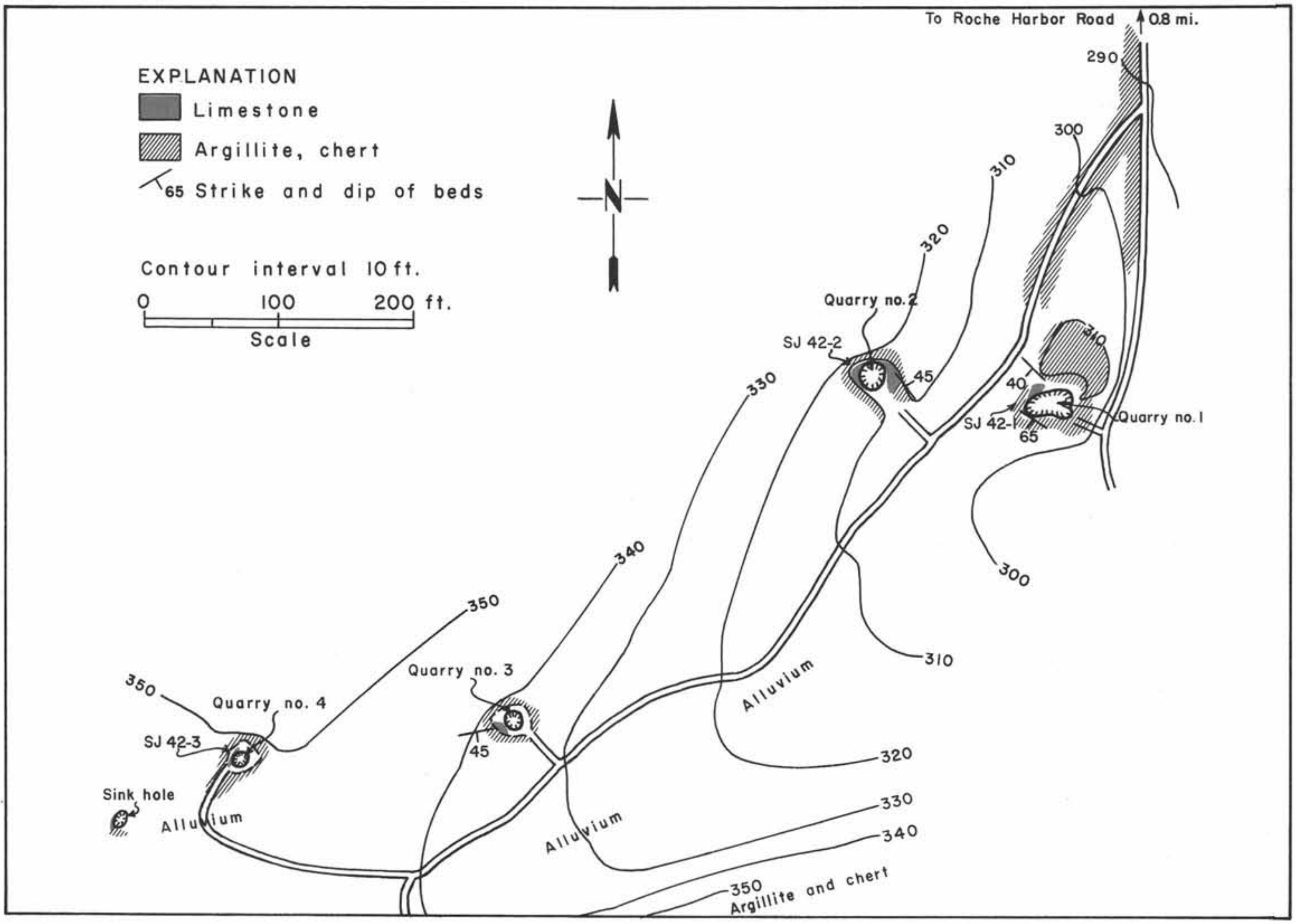


FIGURE 30. — Johnson quarries. SW$\frac{1}{4}$ sec. 29, T. 36 N., R. 3 W. Geology by W. R. Danner, C. F. McKillop, and A. M. Rivisto. Base map by compass and tape survey.

Geology and description. — The limestone forming this deposit appears to be composed of a series of small lenses or pods interbedded in a sequence of calcareous and cherty argillite. The sequence is complexly folded and faulted. At least four small quarries have been worked on the outcrops, and most of the limestone has been removed. Where scraps of limestone remain on quarry faces the limestone dips at angles of from 40° to 70° S. The south side of most of the quarries is bordered by glacial drift and soil. Some of the quarry walls are formed by fault surfaces. Quarry No. 2 appears to be cut into the crest of a small anticline with dip-slip faulting on the west limb of the anticline and a fault cutting the fold at right angles on the north limb of the anticline.

The limestone exposed in the quarries is light blue gray in color and mostly crystalline in texture. Some limestone fragments lying on the roads around the quarries are not crystalline, and when examined in thin section they are seen to be composed of pseudo-oölites and echinoderm fragments in a dense groundmass. It is not known whether this limestone came from the Johnson outcrops. No fossils were found, and the geologic age of the limestone is unknown.

At the west end of the limestone outcrops is a sinkhole in crystalline blue-gray limestone. The sinkhole is on a wide flat area at the base of a north-facing scarp. The hole is 8 feet long north-south and about 4 feet wide. Its maximum depth is 8 feet. The earth-filled bottom of the sinkhole slopes west underneath an overhanging lip of limestone. A small solution pit is exposed in the west wall of Quarry No. 4.

Quality.—Small amounts of chert and argillaceous material are visible in the limestone outcrops.

Chemical analyses of Johnson limestone

(Mark Adams, analyst)

Sample no.	Location	Sample length (feet)	$CaCO_3$	$MgCO_3$	Loss on ignition	CaO	MgO	SiO_2	R_2O_3	P_2O_5
SJ 42-1	Across strike, west wall, Quarry 1, east end of deposit --------	10	98.79	0.25	42.96	55.50	0.12	0.86	0.25	0.128
SJ 42-2	Quarry 2, north face ----------	5	97.13	0.31	42.86	54.57	0.15	1.27	0.58	0.051
SJ 42-3	Quarry 4, composite all faces -------	—	93.75	0.40	40.95	52.67	0.19	5.38	0.41	0.045

Ownership and development.—The owner of this limestone (1959) is John Johnson, Friday Harbor, Wash. Four or possibly five small quarries were developed by the Mitchell Bay Lime Company prior to 1941. A total of 1,500 to 2,000 tons of limestone is believed to have been removed from all the quarries. Only a few tons of limestone is still present in outcrops and quarries. One small outcrop exposed on a flat valley bottom is untouched. Drill holes are visible in the vicinity of the quarries, but the results of this drilling are unknown.

References.—Northern Pacific Railway Co. (1941, unpublished notes, p. 13), Guard (1943, unpublished field notes).

Rocky Bay Quarries

Location, size, and accessibility.—The Rocky Bay deposit is about 2,000 feet south of Rocky Bay and about 400 feet north of the Roche Harbor road on the northeast side of San Juan Island in the $NW\frac{1}{4}NW\frac{1}{4}$ sec. 29, T. 36 N., R. 3 W. Limestone crops out at the crest of a gently north-sloping hillside.

Outcrops occur over a distance of 350 feet east-west, and the maximum width is about 75 feet north-south. Most of the available limestone has been removed by quarrying.

Geology and description.—The limestone appears to consist of a lenticular bed, bluish gray in color and crystalline in texture, interbedded with argillite. A 40-foot-wide bed of argillite divides the limestone into two distinct outcrops. Rocks containing the limestone appear to dip south at angles of from 15° to 45°, but at the west end of the quarry the dip is westerly. Outcrops are extensively sheared, and several small faults cut the limestone. Outcrops occur for an east-west

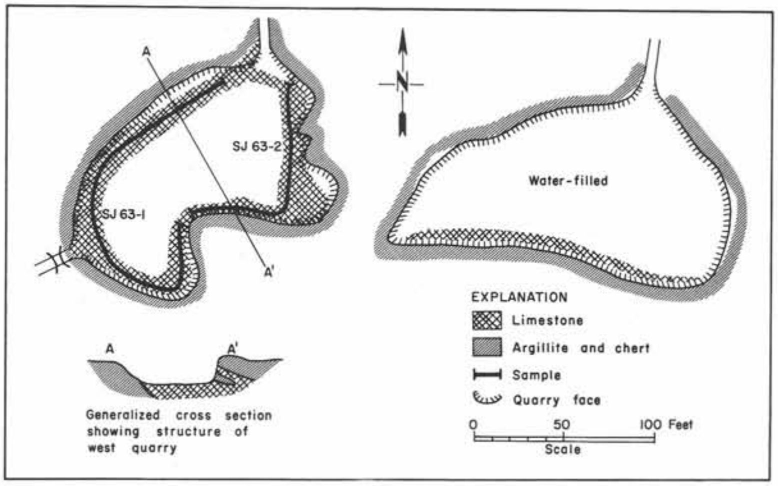


FIGURE 31.—Rocky Bay quarries. NW¼ sec. 29, T. 36 N., R. 3 W. Geology by W. R. Danner, C. L. Smith, and C. F. Royse, Jr. Base map by compass and tape survey.

distance of 350 feet. Argillite and graywacke crop out to the east and west of the limestone. Limestone is reported to have been encountered in a well a few hundred feet to the east of the quarries.

Small solution cavities are present in the south quarry wall near the west end, but none are large enough to enter.

No fossils have been found in this limestone. Its geologic age is unknown but is thought to be Permian.

Quality.—Argillaceous material in thin beds is visible in the limestone outcrops.

Ownership and development.—This property is known both as the "Young Farm" and the "Rocky Bay Ranch." It is now jointly owned by

Chemical analyses of Rocky Bay limestone

(Mark Adams, analyst)

Sample no.	Location	Sample length (feet)	$CaCO_3$	$MgCO_3$	Loss on ignition	CaO	MgO	SiO_2	R_2O_3	P_2O_5	Na_2O (ppm)	K_2O (ppm)	TiO_2 (ppm)	S (ppm)
SJ 63-1	West end, south side of quarry	225	97.27	0.48	42.86	54.65	0.23	1.35	0.43	0.048	} 100	560	250	470
SJ 63-2	East end, south side of quarry	125	85.52	0.90	38.21	48.05	0.43	11.87	1.13	0.033				

M. A. Tennant, C. R. Danforth, and H. A. Snyder. Two quarries were worked on the deposit about 1929 or 1931. The limestone is supposed to have made good pulp rock and was loaded onto scows at Rocky Bay for shipment to paper mills.

The maximum depth of the western quarry is 37 feet. The eastern quarry was partly filled with water at the time of investigation, and its depth is unknown. About 4,500 tons of limestone is supposed to have been removed from these quarries. A small tonnage of limestone is still available, but the limestone dips south under argillite. To quarry it, an increasing thickness of bedrock overburden would have to be removed, as well as the farmhouse a short distance to the south.

Reference.—Guard (1943, unpublished field notes).

Bell Quarry

Location, size, and accessibility.—Bell is the name applied to an abandoned limestone quarry in the NE¼SE¼NE¼ sec. 29, T. 36 N., R. 3 W., on the northeast side of San Juan Island. Limestone lies at the crest of a northeast-sloping hill at an altitude of approximately 215 feet. It forms a lens about 120 feet long, with a maximum width of 40 feet. Limestone is exposed vertically for about 15 feet.

The outcrop area is partly covered with a dense second growth of trees and brush growing on soil around knolls of bedrock. The limestone can be reached by following 300 feet of old quarry access road east from the Roche Harbor road about 4 miles north of Roche Harbor or 1.2 miles north of the Egg Lake road-Roche Harbor road junction. This access road has been abandoned, and a highway drainage ditch crosses it at its junction with the Roche Harbor road.

Geology and description. — Limestone forms a northwest-striking lenticular body interbedded in a sequence of ribbon chert, argillite, and greenstone. Its strike is approximately N. 15° W., and at the northeast side of the outcrop the limestone dips 40° SW. The rocks exposed at the south end of the quarry face look as if they might form the trough of a small synclinal structure. The eastern side of the limestone is bordered by ribbon chert, argillite, and greenstone. The western side is ribbon chert and argillite. Small amounts of ribbon chert and argillite are interbedded in the limestone along its strike. The limestone narrows to less than 15 feet in width near its north end and pinches out in chert. Although the southern end of the limestone body is not exposed, it is believed to have been at the position that is now the quarry entrance.

The limestone has a dense texture, is a light blue-gray color, and is cut by numerous calcite veinlets. In thin section the limestone is seen to be in part finely crystalline in texture. One of the specimens studied in thin section contains minute filament-like shells of small pelagic pelecypods. No fossils could be identified, and the age of the deposit is unknown but is thought to be Permian. The limestone is quite similar in appearance to that exposed on the east side of Young Hill south of Roche Harbor.

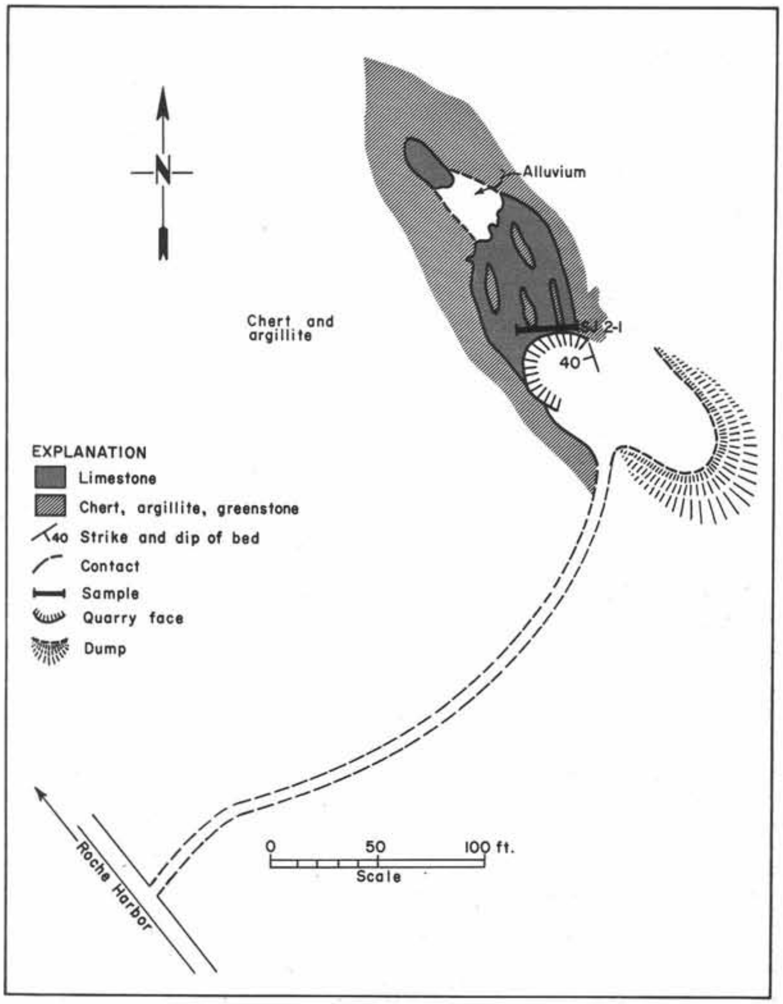


FIGURE 32. — Bell deposit. NE¼ sec. 29, T. 36 N., R. 3 W. Geology by W. R. Danner, C. F. McKillop, and A. M. Rivisto. Base map by compass and tape survey.

Quality. — One sample was analyzed from the section exposed on the east side of the quarry. Small beds of ribbon chert within this section give it a high silica content.

Chemical analysis of Bell limestone

(Mark Adams, analyst)

Sample no.	Location	Sample length (feet)	$CaCO_3$	$MgCO_3$	Loss on ignition	CaO	MgO	SiO_2	R_2O_3	P_2O_5
SJ 2-1	North side quarry ---------	15	50.83	9.17	23.01	28.57	0.62	44.74	2.18	0.04

Ownership and development. — This limestone is owned (1959) by Dr. J. M. Bell, who lives about three-fourths of a mile south of the deposit and east of the Roche Harbor road. It was quarried at one time, but the date of this operation and the use of the limestone are unknown. Only a few hundred tons of limestone was removed, and it may have been used for road surfacing. There are a few small exploratory pits on top of the outcrop. This quarry might produce a few hundred tons of hand-sorted limestone of higher grade than indicated by the chemical analyses, but the small size of the deposit does not seem to warrant its further development, except possibly for ornamental stone or for rock gardens.

Bell Deposit No. 2

Location, size, and accessibility. — The Bell No. 2 limestone deposit is in the NW¼SW¼ sec. 28, T. 36 N., R. 3 W., about 1,200 feet north of Bench Mark 223 (Friday Harbor topographic map) on the east side of the Roche Harbor-Friday Harbor highway at an altitude of about 220 feet. It crops out about 10 feet east of the highway and consists of a poorly exposed mound of limestone about 25 feet long north-south, 15 feet wide, and 10 feet high. It is easily accessible by about 3-3/4 miles of paved road north from Friday Harbor. The outcrop area is covered with dense brush and second-growth trees.

Geology and description. — The limestone is crystalline in texture and light gray in color. It is interbedded in a sequence of ribbon chert, argillite, and volcanic rocks. The limestone is poorly exposed, but on the west side of the outcrop a contact with chert and argillite is visible. The outcrop forms a small mound east of the highway and was originally covered with vegetation and not visible, but in 1962 it was partly cleared of vegetation by a road crew.

Quality. — The quality of the limestone is unknown, but it contains some visible dolomitic, black carbonaceous, and chert impurities.

Ownership and development. — The limestone is believed to be owned by Dr. J. M. Bell, who lives about a quarter of a mile to to the southeast. It has never been developed. It may not have been recognized as a limestone outcrop before a highway crew cleared brush from it in road work during 1962. Brush and soil conceal extension of the limestone to the east.

Other Outcrops of Limestone, Northeast San Juan Island

South along the Roche Harbor road from the Bell limestone outcrop, other small limestone lenses and pods are exposed in a roadcut in the SW¼ sec. 28, T. 36 N., R. 3 W. None are large enough to produce a ton of rock, but they indicate the occurrence of a limestone-bearing unit in this area. Several small solution cavities are exposed in the same roadcut.

It is to be noted that the several small limestone pods in the northeast part of San Juan Island appear to occur in a sequence of rocks that is predominantly ribbon chert at the bottom and clastic sedimentary rocks at the top. The limestone occurs in the transitional zone between these two rock types. The ribbon chert part of the sequence parallels the northeast coastal part of the island and in many places forms a steep slope down to the shore. The clastic sequence forms a relatively flat upland area above and to the west of the chert.

KRUMDICK OCCURRENCE

Location, size, and accessibility. — The Krumdick limestone occurrence is reported as being in sec. 19, T. 36 N., R. 3 W., but could not be found by the author.

Geology and description. — The limestone is described as consisting of one small lens (containing about 1,000 tons) in slate.

Quality. — Unknown.

Ownership and development. — The deposit is reported to have had some production in the past.

Reference. — Northern Pacific Railway Co. (1941, unpublished notes, p. 13).

EUREKA DEPOSIT

Location, size, and accessibility. — The various outcrops of limestone known jointly as the Eureka deposit are in the SW¼ and SE¼ sec. 34, T. 36 N., R. 3 W., on the east coast of San Juan Island. Some outcrops are on the beach, others are 1,000 feet or more inland. The limestone outcrop area is approximately 2 miles north of Friday Harbor. It can be reached by 3.7 miles of road from Friday Harbor and by 1 mile of private graveled road extending east from the Roche Harbor road in the NW. cor. sec. 3, T. 35 N., R. 3 W. Most of the various limestone outcrops can be reached by trail or road. There are at least 10 small lenses of limestone exposed over an area of a quarter of a square mile. The largest of these lenses is about 250 feet long and from 10 to 40 feet wide. The largest quarried limestone body probably produced less than 2,500 tons.

The outcrops are on a gently east-sloping hillside covered with a dense second growth of trees and brush. Their altitudes range from 0 to 140 feet above sea level.

Geology and description.—The limestones of the Eureka deposit consist of at least 10 outcrops and one sinkhole area, which are believed to represent individual lenses or pods of limestone. Seven of the bodies have been quarried. The limestone forms thin lenticular beds in a sequence composed of highly sheared argillite, containing chert, limestone, and volcanic rock fragments, interbedded with ribbon cherts and greenstone. The sequence strikes N. 30°-80° W. and dips 30°-60° SW.

The limestone is light blue gray in color and mostly crystalline in texture. No fossils were found in the outcrops, but a block of limestone used to build a retaining wall along the shore contains Permian fusulinids believed to belong to the genus Schwagerina. If this block was obtained locally, the fossils indicate a Permian age for the limestone.

Small solution cavities are present in the quarries and outcrops, and there is one small group of sinkholes in glacial drift at the north end of the area. A spring tapped in one of the quarries has provided fresh water to local residents for many years.

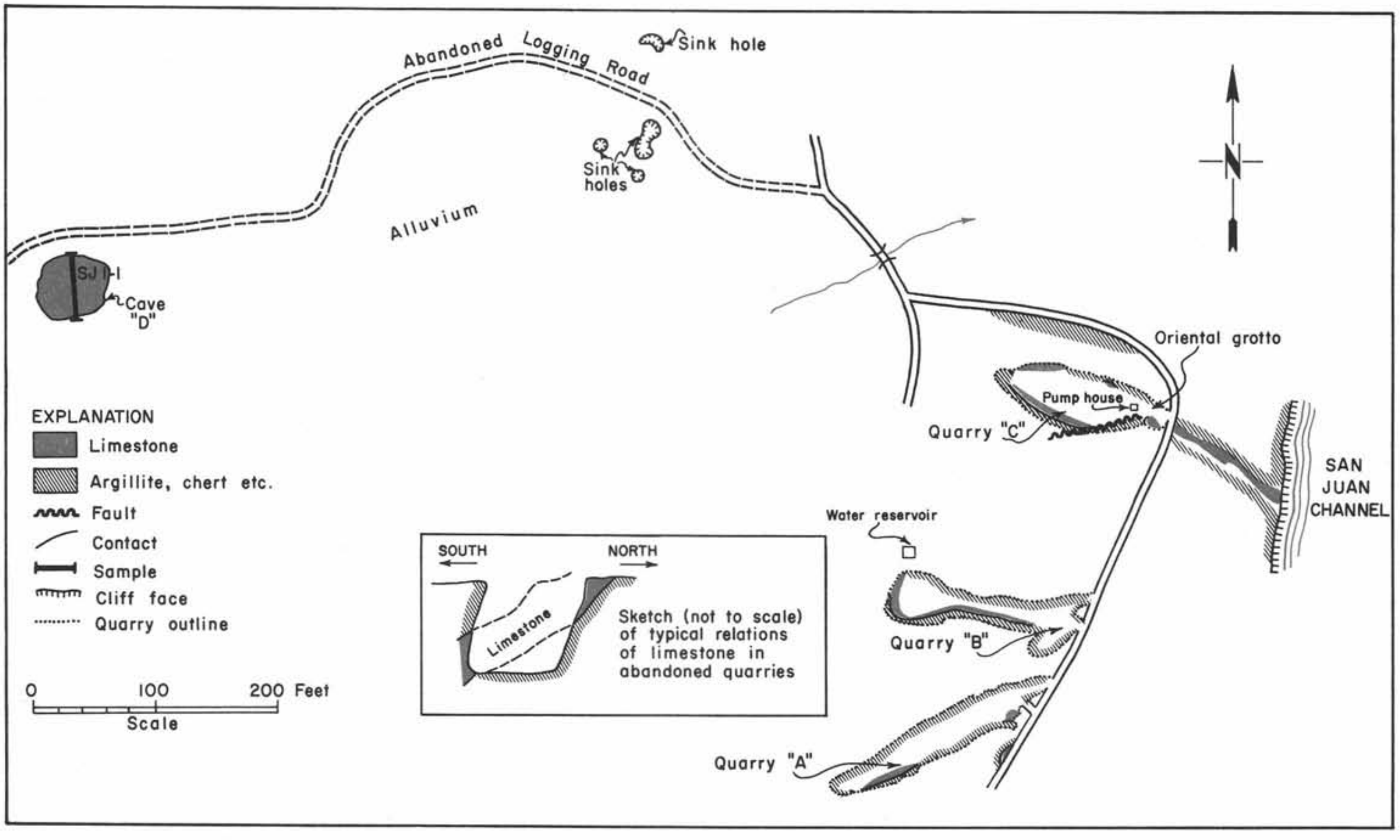


FIGURE 33.—Eureka deposit, north part. S½ T. 36 N., R. 3 W. Geology by W. R. Danner, C. F. McKillop, and A. M. Rivisto. Base map by compass and tape survey.

Description of individual quarries and outcrops.—Outcrops A, B, and C are a short distance north of the D. M. Salsbury home on the hillside above a 15- to 20-foot-high beach cliff. They are at an altitude of approximately 40 feet above sea level. Very little limestone is left in the three quarries. The original limestone beds appear to have been between

8 and 15 feet thick. They dip 30°-40° S., the dip angle varying greatly along the strike and down dip. Bedrock underlying and overlying the limestone consists of black argillite. The contact on the south side of the northernmost quarry is in part a fault. The quarries range from 120 to almost 200 feet in length, and the width ranges from 10 to 40 feet. The three quarries, trending east-west, are separated from each other over a north-south distance of approximately 250 feet.

The most northerly quarry is on a bed of limestone that can be traced 100 feet eastward down to within 10 feet of the beach. No extensions of limestone were seen to the west of any of the quarries. The very little limestone remaining in the excavations is usually at the bottom of the south face, on the down-dip side. A small amount of limestone is present on parts of the northern walls.

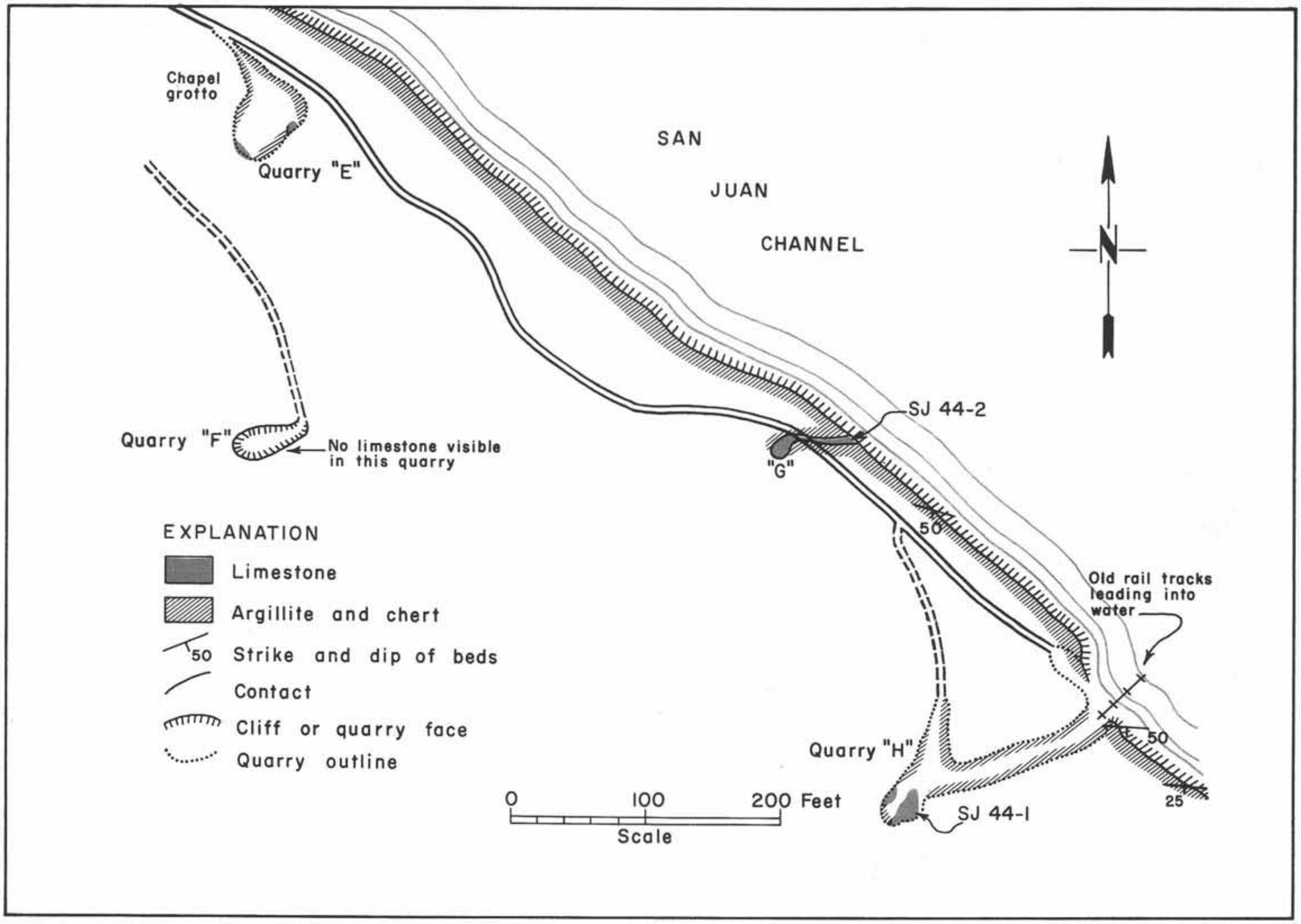


FIGURE 34.—Eureka deposit, central part. SE¼ T. 36 N., R. 3 W. Geology by W. R. Danner, C. F. McKillop, and A. M. Rivisto. Base map by compass and tape survey.

A sinkhole area lies approximately 500 feet northwest of outcrop C on both sides of an old logging road. Sinkholes occur over an area about 120 feet long north-south and 20 to 50 feet wide. At least 4 small sinkholes 2 to 5½ feet deep were found in glacial drift. No bedrock is visible.

Outcrop D is approximately 400 feet west of the above-described sinkhole area. It consists of a moundlike outcrop of crystalline limestone approximately 5 feet high and covering an area of approximately 2,500 square feet on the south side of an old logging road. The limestone is much fractured and resembles a heap of limestone blocks. Several solution cracks lead down into it. One on the southeast side is large enough to crawl into a short distance. This hole extends westward for approximately 4 feet, then bends to the right. The walls show solution action. Second-growth trees are growing on top of the limestone, and stumps of trees cut during former logging operations are also present. Several shallow prospect pits have been dug into the glacial drift and soil surrounding the outcrop.

Small limestone pods not more than 2 or 3 feet long and $1\frac{1}{2}$ feet wide were found cropping out on the wooded hillside a mile to the north, and a few tiny pods crop out along the beach below.

Outcrop E is approximately 500 feet southeast of the Salsbury home, on the west side of a road that is parallel to the beach on top of the beach cliff. A quarry about 60 feet long and 40 feet wide has been cut into what appears to be the crest of a small anticlinal structure. Limestone is visible only as remnants on the floor at the northwest and southeast sides of the quarry. The limestone bed is estimated to have been about 4 feet thick. There is a small rock-ringed pond on the quarry floor, and this quarry is known locally as the "Chapel Grotto."

Outcrop F is about 700 feet southeast of the Salsbury home, on the west side of an old road near the ruins of some old buildings. It consists of a pit about 55 feet long, 10 to 15 feet deep, and 15 feet wide, believed to have been a quarry but used now as a garbage dump and heavily overgrown with vegetation. No limestone is visible.

Outcrop G is about 450 feet southeast of Outcrop E. It is a thin bed of limestone cropping out on the beach cliff and crossing the road above. The limestone is exposed for a distance of about 40 feet northwest-southeast. This bed has a maximum thickness of about 4 feet but averages between 2 and 3 feet. It is exposed vertically for about 20 feet and is cut by numerous faults of small displacement.

Outcrop H is in an abandoned quarry about 300 feet southeast of Outcrop G. This quarry opens out onto the beach and also has an entrance on the north side above the beach. The quarry is about 175 feet long and 20 feet wide. A little limestone is exposed only at the southwest end of the quarry. On the beach, ribbon cherts with small limestone pods are exposed on the sides of the quarry entrance. A 2-foot bed of greenstone is exposed on the north side of the quarry entrance.

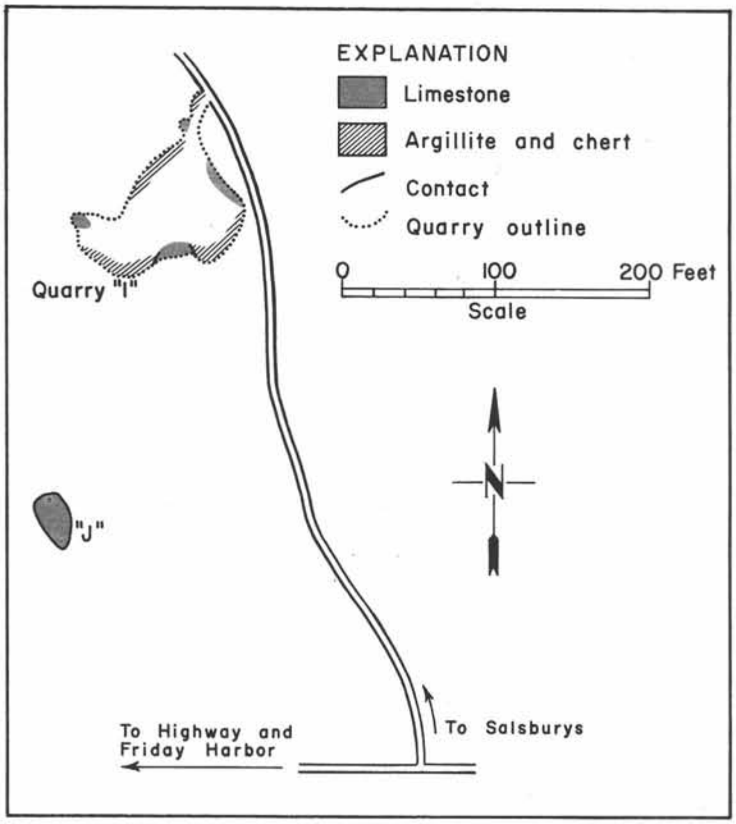


FIGURE 35.—Eureka deposit, south part. SE$\frac{1}{4}$ T. 36 N., R. 3 W. Geology by W. R. Danner, C. F. McKillop, and A. M. Rivisto. Base map by compass and tape survey.

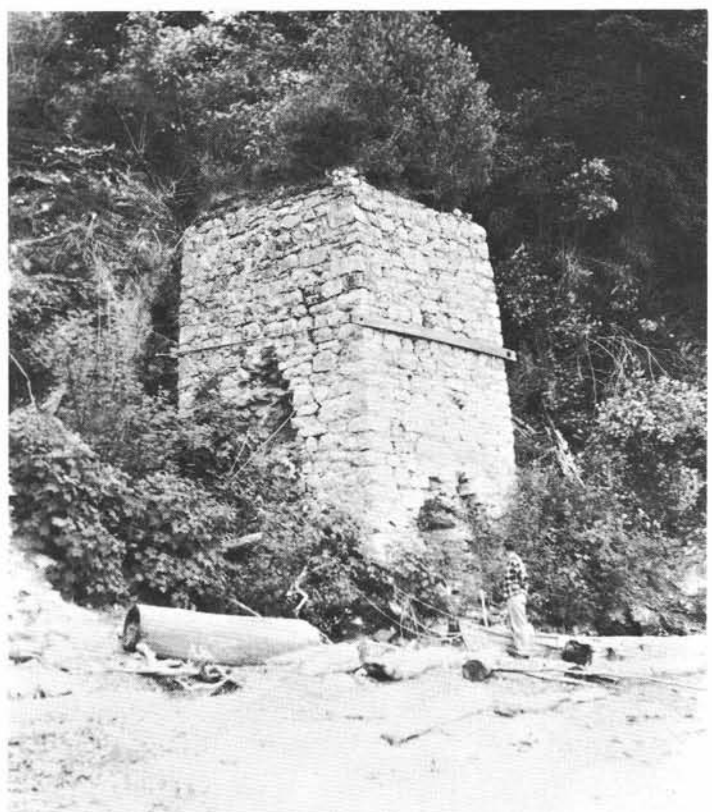


FIGURE 36.—Old limekiln at Eureka deposit. Northerly of two kilns. View looking northwest, 1959.

South of this quarry and inland from the beach, limestone fragments and boulders are found in various places. No outcrops could be seen, but the area is covered with soil and dense brush. This limestone probably is debris from the quarry operations rather than float from concealed outcrops.

Outcrop I, on the west side of the road to the D. M. Salsbury residence about 420 feet east of the junction with the graveled road leading to the highway, is a small abandoned quarry partly filled with water during wet weather. Trees of western red cedar a foot in diameter are growing on the quarry floor. Blue-gray crystalline limestone is exposed in several places on the north and south walls. This quarry has a length of 120 feet and a maximum width of 70 feet. Its greatest depth is 12 feet, on the south side.

One hundred and fifty feet southwest of Outcrop I, on a gently sloping hillside, is exposed a mass of moss-covered limestone fragments about 30 feet by 15 feet in area. This mass appears to be a collapse area of limestone fragments similar to Outcrop D, to the north.

Quality.—The different outcrops included as the Eureka limestone are variable in composition. Some contain magnesium and others silica as major impurities.

Chemical analyses of Eureka limestone

(Mark Adams, analyst)

Sample no.	Location	Sample length (feet)	$CaCO_3$	$MgCO_3$	Loss on ignition	CaO	MgO	SiO_2	R_2O_3	P_2O_5
SJ 1-1	Outcrop D, NW. part of limestone area ----------	50	86.25	9.17	44.16	50.48	4.39	0.40	0.43	0.01
SJ 44-1	Quarry H, west end -----------	40	95.96	0.60	42.47	53.87	0.29	3.02	0.49	0.036
SJ 44-2	Beach outcrop, south end ------	20	97.45	0.23	42.61	54.75	0.11	1.52	0.15	0.048

Ownership and development.—This limestone occurrence is thought to have been opened up by an Englishman named Roberts during the joint military occupation of San Juan Island by the British and Americans. In 1863 American squatters attempted to seize it from him through an illegal order of the local justice of the peace. Roberts drowned later that year. It is probable that a kiln and several buildings were in existence when in 1881 a patent was issued to William McLachlan for the property, then known as Eureka Lime Kiln. A partnership was formed with William McLachlan, Daniel McLachlan, and Thomas H. Lee. Another limekiln was constructed along with other buildings, so that the property contained a cooper shop, homes, shed, wharf, blacksmith shop, and later a cookhouse and a bunkhouse. Lime was shipped to Seattle and Tacoma. In 1887 the property was taken over by two men named Washams and Elliott. Production is thought to have ceased about 1890. Seven small quarries were developed and abandoned. The small amount of limestone remaining in the quarries and in the two untouched outcrops totals only a few hundred tons. One of the old kilns has been mostly demolished, and its stone and brick has been used in local construction. The other kiln has been preserved by the Salsburys. In 1959 the property was owned in part by Mrs. D. M. Salsbury and in part by her relatives.

References.—Glover (1936, p. 56), Northern Pacific Railway Co. (1941, unpublished notes, p. 13), Moore (1953).

South Coast of San Juan Island

Several small limestone outcrops occur along the south coast of San Juan Island and are described briefly below. None are of economic importance, but they are reported here because of their geological interest and in order to make this report as complete as possible.

Cattle Point.—Several small limestone lenses crop out on a small point just south of the most easterly projection of San Juan Island at Cattle Point, in the SE¼ sec. 8, T. 35 N., R. 2 W. The largest lens is about 10 feet long and 3 feet wide. The limestone is gray in color, finely crystalline in texture, and interbedded with graywacke, black argillite, chert, and greenstone. The sequence strikes approximately N. 60° W. and dips steeply to the south. A few hundred feet to the west along the south coast of San Juan Island are other small limestone outcrops, some of which look as if they are fragments rather than depositional bodies. The largest limestone body seen is 3 feet long and about 8 inches wide.

Eagle Point.—Numerous small pods of limestone crop out along the south coast of San Juan Island for about a mile across sec. 11, T. 34 N., R. 3 W. The largest are 10 feet or more in length and as much as 3 feet in thickness. They are interbedded with tuffaceous green argillite, ribbon chert, and thin greenstone flows. The sequence containing the limestone strikes about N. 70° W. and dips about 50° NE.

False Bay.—About 1,400 feet west of the west side of False Bay a lens of limestone, approximately 5 feet long and 2 feet at its widest point, crops out in the upper part of a beach cliff. It is in the NW¼SW¼ sec. 33, T. 35 N., R. 3 W., and is interbedded with volcanic rocks and ribbon chert.

Hannah Area

Location, size, and accessibility.—Two small outcrop areas very difficult to find occur in the southwest interior of San Juan Island.

Outcrop Area A is in a small creek bed in the SE¼SW¼ sec. 19, T. 35 N., R. 3 W., at an altitude of slightly less than 300 feet. The exposure is about 5 feet high, 4 feet wide, and 6 feet long. The area is logged-off land, brushy and rocky, and can be reached by following an old logging road about half a mile from the home of Ed Hannah, on the West Side road, to a position above the creek.

Outcrop Area B is about in the center of the N½NE¼ sec. 30, T. 35 N., R. 3 W., in a relatively flat and exceedingly brushy area north of a large pasture. It consists of two limestone outcrops, a northern one about 50 feet long and 10 feet wide, and a southern one about 15 feet long and about 3 feet wide. The altitude of this deposit is about 180 feet. It can be reached by driving about 3/4 mile on an old logging road from the home of Ed Hannah, on the West Side road, and then hiking about 400 feet north through dense brush.

Geology and description.—Limestone in Area A consists of an outcrop on the west side of a small creekbed heavily overgrown with brush. The outcrop is about 5 feet high and is overlain by glacial drift. A cave, the entrance of which is about 2 feet high and 4 feet wide, extends back into the outcrop for about 6 feet, at which point the roof of the cave joins the floor. The cave is filled with water. Argillite is exposed to the west of the limestone. Surrounding outcrops are made up mostly of ribbon chert. This limestone appears to be a very small body but is too poorly exposed to show much about its size and extent. The limestone is tough, gray in color, and crystalline in texture. It contains interbedded streaks of black carbonaceous material.

Outcrop Area B is on the southwest side of a small rocky ridge rising about 8 feet above surrounding flatlands. The limestone is covered with moss and dense brush. It appears to consist of a narrow lens striking northeastward and dipping steeply to the west. Ribbon chert and cherty argillite underlie it. The limestone appears to extend beneath glacial drift to the west.

About 100 feet to the southwest on a bearing of about S. 28° W. is a second limestone outcrop, which forms a small solution-pitted ridge in a swampy area. It is exposed for a length of about 15 feet and has a maximum width of about 3 feet. The limestone is finely crystalline in texture and bluish gray in color. It is surrounded by soil and glacial drift.

Quality.—Analyzed samples from these outcrops are composed of high-calcium limestone.

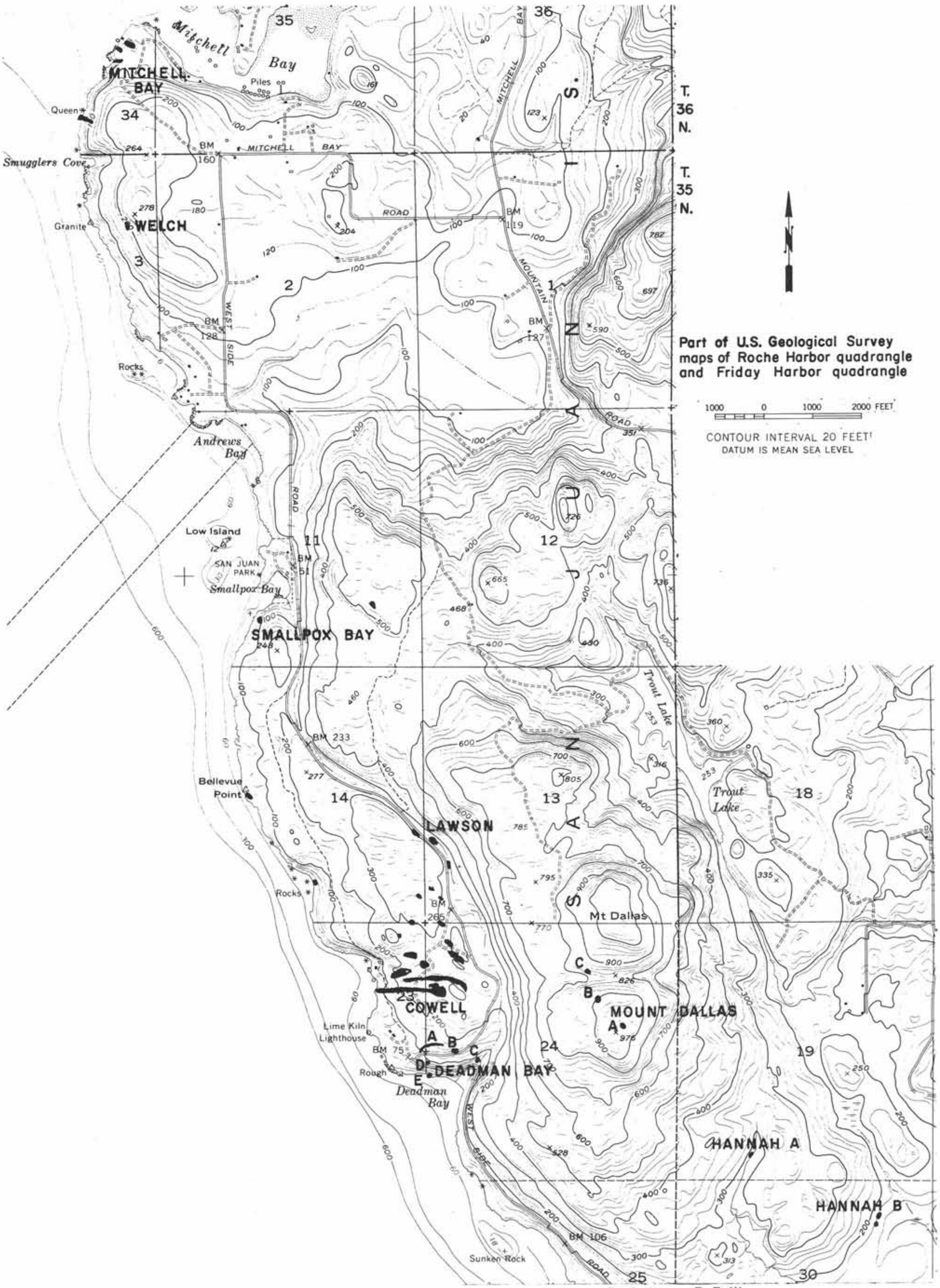


FIGURE 37. — Limestone deposits of western San Juan Island.

Chemical analyses of Hannah limestone

(Mark Adams, analyst)

Sample no.	Location	Sample length (feet)	$CaCO_3$	$MgCO_3$	Loss on ignition	CaO	MgO	SiO_2	R_2O_3	P_2O_5
SJ 4-1	Outcrop A -------	6	97.56	0.71	43.00	54.87	0.34	0.61	0.96	0.10
SJ 4-2	Outcrop B -------	65	96.01	1.38	43.32	53.94	0.66	0.80	0.71	0.08

Ownership and development.—The land containing the limestone is owned by Edward Hannah, who lives on the hillside above the West Side Highway, west of the property. These limestone outcrops have been known for many years, but there has been no exploration or development. Outcrop B, where concealed and overlain by glacial drift, should be explored to determine its size.

Mount Dallas Deposits

McLellan (1927, p. 166) reported: "A large number of small limestone lenses occur on Mount Dallas Range. In many cases the individual lenses do not exceed fifteen feet in length and two feet in thickness." A search in the vicinity of Mount Dallas located only three small limestone lenses, though reports were received of limestone bodies in localities other than those found. None of the deposits investigated were large enough to be of commercial value, and all were in the NE¼ sec. 24, T. 35 N., R. 4 W.

Outcrop A.—Outcrop A is a limestone pod 2 feet by 3 feet in size, not well exposed, in a small valley trending northwest-southeast across the high point of the south peak of Mount Dallas. The limestone is light gray in color, crystalline in texture, and interbedded with chert and volcanic rocks. It crops out at an altitude of 940 feet.

Outcrop B.—Limestone of Outcrop B is at an altitude of about 890 feet at the northwest part of the south peak of Mount Dallas. It is about 10 feet long and 2 feet wide. The limestone is dense to crystalline in texture and contains numerous small interbedded layers of shale and chert.

Outcrop C.—Limestone of Outcrop C is at an altitude of approximately 840 feet on the southwest side of the main peak of Mount Dallas. It consists of a limestone pod about 3 feet by 4 feet in size composed of alternating layers of chert and limestone.

Reference.—McLellan (1927, p. 166).

Cowell Quarries

Location, size, and accessibility.—The Cowell limestone deposit is in the NE¼ sec. 23 and NW¼ sec. 24, T. 35 N., R. 4 W., on the west coast of San Juan Island north of Deadman Bay. The main part of the occurrence consists of three large irregular lenticular beds ranging from 800 to 1,500 feet in length and from 50 feet to slightly over 300 feet in width. Eleven smaller pods, usually less than 100 feet in length and 50 feet in width, crop out to the north of the main outcrops.

Limestone extends from sea level to an altitude of over 320 feet, but most of the outcrops occur on a relatively flat benchlike area ranging from 200 to 320 feet in altitude. The terrain is mostly open, rocky, and grass covered, but areas of dense brush and trees are common. Roads lead over the property to quarries developed on the larger lenses. The area is accessible by water on the west side, but the coastline is open and for the most part unprotected. The area is also accessible from the east via the West Side road and is 10 to 12 miles by road from Friday Harbor. A small harbor suitable for barges is 2 miles by road to the north at Smallpox Bay.

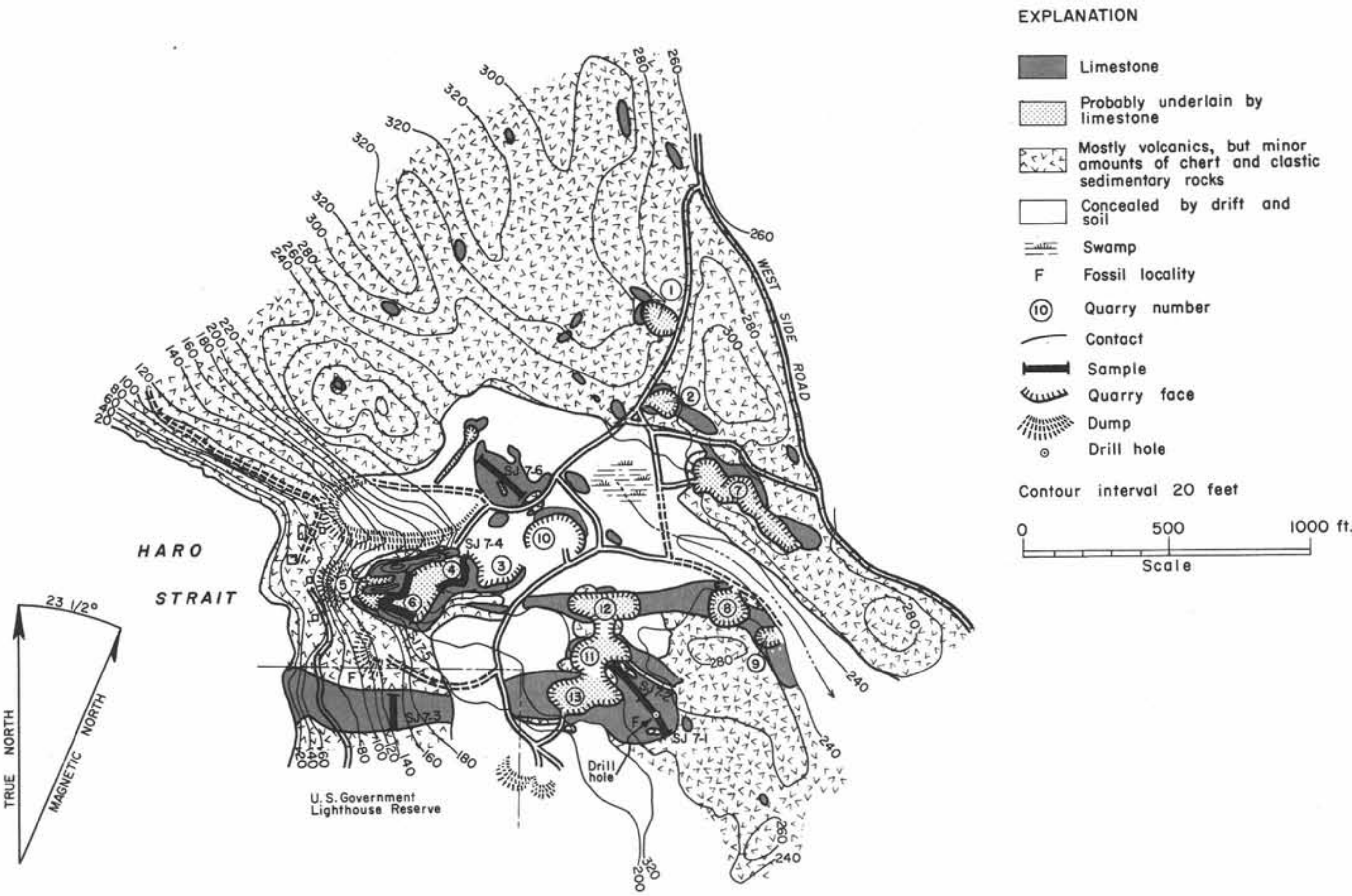


FIGURE 38.—Cowell limestone deposits. Secs. 23 and 24, T. 35 N., R. 4 W., San Juan Island. Geology by W. R. Danner, C. F. McKillop, and A. M. Rivisto. Plane table survey.

Geology and description.—The Cowell deposit consists of irregular lenticular bodies of limestone interbedded in a sequence composed predominantly of spilitic basalts, but having lesser amounts of ribbon chert, green lithic sandstone, and argillite. It is difficult to tell whether one major limestone body, repeated by folding and faulting, makes up the three major outcrop belts exposed on the property and adjacent area or whether these are three distinct beds. Identical fossils in at least two of the outcrop belts suggest the first alternative.

The limestone-bearing sedimentary and volcanic rocks of the Cowell property and vicinity are at the south end of an area of volcanic rocks that extends northward 2 miles to just north of Smallpox Bay. North, south, and east of this belt the bedrock outcrops are made up predominantly of ribbon chert.

Description of individual outcrops.—The southernmost limestone outcrop belt is exposed on the west in a sea cliff, where it has a maximum width of approximately 200 feet. It can be traced from sea level to an altitude of about 197 feet over a distance of about 550 feet inland. It then disappears under glacial drift. It is again exposed about 150 feet to the east, on the east side of a quarry access road, and can be traced 600 feet farther east to where it appears to pinch out rather abruptly in argillite. Its maximum width here is about 300 feet. The limestone is interbedded with tuffaceous argillites and spilitic volcanic rocks. Recognizable bedding is rarely visible, but where present it indicates an east-west to northeast-southwest strike and a steep dip to the south. The south contact as seen at the quarry entrance is a highly sheared zone, proably a fault, but outcrops of the contact elsewhere are not readily identifiable as faults. Wedges of argillite appear in part to be faulted into the limestone, and in some places in the quarry walls slices of limestone and argillite are intermingled with each other.

The limestone exposed in this southern outcrop belt is dense to crystalline in texture and is blue gray in color. It contains many irregular stringers of secondary chert or jasperoid and is partly dolomitized. Where the magnesium content is high, the limestone has a sugary appearance. An 8-inch-thick bed of coquina composed of Permian fusulinids is traceable

FIGURE 39.—Cowell limestone deposit. View looking southeast.

along a line striking about N. 50° E. across the east end of this outcrop, and on weathered surfaces specimens of a large Neoschwagerina are easily visible. Individual, isolated fusulinids are visible at other places in the limestone, but most fossils have been destroyed by recrystallization. To the east is a relatively flat area exposing mostly volcanic rocks, argillite, and chert. A few tiny limestone pods also occur. On a dump at the south end of this area in 1959 were specimens of vuggy limestone containing a black solid hydrocarbon.

The middle limestone outcrop belt starts approximately 300 feet east of the shore at an altitude of about 160 feet and is traceable for over 1,600 feet inland. Near its west end it is over 200 feet wide, but it appears to pinch out at depth and westward. Eastward along its strike it widens to almost 600 feet, but the central part of the outcrop area is largely covered with glacial drift, and whether the scattered exposures seen there belong to the same body is not known. Small beds of argillite, volcanic rocks, and chert occur within the limestone. Near its eastern end the limestone thins to less than 100 feet in width and finally pinches out on the south side of a small intermittent stream. A few small sinkholes occur in this area, and a solution crevice is visible on the south wall of the last small quarry to the southeast.

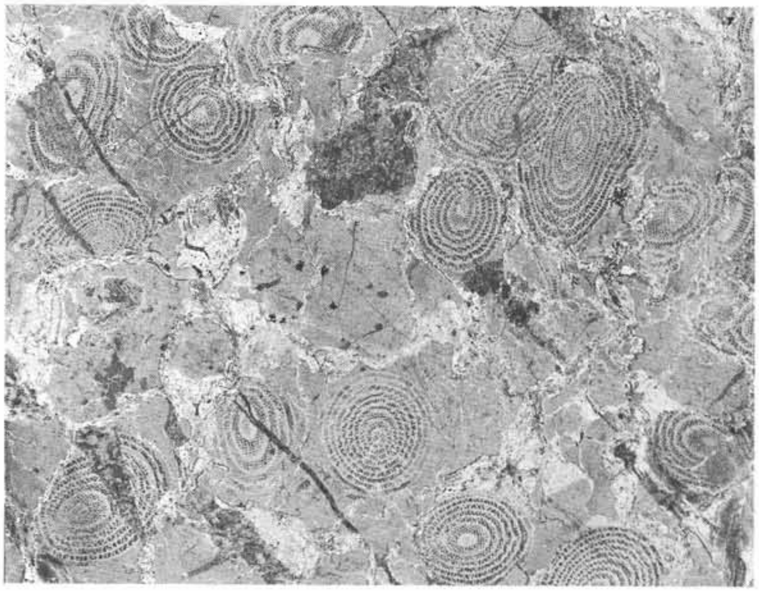


FIGURE 40. — Permian fusulinid Neoschwagerina. Cowell deposit. Negative print from acetate peel. X 2¼.

The west end of this limestone bed apparently formed a towering cliff outcrop and was the site of early development of the property. Later development was carried on inland to the east.

The limestone is light gray in color and finely crystalline in texture. Much of it is magnesium rich, and irregular masses of brownish-gray chert or jasperoid are numerous. Farther east it becomes argillaceous, and where it pinches out it contains a considerable amount of chert. Permian fusulinids and other Foraminifera are in this limestone along its southern contact at the west end of the outcrop area and at the northeast corner of Quarry No. 8, to the east. The fossils at this latter locality are large specimens of Neoschwagerina and occur in a shaly facies of the limestone. Several faults and shear zones are visible in the volcanic rocks and sediments at the west end of the outcrop and in the various quarries.

Several knobs of limestone are exposed in a drift-covered area immediately north of this middle outcrop belt and may be part of the same body. The most northwesterly outcrop has been partially quarried and has a spring in the quarry floor. The limestone also contains a small solution cavity.

To the northwest is an area of bedrock knolls containing several small pods of ribbon chert and limestone interbedded in volcanic rocks. Pillow structure in the volcanic rocks is well exposed in cliffs near the shore. Northward along the shore there are excellent exposures of volcanic breccia.

The third outcrop belt is much smaller than the other two and is at the northeast side of the limestone outcrop area. Exposures of limestone spread over a strike distance of about 800 feet, but they are not continuous. The maximum width of the limestone is about 120 feet. Volcanic rocks appear to surround most outcrops and make this a series of small limestone lenses rather than one continuous body.

Quality. — The quality of the Cowell limestone deposit is quite variable. Some outcrops contain high-calcium limestone, whereas in others the limestone is rich in magnesium and silica. The variation in quality has been a detrimental factor for the use of the limestone in previous operations. The high-magnesium limestone is characterized by its buff color and sugary texture. Silica is commonly present as irregular masses of brown- to buff-colored, transluscent to opaque jasperoid.

Ownership and development. — Thirteen small quarries have been developed on the property, which is owned (1961) by Miss Ruth Brown, of Four Winds, Deer Harbor, Wash. The limestone was first developed about 1860, when Augustus Hibbard opened a quarry and built a limekiln on the site. In 1870 the Federal census reported that the firm employed 18 persons and in 12 months had produced 13,000 barrels of lime worth $26,000. By 1879, production had reached 20,000 barrels annually. Later, the property was acquired by Henry Cowell and Company, of San Francisco, and limestone was burned for lime in kilns constructed of local limestone and Sucia Island sandstone, and lined with a double row of fire brick. Two kilns with a total capacity of 230 barrels of lime per day were operated in 1901. A kiln remaining on the property bears the date 1918. McLellan (1927) reported: "The quarry is located about 200 feet above the kilns, and the rock is delivered by means of cable cars using the gravity system."

Chemical analyses of Cowell limestone

Sample no.	Location	Sample length (feet)	$CaCO_3$	$MgCO_3$	Loss on ignition	CaO	MgO	SiO_2	R_2O_3	P_2O_5	Na_2O (ppm)	K_2O (ppm)	TiO_2 (ppm)	S (ppm)
					Analyses of samples collected for this report, Mark Adams, analyst									
SJ 7-1	SE. outcrop, south part	160	90.26	7.06	43.41	50.71	3.38	1.59	0.90	0.1	260 (SJ 7-1 and SJ 7-2)	560	325	180
SJ 7-2	SE. outcrop, north part	160	85.51	7.29	41.68	48.04	3.49	5.17	1.11	0.03				
SJ 7-3	Coast Guard property	120	93.46	4.34	43.56	52.51	2.08	0.93	0.50	0.03				
SJ 7-4	East end, main outcrop	160	84.17	12.60	43.98	47.29	6.03	1.20	0.70	0.17	270 (SJ 7-4 and SJ 7-5)	530	1/	60
SJ 7-5	West end, main outcrop	280	85.44	11.12	42.63	47.58	5.79	3.63	0.61	0.088				
SJ 7-6	Limestone outcrops north of main outcrop	200	94.48	2.96	43.19	53.08	1.42	1.15	0.91	0.045				
					Analyses from other sources									
	Unknown 2/				43.20	52.35	2.30	1.60	3/ 0.42					4/
	Quarry 1 5/	Composite chip samples	81.82	4.60										
	Quarry 2 5/	--- do ----	90.76	1.35										
	Quarry 3 5/	--- do ----	83.00	6.10										
	Quarry 4 5/	--- do ----	73.83	10.15										
	Quarry 5 5/	--- do ----	66.21	7.36										
	Quarry 6 5/	--- do ----	85.48	2.90										
	Quarry 7 5/	--- do ----	87.16	2.73										
	Quarry 8 5/	--- do ----	93.96	1.92										
	Quarry 10 5/	--- do ----	86.98	1.83										
	Quarry 11 5/	--- do ----	89.00	1.37										
	Quarry 12 5/	--- do ----	87.33	3.65										

1/ Less than 30. 2/ Hodge (1938, p. 15). 3/ $Al_2O_3 = 0.30$, $Fe_2O_3 = 0.12$. 4/ 0.01 percent SO_3. 5/ Private report, unpublished.

The lime from this operation was shipped to cities and towns around Puget Sound; to Portland, Oregon; and reportedly to San Francisco and Hawaii. At one time a small dock existed on the property and the lime was shipped from here during calm weather. The coastline is exposed to the prevailing southwesterly winds and offers little or no protection to ships. The shore is mostly cliffs, and it drops off steeply. Less than 200 feet from shore the water reaches depths of 60 feet or more. Ruins of five kilns, a barn, a bunkhouse, and outbuildings remain on the property.

Between 1940 and 1950 The Olympic Portland Cement Company, of Bellingham, leased the property from Henry Cowell and Company and opened many of the small quarries on the east side of the area. The rock was used for pulp rock and cement and was trucked 2 miles north to be loaded onto scows at Smallpox Bay. It was shipped to Bellingham, Seattle, Tacoma, Port Angeles, Hoquiam, and Shelton. Operations ceased because of the poor quality of the rock. In recent years some of the waste material has been used for road surfacing on the island. Dumps containing a total of several thousand tons of limestone fragments of various sizes remain on the property.

At least 800,000 tons of limestone is believed to be contained in outcrops at the southwest corner of the area on the U.S. Government Lighthouse Reserve. The proximity of this to the lighthouse installations has prevented its development.

References.—Landes (1902, p. 187), McLellan (1927, p. 166), Glover (1936, p. 56), Hodge (1938, p. 187), Northern Pacific Railway Co. (1941, unpublished notes, p. 13), Mathews (1947, p. 52), McDonald (1959, p. 4-5).

Deadman Bay Deposits

Location, size, and accessibility.—At least five small lenses of limestone are interbedded with volcanic rocks at Deadman Bay and to the north in the SW¼NW¼ sec. 24 and the NW¼SW¼ sec. 24, T. 35 N., R. 4 W., along the west coast of San Juan Island. The largest group of outcrops can be traced intermittently for 600 feet; the group does not form a continuous bed but consists of small lenses and pods, some only a foot or more in width and usually less than 10 feet in width. The other limestone bodies are much smaller. All are on or within a few feet of the West Side road.

Geology and description.—The north side of Deadman Bay is composed mostly of outcrops of amygdaloidal basalts and volcanic breccias containing minor amounts of ribbon chert, argillite, and limestone. Southeast of Deadman Bay, outcrops along the coast are composed largely of ribbon chert. The local structural trends are predominantly northwesterly with steep northeasterly dips, but minor variations are common.

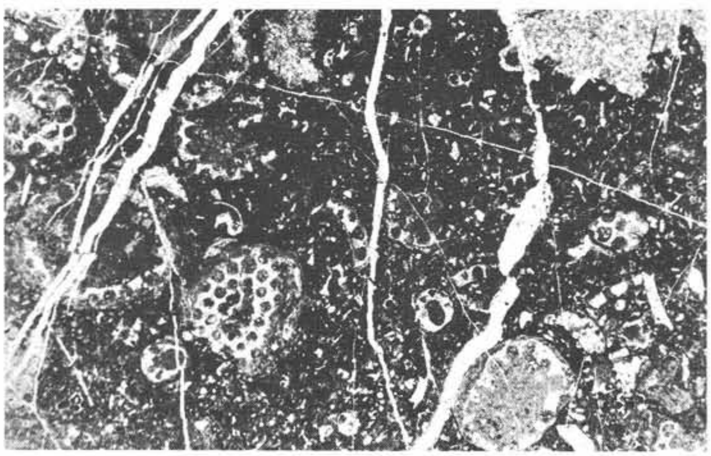


FIGURE 41.—Permian alga Gyroporella, Deadman Bay deposit A, San Juan Island. X 5.

The largest limestone outcrop area (A) is exposed close to the West Side road near its junction with the road to the Lime Kiln Lighthouse. It can be traced by intermittent outcrops northeastward in a gentle arc for approximately 600 feet. The limestone is gray in color, partly recrystallized, and contains small masses of chert or jasperoid. In some places it is composed of the remains of Permian calcareous algae. Very few outcrops are more than 10 feet in width, and adjacent rocks are largely volcanic, though ribbon chert and clastic sediments are present. Near the southwest end of this area on the road is another limestone lens about 25 feet long and 3 feet wide striking northeast-southwest.

A second limestone body (B) is exposed in a roadcut on the West Side road about 800 feet east of where the boundary line between secs. 23 and 24 crosses the road. The limestone crops out northwestward for about 120 feet and has a maximum exposed width of 25 feet. It is mostly recrystallized. It is poorly exposed, so its total area is unknown. One small outcrop is known south below the road, and may be an extension of this deposit.

A third limestone body (C) is exposed on the west side of a creek draining into Deadman Bay about 50 feet north of where the West Side road crosses the creek. It is surrounded by glacial drift and dense vegetation and crops out in a knob 3 to 4 feet wide, 4 to 6 feet long, and 6 feet high. The outcrop occurs 10 feet above the creekbed. Ribbon chert is exposed below the limestone in the creekbed.

A fourth limestone outcrop (D) occurs just north of the West Side road on the switchback below and east of the entrance to the Lime Kiln Lighthouse Reserve. The limestone is only a few square feet in area and is surrounded by volcanic rocks. Several smaller limestone outcrops, mostly measured in square inches, occur in the vicinity.

A small limestone lens (E) crops out on a small peninsula in Deadman Bay approximately along the boundary line between secs. 23 and 24. It is mostly covered by water at high tide.

Quality.—The poorly exposed outcrop C was sampled by taking random chips from various parts of the outcrop for a composite sample. It is a high-calcium limestone.

Chemical analysis of Deadman Bay limestone

(Mark Adams, analyst)

Sample no.	Sample length (feet)	$CaCO_3$	$MgCO_3$	Loss on ignition	CaO	MgO	SiO_2	R_2O_3	P_2O_5
SJ 66-1	Composite	96.12	1.06	43.12	54.00	0.51	1.16	0.61	0.014

Ownership and development. — Most of the small bodies making up this occurrence are on property owned by Miss Ruth Brown, of Four Winds, Deer Harbor, Orcas Island, Wash. A few are on property of the United States Government Lighthouse Reserve. There has been no development, and all are too small to be of economic value. Outcrops C and D are so poorly exposed that determination of their extent is impossible, but they are not likely to be large enough to justify exploration.

Limestone Outcrops North of Cowell Quarries Along West Coast of San Juan Island

Several small pods and lenses of limestone are known to occur along the west coast of San Juan Island from the Cowell quarries north to Smallpox Bay. Those visited are briefly described below. None are large enough to be of economic value.

A small pod of limestone is exposed at water level in the SW¼SE¼ sec. 14, T. 35 N., R. 4 W., approximately 2,000 feet north along the coast from the Cowell quarries. It has been partly eroded away by wave action, which formed a narrow indentation in the beach cliff. The limestone outcrop is from 2 to 4 feet in width, and its extension inland is covered by glacial drift and soil. Only a few square feet of limestone is exposed, and it is believed to be of no economic value.

Bellevue Point. — Just south of Bellevue Point in the SE¼NW¼ sec. 14, T. 35 N., R. 4 W., a body of limestone is exposed at low tide in the beach cliff. It is overlain by a lens of ribbon chert and surrounded by volcanic rocks. The limestone is exposed for 30 feet north-south along the shore, is about 5 feet thick vertically, and has an exposed maximum width of 5 feet east-west.

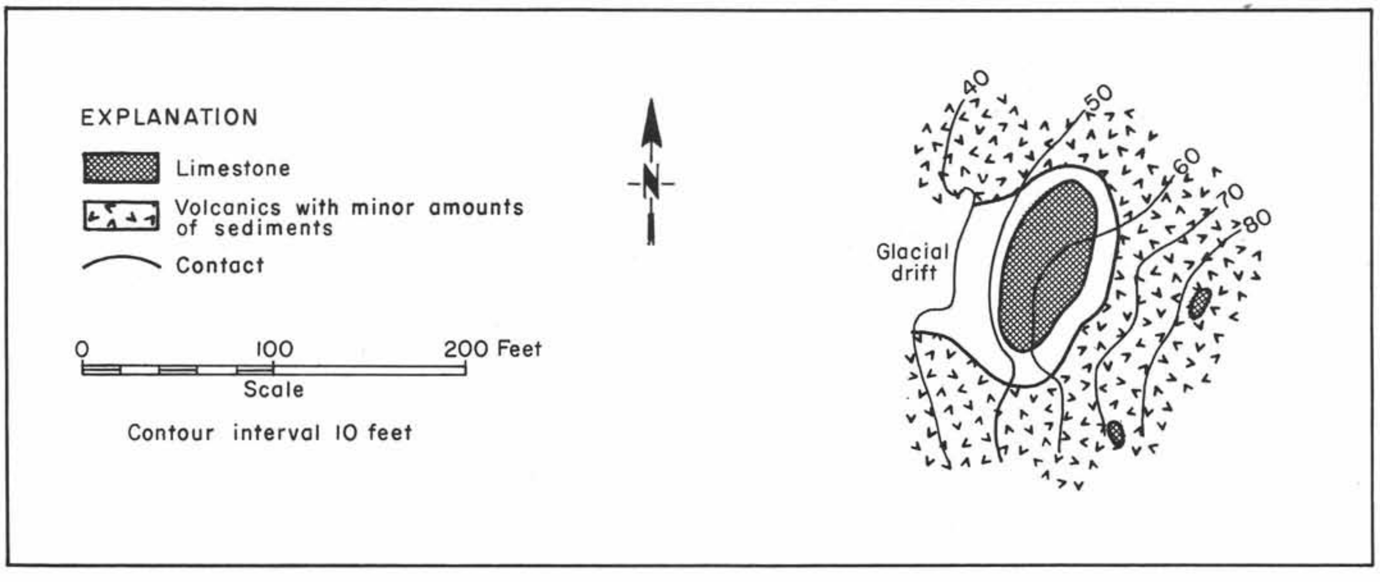


FIGURE 42. — Smallpox Bay deposit. SE¼SW¼ sec. 11, T. 35 N., R. 4 W. Geology by W. R. Danner, C. F. McKillop, and A. M. Rivisto. Base map by compass and tape survey.

Smallpox Bay.—A small knob of limestone is exposed on the hillside just south of the seaward entrance to Smallpox Bay in the SE¼SW¼ sec. 11, T. 35 N., R. 4 W. It is about 200 feet south of the shore and lies at an estimated altitude of 50 feet above sea level. It forms a lens in volcanic rocks, but the contact between limestone and volcanics is mostly concealed by glacial drift and soil. The limestone is light gray in color and finely crystalline in texture. It crops out north-south over a distance of approximately 9 feet and east-west for a maximum width of 40 feet. Its vertical exposure is approximately 15 feet. A series of chip samples was taken across the width and length of the outcrop, and its analysis indicates a magnesian limestone.

Chemical analysis of Smallpox Bay limestone

(Mark Adams, analyst)

Sample no.	Sample length (feet)	$CaCO_3$	$MgCO_3$	Loss on ignition	CaO	MgO	SiO_2	R_2O_3	P_2O_5
SJ 6-1	40	83.14	13.16	43.11	46.71	6.30	1.75	1.87	0.22

A small limestone pod about 15 square feet in area is exposed about 100 feet southeast of the Smallpox Bay limestone. It is white to light gray in color, crystalline in texture, and contains small beds of chert or jasperoid.

About 75 feet east of the Smallpox Bay limestone is another small limestone outcrop, about 60 square feet in area. The limestone is interbedded with volcanic and sedimentary rocks.

West Side Road.—In the SW¼SW¼ sec. 13, T. 35 N., R. 4 W., a small area of limestone crops out along the east side of the West Side road. The occurrence is about 1,050 feet north of the northern entrance to the Cowell quarries. The limestone outcrop is in a grassy area adjacent to the highway, and is so poorly exposed that it is not known for certain whether the limestone represents an outcrop or partly buried float. The limestone is dark bluish gray in color and finely crystalline in texture. Small outcrops, only a few square feet in area, occur on the hill to the west, in the SE¼ sec. 14.

The limestone occurrences Nos. 1 through 4 are all on property owned by Miss Ruth Brown, Four Winds, Deer Harbor, Orcas Island, Wash.

A small exposure of limestone is at an altitude of approximately 520 feet in the NW¼SE¼SE¼ sec. 11, T. 35 N., R. 4 W. It consists of two outcrops that are separated by a narrow strip of glacial drift and soil. The outcrop area is about 45 feet long north-south and 35 feet wide. The height of the outcrop is about 4 feet. Argillite and chert are in contact with the limestone on its northeast side and crop out in the immediate vicinity on all sides. The occurrence is too small to be of economic value. The owner of the limestone is unknown.

Lawson Cave Deposit

Location, size, and accessibility.—The southern part of the Lawson Cave limestone deposit is in the NW¼SW¼ sec. 13, and the northern part is in the NE¼SE¼ sec. 14, T. 35 N., R. 4 W., at altitudes between 285 and 310 feet on the west side of San Juan Island. The southern part consists of a discontinuous outcrop belt approximately 120 feet in total length and 10 to 20 feet in width. The northern part consists of an outcrop belt 130 feet long and from 20 to 30 feet in width. The southern outcrops lie about 40 feet east of the West Side road, and the northern outcrops about the same distance west. They are easily accessible by automobile. The limestone is about 1½ miles by road from the small harbor at Smallpox Bay. The terrain is rocky and partly covered with brush and trees.

Geology and description.—The southern part of this limestone occurrence consists of at least three knoblike outcrops with intervening sinkholes, aligned about N. 50° W. It is thought that the area between outcrops, covered by drift, is also underlain by limestone. Individual outcrops are 10 to 20 feet in width and are composed of finely crystalline gray to white limestone. A swamp covers the trace of the outcrop to the north, and glacial drift and soil, to the south.

The northern outcrop consists of one small body of limestone overlain by volcanic rock. It is exposed on the west side of the West Side road and is partly concealed by vegetation. It contains a small solution cavity known locally as Lawson Cave (sometimes called Roadside Cave). The entrance to the cave is about 3 feet wide and slants down steeply to a nearly level floor at a depth of approximately 6 feet. At this place the cave is estimated to be between 8 and 10 feet in width. Local residents reported that they had gone in some 15 feet. At the time the cave was examined, the bottom contained several inches of water. Northwest of the cave a continuous belt of limestone is exposed for about 130 feet. The outcrop has about 10 feet of relief. A few feet to the west, volcanic rocks crop out on the hillside, and to the east along the road are outcrops of argillite. The limestone is light gray in color and finely crystalline in texture.

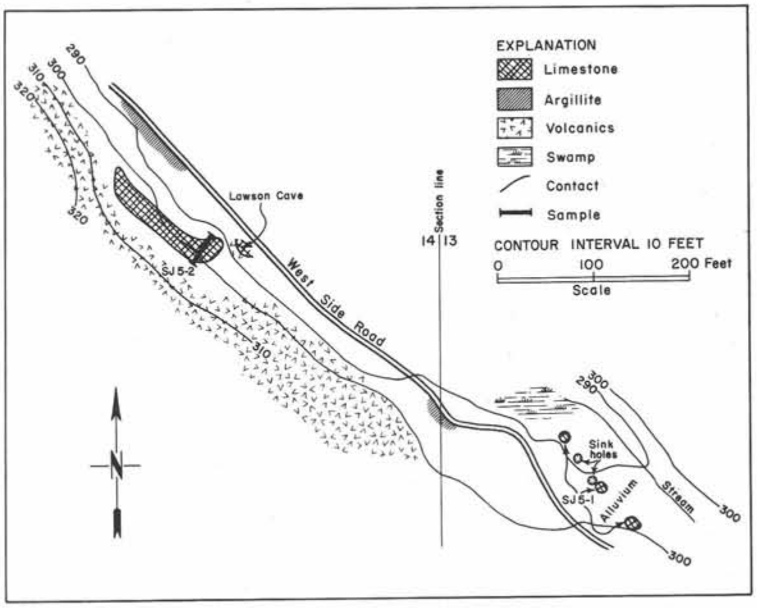


FIGURE 43.— Lawson Cave deposit. SW¼ sec. 13 and SE¼ sec. 14, T. 35 N., R. 4 W. Geology by W. R. Danner, C. F. McKillop, and A. M. Rivisto. Compass and tape survey.

Quality.— The limestone in these outcrops is of high-calcium type.

Chemical analyses of Lawson Cave limestone

(Mark Adams, analyst)

Sample no.	Location	Sample length (feet)	$CaCO_3$	$MgCO_3$	Loss on ignition	CaO	MgO	SiO_2	R_2O_3	P_2O_5
SJ 5-1	East side of road	Composite of all outcrops	97.81	0.58	43.61	54.95	0.28	0.27	0.40	0.07
SJ 5-2	West side of road	30	95.83	1.98	42.92	53.84	0.95	0.77	1.27	0.15

Ownership and development.— The southern part of the limestone, in sec. 13, is owned by Miss Ruth Brown, of Four Winds, Deer Harbor, Orcas Island. The northern part in sec. 14, is owned by the Lawson Estate (1959), most of the heirs to which live on San Juan Island. The deposit has never been developed. The northern part could supply probably 2,500 tons of limestone, assuming a depth of at least 20 feet. However, if the occurrence were quarried, its nearness to the West Side road would require a diversion of the road. Under present conditions it is probably uneconomical to develop this limestone.

Reference.— Halliday (1963, p. 61).

Welch Deposit

Location, size, and accessibility.— The Welch limestone deposit is in the NE¼ sec. 3, T. 35 N., R. 4 W., on the west coast of San Juan Island at an estimated altitude of 160 feet above sea level. It is about 1,500 feet south of Smugglers

Cove and about 500 feet inland from the shore. Four small limestone pods make up this occurrence; the largest of these is exposed for a width of 4 feet and a length of 70 feet. The outcrop is accessible by a wagon road leading to Smugglers Cove and then south, starting from just south of the junction of the Mitchell Bay road and the West Side road. The distance to the outcrop along this road is estimated to be about 3,300 feet. Just a few feet east of the roadside the limestone crops out on a brush-covered slope. Second-growth trees and thick brush cover the surrounding area.

Geology and description. — The occurrence consists of four pods of white to bluish-gray crystalline limestone interbedded in ribbon chert and volcanic rocks. Three of the limestone bodies are close together in a sequence of ribbon chert. The largest is exposed for a width of 4 feet and extends approximately 70 feet east-west. It is in contact with northward-dipping ribbon chert on the north and glacial drift and soil on the south, east, and west. A second limestone body is exposed about 20 feet to the north of the first and is about 1½ feet thick and crops out for a length of only 8 feet. It is in contact with north-dipping ribbon chert to the north and to the south. A third limestone body is approximately 12 feet north of the second and is only about 1 foot thick and 5 feet long. It also is in contact with north-dipping ribbon chert. The fourth limestone pod crops out over only a few square feet and is interbedded with volcanic rocks about 200 feet north of the others. The sedimentary rocks dip from 10° to 80° northward in this area and strike almost east-west.

Quality. — No samples were analyzed because of the small size of these limestone outcrops, but field examination indicated the limestone to be relatively free of visible impurities.

Ownership and development. — The owner of the area in 1959 was R. E. Welch. There has been no development. The limestone bodies are too small to have any economic value, but they are of interest in indicating the possibility of other limestone bodies in this area, which is covered with dense vegetation.

Mitchell Bay Quarry

Location, size, and accessibility. — The Mitchell Bay limestone deposit is in the NE¼SE¼ sec. 34, T. 36 N., R. 4 W., on the west coast of San Juan Island just south of the entrance to Mitchell Bay. The main part of the deposit consists of an abandoned and flooded quarry adjacent to the beach. This quarry is about 250 feet long and 100 to 150 feet wide. The walls are between 70 and 80 feet above the water level at their highest point. The quarry is easily accessible by boat and can be reached also by about 4,000 feet of wagon road starting at the intersection of the Mitchell Bay road and the West Side road. A steep and rough branch road extends a few hundred feet to the quarry entrance. The terrain is covered with a dense second growth of trees and brush.

Geology and description. — The limestone occurrence has been described previously as being composed of three limestone lenses in argillite (Valentine, 1960), but whether this reference was to the limestone deposit quarried or to other nearby outcrops is not known. A study of the quarry indicates that there are two beds of limestone separated by a bed of argillite 30 feet thick. The average strike is about N. 60° W., and the dip, about 70° SW. The limestone appears to thin toward the east, or rear of the quarry, and is overlain in that direction by 10 to 20 feet of sandy glacial till. The wall rock underlying and overlying the limestone is composed mostly of volcanic rocks and minor amounts of ribbon chert.

Limestone on the quarry dump contains chert and dolomite impurities. The limestone is light gray to buff in color, and most of it is finely crystalline in texture. No fossils are visible.

Many small pods and lenses of limestone crop out in the cliffs along the shore, both to the east of the quarry and southwest toward Smugglers Cove, but none are large enough to provide more than a few tons. One of the limestone beds is about 250 feet in length and can be traced up from the beach to a height of 78 feet, but is mostly less than 1 foot in thickness.

The rocks cropping out along the coast of San Juan Island in this area consist mostly of basalts, volcanic breccias, and tuffs, but there are many interbedded pods, lenses, and beds of chert, clastic sediments, and limestone. The sequence is steeply dipping, in part northward and in part southward, and is cut by numerous small faults. Erosion by waves along these faults in beach outcrops and the differing resistance of the rocks along the beach have produced a highly indented coastline with many small sea caves, peninsulas, and coves. South of Smugglers Cove, ribbon chert is the dominant rock type.

Much of the limestone in this sequence, when freshly broken, smells distinctly bituminous. Some of the limestone lenses are brown in color and appear to contain a high percentage of organic material. Fossils have been found at only one locality, about 400 feet southwest of the quarry at the head of a small cove. Here a small bed of argillaceous limestone about 2 feet thick crops out on the beach. Its trace inland is concealed by glacial drift and soil. The upper 1 foot of this limestone bed is largely a coquina of Permian fusulinids. The lower 1 foot is a dense-textured limestone containing only a few specimens of fusulinids but abundant remains of calcareous algae. These algae are tentatively identified as belonging to the genera Gyroporella and Mizzia. John W. Skinner, of the Humble Oil Company, identified fusulinids sent to him from this locality as belonging possibly to three different species of Schwagerina. One species resembles Schwagerina royandersoni in shape but is smaller, and another resembles Schwagerina caurus. It is thought that the limestones of the Mitchell Bay area are middle Permian in age and perhaps slightly older than the limestones of the Cowell deposit to the south.

Quality.—The limestone still exposed at the northwest end of the quarry was sampled across the strike. Its analysis indicates a magnesian limestone.

Chemical analysis of Mitchell Bay limestone

(Mark Adams, analyst)

Sample no.	Location	Sample length (feet)	$CaCO_3$	$MgCO_3$	Loss on ignition	CaO	MgO	SiO_2	R_2O_3	P_2O_5
SJ 45-1	NW. end of abandoned quarry	150	83.67	14.56	43.98	47.01	6.97	1.76	0.29	0.132

Ownership and development.—The Mitchell Bay limestone quarry is owned by Gordon Clauson, of Seattle. It was quarried first about 1933 by the Puget Sound Pulp and Timber Company. The abandoned quarry is flooded, and the trace of the limestone along the strike southeastward is covered with 10 to 20 feet of glacial sediments. The deposit is considered to be worked out, and no longer has any economic value. The pond in the bottom has been used as a swimming pool and in 1959 was leased to a nearby resort.

It is possible that one or more of the small limestone bodies near the quarry and on the beach were quarried at one time, but no definite quarry sites were found.

References.—Glover (1936, p. 56), Northern Pacific Railway Co. (1941, unpublished notes, p. 13), Valentine (1960, p. 54).

Limestone Point Quarry

Location, size, and accessibility.—The Limestone Point limestone deposit is in the NE¼ sec. 18, T. 36 N., R. 3 W., at the northeasterly tip of San Juan Island at sea level. An abandoned quarry is approximately 130 feet long north-south and 55 feet wide. The limestone is easily accessible by boat, as the quarry is on the shore. The occurrence can be reached on land by following the Limestone Point subdivision road branching east off the Lonesome Cove Resort road.

Geology and description.—The Limestone Point deposit forms a small knoblike outcrop jutting into the waters of Spieden Channel at the northeast tip of San Juan Island. The outcrop is about 300 feet long and 300 feet wide, and is composed of ribbon chert with thin interbedded limestone layers. At its highest point it reaches an altitude of 71 feet above sea level. A small part of the limestone at its northeast end has been quarried. The remaining rock is well-bedded limestone almost free of chert. The bedded limestone consists of alternating layers of dense gray calcilutites and organoclastic-oölitic limestones ranging from an inch to several feet in thickness. Examined in thin section, the dense beds were seen to be composed of a calcilutite containing numerous small calcite spheres that may be replaced radiolaria, thin filaments of calcite

FIGURE 44.— Limestone Point quarry. View looking south from Spieden Channel.

that closely resemble planktonic pelecypod shells, and a few coarse fragments of pelecypods, gastropods, brachiopods, and echinoderms. A few small fragments of volcanic rock were observed in one section. Small brachiopods were seen embedded in the limestone but are so poorly preserved that they could not be identified. The contact of the dense layers and the organoclastic limestone is usually a thin parting of greenish shale. Stylolites cut all the limestone types.

The oölitic-organoclastic limestone is quite variable in composition. Some small layers are composed entirely of oölites and pellets in a finely crystalline calcite matrix. Other layers are composed of a finely ground hash of organic debris consisting principally of fragments of brachiopods, pelecypods, bryozoans, echinoderms, and foraminifera. Other layers seem to be composed in part of algal material. Unfortunately, the fossil fragments are too broken up for identification. One thin section made from limestone collected at this locality in 1960 contained a single specimen of the foraminifer Pachyphloia Lange, which is common in middle Permian limestones of western Washington and also Sumatra (Lange, 1925), the Northern Caucasus (Miklucho-Maklai, 1954), and the middle and upper Permian of Japan (Huzimoto, 1936).

South of the quarry the limestone is interbedded with ribbon chert, which gradually increases in quantity until the limestone disappears completely. Several faults cut Limestone Point and have broken the limestone-chert sequence into blocks of different orientation. Beds exposed on the quarry floor strike northeastward and dip steeply to the northwest. On the south side of the quarry a block separated from the rest of the limestone by a fault has a northwesterly strike and a dip to the southwest.

Quality.—The limestone exposed on the quarry floor and immediately adjacent to the quarry walls is a high-calcium type. The remainder of Limestone Point is composed of limestone interbedded with chert, and the silica content is too high for the limestone to have any commercial value.

Chemical analyses of Limestone Point limestone

(Mark Adams, analyst)

Sample no.	Location	Sample length (feet)	$CaCO_3$	$MgCO_3$	Loss on ignition	CaO	MgO	SiO_2	R_2O_3	P_2O_5
SJ 43-1	Quarry face, south side -----	55	96.22	1.00	42.85	54.06	0.48	1.71	0.95	0.113
SJ 43-2	Quarry floor -----	130	95.46	1.23	42.63	53.63	0.59	2.35	1.13	0.200
SJ 61-1	SE. side of peninsula ------	100	54.55	0.50	24.39	30.65	0.24	43.06	1.59	0.040
SJ 61-3	SE. side of quarry face ----------	50	96.12	1.15	42.92	54.00	0.55	1.44	1.01	0.205

Ownership and development. — This limestone was formerly owned by the Roche Harbor Lime and Cement Company. When the company's property was sold in 1956 and converted into a resort, the Limestone Point area was subdivided, and subsequently two homesites were laid out on Limestone Point. These are now privately owned. The best grade of limestone was quarried from the deposit at some time prior to 1927. If the quarry floor were lowered only a few feet more, it would be covered by the sea at high tide. The limestone is thus considered to have no economic value, as the high-grade rock occupied only a small area and most of this was quarried.

The ruins of a small limekiln are on the southeast side of Limestone Point. The kiln is built of blocks of limestone and granite; its ruins are about 10 feet square and 3 to 4 feet in height. A mass of lime on the bank below indicates that the kiln was at one time in production, but its history is unknown.

Limestone Point is of interest to biologists as well as geologists, as unique marine flora and fauna inhabit the limestone cliffs below sea level. Also, many different types of wild flowers grow on the grassy slopes of the point and occur in numbers and varieties not usually found elsewhere on the San Juan Islands.

References. — McLellan (1927, p. 167), Glover (1936, p. 56), Northern Pacific Railway Co. (1941, unpublished notes, p. 13), Valentine (1960, p. 54).

Davison Head Deposit

Location, size, and accessibility. — The Davison Head limestone deposit is in the NE¼ sec. 14 and NW¼ sec. 13, T. 36 N., R. 4 W., on the north coast of San Juan Island, just south of Davison Head. Argillaceous limestone is interbedded with shales and sandstones in a sequence about 45 feet thick, of which about 24½ feet is limestone. The length of the deposit is unknown, as, except for the beach outcrop, it is covered with glacial drift and soil. The occurrence is easily accessible by boat. It can also be reached from Roche Harbor by following approximately 1 mile of wagon road starting at the Roche Harbor resort. Part of this road has a high center and is rough for automobiles other than jeeps or trucks. The road leads to the gravel bar that joins Davison Head to the main part of San Juan Island. The first limestone outcrop is about 100 feet east of the gravel bar along the beach on the main part of San Juan Island. The terrain adjacent to the outcrops is covered with brush and dense second-growth timber.

Geology and description. — The rocks cropping out at Davison Head and vicinity are believed to be of Late Triassic age. At two places along the beach the Late Triassic pelecypod *Halobia* is found in argillaceous limestones. In British Columbia the sequences just above the *Halobia* fossil zone usually contain large deposits of limestone, but in western Washington, limestone makes up only a very minor part of the section and does not appear to occur in commercial quantities.

Very thin beds of Triassic limestones occur also on the north and south sides of Davison Head. Calcareous shales are common elsewhere in the Triassic section. On the south side of Davison Head there is a discontinuous band of dense gray limestone, mostly less than 1 foot in thickness, in many places containing layers of pebbles and sand. On the north side of Davison Head, impure limestone lenses as much as 3 and 4 feet thick crop out, but few of them extend more than 20 feet along strike. Two types of limestone are present: one is a thin-bedded, dense-textured, and bluish-gray calcilutite, and the other is a massive, bluish-gray calcarenite. Boulders of a similar-appearing but more crystalline textured limestone are found on the beaches, but their source is unknown.

FIGURE 45. — *Halobia* limestone, Triassic Haro Formation, south of Davison Head, San Juan Island. Limestone composed almost entirely of distorted and broken shells. X 6.

The largest limestone outcrops occur on the beach south of Davison Head in a sedimentary rock sequence that strikes N. 15°-25° W. and dips from 80° SW. to almost vertical. A section measured across the limestone-bearing part of the sequence is as follows:

West side, top of section:	Ft	in
Argillaceous limestone	10	6
Sandstone and shale	7	3
Argillaceous limestone	1	9
Strike fault		
Argillaceous limestone	3	3
Calcareous shale	4	0
Shale	2	6
Laminated limestone	9	0
Shale and graywacke	5	8
East side, bottom of section.		

No additional limestone is exposed in the immediate vicinity, but other rock types continue the section. Of about 38 feet 3 inches of section, 24½ feet is limestone. The section is covered with glacial drift and soil to the south, so the extent of limestone along strike is unknown.

A second outcrop of limestone is about 1,800 feet east of the gravel bar joining Davison Head to San Juan Island. This, too, is a beach outcrop. It is about 25 feet south of the southernmost outcrop of known Triassic clastic sedimentary rocks along the coast and is in contact with glacial drift and soil to the north, west, and south. It consists of:

North end of section: Top	Ft	in
Laminated limestone, jasperoid nodules	3	6
Shale and breccia	2	6
Limestone	1	6
South end of section: Bottom		

The sequence strikes N. 68° E. and dips 80° SE. Glacial drift conceals its extent inland. At low tide another limestone outcrop is visible on strike a few feet to the east on the beach.

Both of these limestones contain finely laminated beds that are made up of masses of distorted shells of the Late Triassic pelecypod *Halobia*. The second outcrop also contains poorly preserved remains of a Pecten. The best preserved *Halobia* shells occur in the more argillaceous limestones of the first sequence, where they are preserved as impressions and sometimes by pyrite replacements. The shells closely resemble adolescent forms of *Halobia superba*. In thin section, one echinoid spine, one ostracod shell, and some globular foraminifera were seen but could not be identified.

Quality.—Analyses indicate that the Triassic limestones are impure argillaceous types.

Chemical analyses of Davison Head limestone

(Mark Adams, analyst)

Sample no.	Location	Sample length (feet)	$CaCO_3$	$MgCO_3$	Loss on ignition	CaO	MgO	SiO_2	R_2O_3	P_2O_5
SJ 50-1	Across strike, western section -	38	65.5	1.23	30.24	36.80	0.59	28.29	3.64	0.059
SJ 50-2	Eastern outcrop, across strike ----	4½	76.45	0.62	34.17	42.95	0.30	19.29	2.85	0.052

Ownership and development. — Davison Head and the adjacent parts of San Juan Island are owned by the Roche Harbor Lime and Cement Company. The Triassic limestones have never been developed and are neither large enough nor of good enough quality to be of economic value.

Reference. — McLellan (1927, p. 167).

O'Neal Island

Location, size, and accessibility. — O'Neal Island is a small island about 800 feet long, lying off Rocky Bay on the northeast coast of San Juan Island. It is in the N$\frac{1}{2}$ sec. 20, T. 36 N., R. 3 W., about 6 miles northwest of Friday Harbor.

The limestone on the island consists of at least four small outcrops ranging in size from 18 feet long and 10 feet wide to approximately 100 feet long and 5 to 10 feet wide.

Although the shore is quite rocky at sea level, the deposit is accessible by boat. The interior of the island is covered with grass, brush, and a few small trees.

Geology and description. — The limestone occurrence consists of at least four outcrops exposed in beach cliffs at the south end of the island. The limestone forms small lenses and irregular masses and fragments interbedded and in fault contact with a sequence composed of black tuffaceous argillite, sandstone, breccia, and chert. Black argillite appears to be the predominant rock type.

The two largest outcrops on the east side of the south part of the island have, at least in part, a fault contact with the enclosing sediments and appear wedge shaped, narrowing downward. The northernmost has an exposed maximum surface width of about 20 feet, the southern, 29 feet. The exposures continue inland for a distance of less than 30 feet.

Just to the north of the northern outcrop the sedimentary sequence lies unconformably on a diorite-amphibolite complex and a basal sedimentary bed composed of sandstone and breccia. The underlying complex makes up the northern part of the island. Another small area of dioritic rock is exposed on the south end of the island as an upfaulted or upfolded block. Shear zones containing highly altered rock are common at the south end of the island, and at least one of these is stained with the copper mineral malachite.

The limestone on the west side of the south part of the island consists of two exposures lying north and south of a small peninsula. The northern outcrop is an irregularly faulted mass exposed for about 100 feet

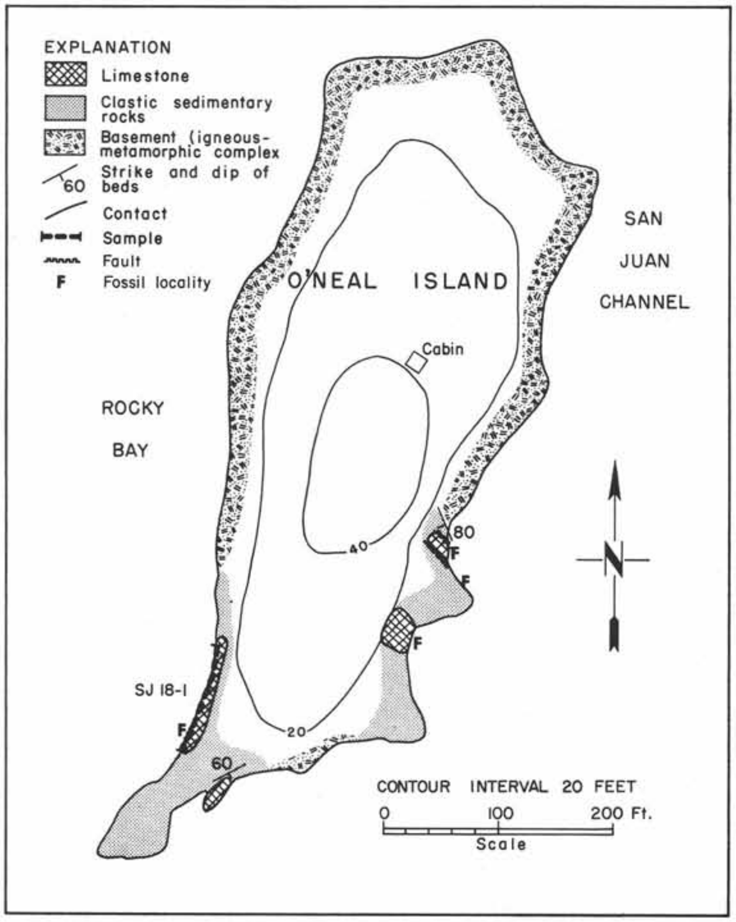


FIGURE 46. — O'Neal Island deposit. Geology by W. R. Danner, C. F. McKillop, and A. M. Rivisto. Topographic base enlarged from U.S. Geological Survey Friday Harbor quadrangle.

along the beach cliff, but it is only a few feet wide. The southern outcrop is about 10 feet wide and 18 feet long and strikes southwestward under the waters of Rocky Bay.

The limestone weathers light gray, but is darker gray on fresh surfaces. It is partly recrystallized and silicified. Irregular silicified and poorly preserved masses of stromatoporoids and corals are common in the limestone on both coasts. On the east coast, argillite exposed at the base of the beach cliff south of the limestone contains specimens of Thamnopora-like coral. The fossils indicate a Devonian age for the limestone-bearing sediments, and this is the only locality (so far discovered) where rocks identified as of Devonian age can be seen to rest unconformably on the older amphibolite-diorite complex found in several places on the San Juan Islands.

Quality.—No samples were taken for chemical analysis because of the small size of the deposit. The weathered surfaces show a considerable amount of silica in many places.

Ownership and development.—The owner of O'Neal Island is A. O. Bruskland, 2314 Alki Avenue, Seattle. There is no indication that this limestone was ever developed. A cabin is located near the north end of the island and is apparently used as a part-time summer home.

The presence of limestone on O'Neal Island was known to the British in the early days of exploration in western Washington, and a general survey of the natural resources of the San Juan Islands (Milton, 1869) reported: "A very small island (O'Neal Island) lying close to the northeast end of San Juan Island, containing only a few acres, is composed almost entirely of limestone." McLellan (1927, p. 98) reported a limestone stratum having a maximum thickness of about 20 feet crossing the southern part of the island. On page 169 he reports further: "The southern end of O'Neal Island is crossed by a limestone layer which trends northeasterly. It has a maximum thickness of about 15 feet and a length of about 100 feet and is consequently too small to have any commercial value. In places it pinches down to a few inches in thickness."

References.—Milton (1869, p. 14-32), McLellan (1927, p. 98, 169).

Henry Island

Henry Island is one of the westernmost of the islands of the San Juan Island group under United States jurisdiction. It is a small island comprising a little over $1\frac{1}{2}$ square miles in area. It is composed of highly folded and faulted sedimentary and volcanic rocks thought to be of Permian age. Several small bodies of limestone are found in this sequence, and, although they are quite small, they have been quarried in at least three localities on the island.

Henry Island Deposit No. 1

Location, size, and accessibility.—The Henry Island No. 1 limestone deposit is on Lot 4 in about the $N\frac{1}{2}SE\frac{1}{4}$ sec. 15, T. 36 N., R. 4 W., on a high bluff overlooking Roche Harbor Bay on the northeast coast of Henry Island. Eight outcrops of limestone are found in the area, the largest of which is about 80 feet long and 15 feet wide. Three of the outcrops contain abandoned quarries. The limestone lies a little over 1 mile northwest of the resort of Roche Harbor and is accessible by water transportation. Limestone outcrops extend from sea level to an altitude of 200 feet and can be traced out by climbing the cliffs from the beach below. The area is covered with scattered clumps of brush and small trees interspersed with rocky and grass-covered knolls.

Geology and description.—The limestone occurs as a line of discontinuous lenses striking N. 50°-70° E. and dipping steeply to the southeast. Eight different outcrops, probably representing separate lenses, were found over a strike distance of 1,200 feet. The lenses are interbedded with or in fault contact with ribbon chert. Individual outcrops range in size from 6 feet in length and 5 feet in width to 80 feet in length and 12 to 15 feet in width.

The limestone is gray in color and dense to crystalline in texture. It becomes more crystalline in texture along the strike toward the northeast. In thin section some of the limestone is seen to be oölitic, and it also contains small frag-

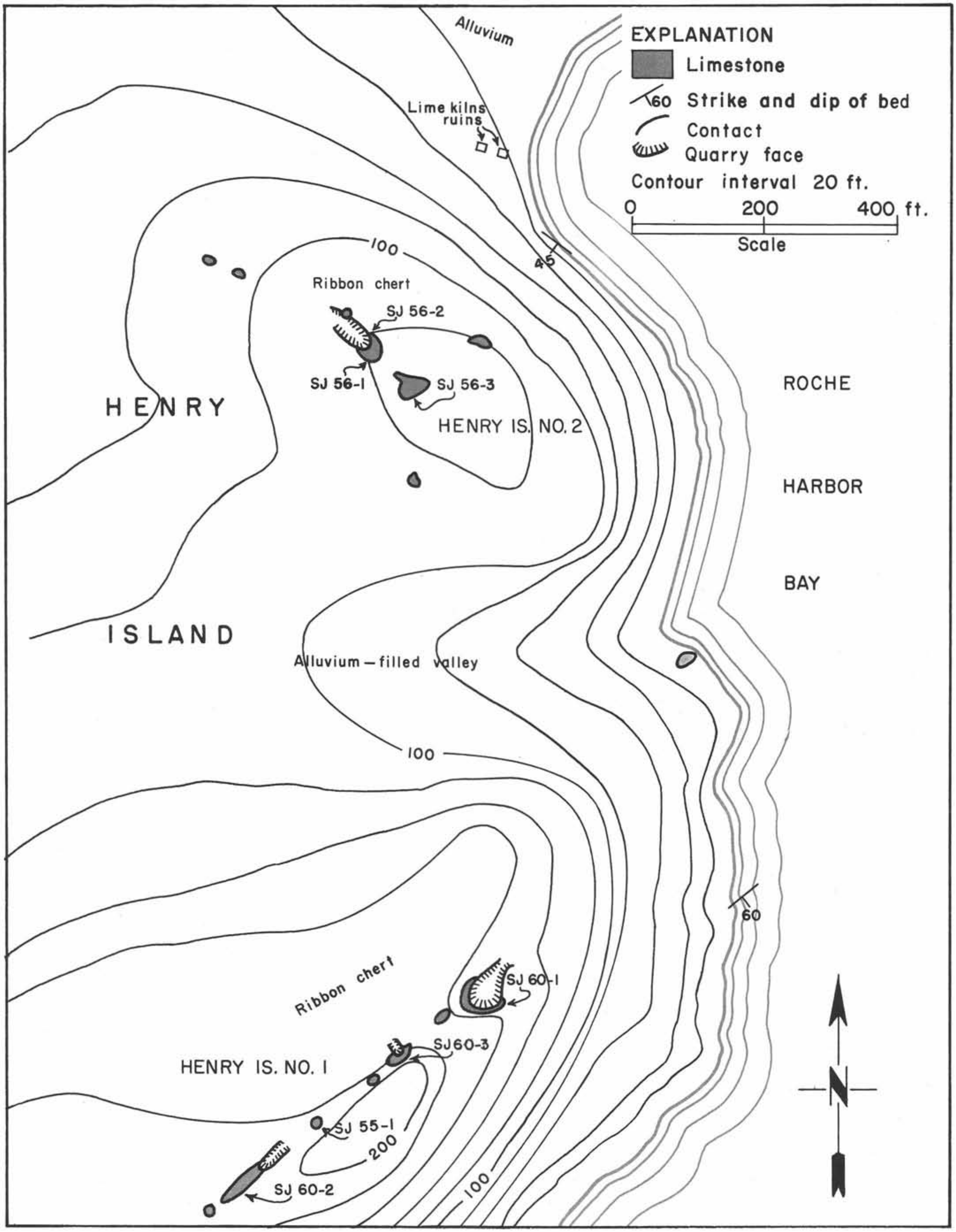


FIGURE 47. — Henry Island deposits Nos. 1 and 2. E½ sec. 15, T. 36 N., R. 4 W. Geology by W. R. Danner, C. F. Royse, Jr., and C. L. Smith. Base and topography from U.S. Geological Survey Roche Harbor quadrangle map.

ments of various types of shells. No identifiable fossils were found; however, the age of the limestone is believed to be Permian on the basis of its similarity in appearance to Permian limestones on neighboring San Juan Island.

Quality.—The limestone of this property was used for making lime and is generally of good quality. However, it contains up to 4 percent silica in the samples analyzed for this study.

Chemical analyses of Henry Island No. 1 limestone

(Mark Adams, analyst)

Sample no.	Location	Sample length (feet)	$CaCO_3$	$MgCO_3$	Loss on ignition	CaO	MgO	SiO_2	R_2O_3	P_2O_5
SJ 55-1	Quarry 2 --------	20	96.77	0.46	42.68	54.37	0.22	1.80	0.51	0.096
					42.79	54.23	0.31	1.72	0.42	
SJ 60-1	Quarry 1 --------	90	96.76	0.64	42.74	54.49	0.30	1.66	0.43	0.041
SJ 60-2	Quarry 3, outcrop				41.85	52.27	0.20	3.87	0.37	0.158
	at west end -----	40	93.84	0.46	41.77	53.18	0.24	3.60	0.45	0.168
SJ 60-3	Outcrops --------	Composite	95.78	0.92	42.57	53.81	0.44	1.97	0.93	0.127

Ownership and development.—The Henry Island No. 1 deposit is owned by Mrs. F. S. Voak, of 909 S. Custer Ave., Miles City, Mont., and by Walter Taylor. It was quarried just prior to 1936 by Dr. J. J. Schultz, Mrs. Voak's father, and the rock was sold to the Orcas Lime Company. Three small abandoned quarries are on the property. The largest is approximately 90 feet long north-south, 75 feet wide, and has a maximum depth of 49 feet at its southwest face. The quarried limestone was loaded onto scows by means of a chute on the cliffs above the waters of Roche Harbor Bay.

The largest remaining limestone outcrop is about 80 feet long, 12 to 15 feet wide, and stands about 5 feet high above the surrounding bedrock. A water-filled trench to the east exposes limestone to a depth of 12 feet. If this depth is maintained for the entire outcrop, then it contains approximately 1,500 tons of limestone. However, the limestone of this body is of poorer quality than other outcrops. All the outcrops together appear to contain less than 5,000 tons.

Henry Island Deposit No. 2

Location, size, and accessibility.—The Henry Island No. 2 limestone deposit is in the $S\frac{1}{2}NE\frac{1}{4}$ sec. 15, T. 36 N., R. 4 W., on a northwest-southeast-trending ridge 120 feet in height on the northeast coast of Henry Island opposite Pearl Island. The limestone is about 800 feet north of the Henry Island No. 1 outcrop area and is accessible by water transportation from the Roche Harbor resort a little over 1 mile to the southeast. Landing on a good gravel beach, one may reach the outcrops by climbing up the hillside to the south above the ruins of two old limekilns. The Henry Island No. 2 deposit appears to contain less than 1,500 tons of quarryable limestone.

Geology and description.—The area contains a group of at least six limestone pods and lenses in ribbon chert. The strike is approximately N. 50° W., and cherts exposed on the beach below and east of the limestone dip about 45° SW. The chert sequence is in places highly contorted, and locally dips to the north. A steep north dip is also visible in a small quarry on the largest of the limestone outcrops. Graywackes and tuffaceous sedimentary rocks are interbedded with the ribbon chert and limestone.

The limestone is light to dark gray in color and mostly crystalline in texture. It is very similar in appearance to other limestone on the northern end of Henry Island and is probably of Permian age. No fossils have been found in it or the associated rocks.

The largest limestone lens on the property is approximately 110 feet long and has a maximum width of less than 50 feet. The other limestone bodies appear to be much smaller.

Quality.—The limestone contains chert or jasperoid and has a variable content of silica. Otherwise, it is a good-quality, high-calcium limestone.

Chemical analyses of Henry Island No. 2 limestone

(Mark Adams, analyst)

Sample no.	Location	Sample length (feet)	$CaCO_3$	$MgCO_3$	Loss on ignition	CaO	MgO	SiO_2	R_2O_3	P_2O_5
SJ 56-1	Quarry, SE. side -	35	98.47	0.43	43.46	55.32	0.21	0.84	0.17	0.010
SJ 56-2	Quarry rim ------	80	97.18	0.25	42.98	54.60	0.12	1.31	0.46	0.018
SJ 56-3	Outcrop, SE. of quarry ---------	Composite	95.85	0.55	42.49	53.85	0.17	2.65	0.39	0.100

Ownership and development.—The Henry Island No. 2 limestone area was acquired by the Roche Harbor Lime and Cement Company some time prior to 1925. When the company was sold in 1956, its property on Henry Island was platted and most of the lots were sold to private individuals for homesites. Jasper Evans is listed as the present owner of the limestone.

The date of development of this property is unknown, but it appears to have been many years ago. One quarry was operated on the largest limestone lens, and the rock obtained was burned in two limekilns near the beach in a cove northeast of the outcrop. The old quarry is approximately 90 feet long northwest-southeast and 50 feet wide. Its maximum depth is 18 feet. Limestone is still exposed for a distance of 16 feet southeast of the quarry, and if it maintains a depth of 18 feet, almost 1,000 tons of limestone remains. The other outcrops are too small to be of economic value, although the outcrop exposed to the southeast of the quarry might supply a few hundred tons if it extends to depth. The small limestone outcrop closest to the kilns has a cut in its north end about 5 feet wide and 2 to 3 feet deep.

Ruins of the two stone limekilns on this property are 25 feet and 50 feet, respectively, from the beach. The kiln farthest inland is about 20 feet high and is built of blocks of fine-grained sandstone obtained from the Cretaceous sandstone quarries on Waldron, Stuart, or Sucia Island. The other kiln, of which very little is left, appears to have been built in part of limestone blocks.

Reference.—McLellan (1927, p. 169).

Henry Island Deposit No. 3

Location, size, and accessibility.—The Henry Island No. 3 limestone deposit is at the SW. cor. sec. 15, T. 36 N., R. 4 W., on a small peninsula on the northwest coast of Henry Island. It is a small deposit of only a few hundred tons cropping out at the water's edge. It is accessible by boat.

Geology and description.—The limestone forms a 5- to 6-foot cliff above high tide for 150 feet along the northwest side of a small peninsula. This peninsula rises to an altitude of 40 feet east of the shoreline and is covered with brush and second-growth trees. A large flat meadow area extends east of the peninsula across Henry Island to Nelson Bay. The depth of the deposit below water level is unknown, but limestone is exposed for another 20 feet on the beach to the south at low tide. The outcrop appears to be formed by the crest of an anticlinal fold. The limestone-chert contact on the north limb dips approximately 50° northward, whereas the limestone-chert contact on the south dips 45° or less to the south. The top of the limestone exposure is overlain by glacial sediments, which extend eastward for about 50 feet to where a knoll of ribbon chert is exposed. Contorted chert beds are interbedded with the limestone at its north end.

Chemical analyses of Henry Island No. 3 limestone

(Mark Adams, analyst)

Sample no.	Location	Sample length (feet)	$CaCO_3$	$MgCO_3$	Loss on ignition	CaO	MgO	SiO_2	R_2O_3	P_2O_5
SJ 58-1	South part ------	100	97.54	0.43	41.65	52.87	0.21	4.25	0.48	0.058
					42.93	54.15	0.17	2.09	0.30	
SJ 58-2	North part ------	75	86.36	0.46	42.65	54.13	0.28	1.97	0.45	0.072

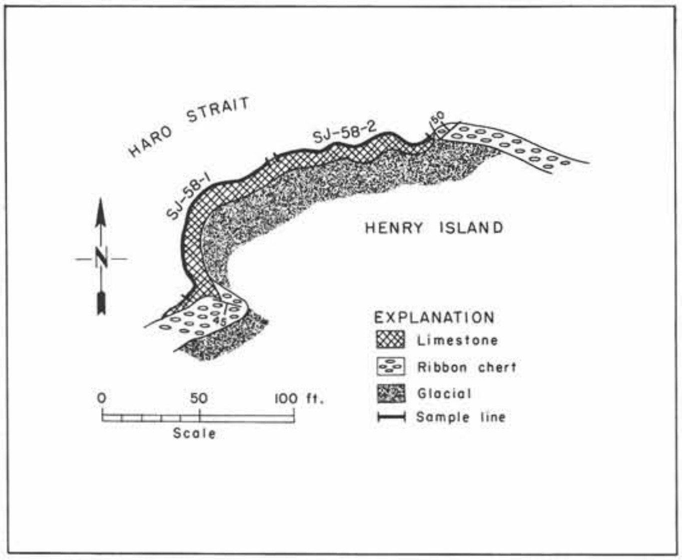


FIGURE 48. — Henry Island No. 3 deposit. SW¼ sec. 15, T. 36 N., R. 4 W. Geology by W. R. Danner, C. L. Smith, and C. F. Royse, Jr. Base map by compass and tape survey.

The limestone is finely crystalline in texture and dark gray in color on fresh surfaces. It weathers to a light-gray color. A few silicified structures that may be of organic origin are visible on weathered surfaces, but none could be identified. The age of the limestone is unknown.

Quality. — Limestone samples collected and analyzed were of high quality except for their silica content, which averaged almost 2 percent.

Ownership and development. — The owner of this deposit is unknown. There has been no development. The amount of limestone above tide level amounts to only a few hundred tons. Bedrock overburden covers the extension of the limestone inland.

Reference. — McLellan (1927, geologic map).

Kellett Bluff Deposit

Location, size, and accessibility. — The Kellett Bluff limestone deposit is in the SW¼SE¼ sec. 21, T. 36 N., R. 4 W., on the top of a benchlike area part way up a high bluff on the southwest coast of Henry Island. It is about ¼ mile north of the Kellett Bluff beacon and crops out at an altitude of approximately 120 feet. This limestone comprises a lens 65 feet long and about 40 feet in maximum width. The terrain consists of bedrock cliffs interspersed with bench areas covered with grass and clumps of oak and Douglas fir. The limestone is not reached easily by scaling the cliffs from sea level, but can be reached most conveniently by hiking up a bulldozed logging road from Open Bay for about a quarter of a mile and then hiking overland north along the bluff for a few hundred feet. Kellett Bluff occupies an exposed position on Haro Strait, and the sea at its base is usually quite rough.

Geology and description. — The Kellett Bluff deposit consists of a lenticular body of limestone surrounded by ribbon chert. The limestone strikes almost east-west and is about 40 feet wide at the west end, on the edge of the bluff overlooking the water. It narrows inland to a width of 6 feet about 35 feet along the strike and pinches out entirely approximately 65 feet inland from the cliff edge. Limestone is exposed vertically for a distance of about 15 feet. No outcrops of limestone were seen on the cliff face extending down toward the water, and thus it would appear that the limestone has a shallow depth.

The limestone is light gray in color and crystalline in texture. In thin section it is seen to be mostly crystalline, and remnants of an original oölitic texture, poorly preserved, show in some slides. The age of the deposit is unknown, but it is believed to be Permian.

Ribbon chert is the predominant rock type forming the southwestern part of Henry Island, and in many outcrops it is strongly contorted. Pods of limestone from a few inches to a few feet in width are found interbedded in the chert to the south and east. Fragments of limestone float are found on the surface in the recently logged area of this part of the island east to Open Bay.

Quality.—A series of chip samples were taken along the length and width of the outcrop, and their composite analysis indicates a high-calcium type of limestone. No igneous dikes or replacement chert bodies were seen in the outcrop.

Chemical analysis of Kellett Bluff limestone

(Mark Adams, analyst)

Sample no.	Location	Sample length (feet)	$CaCO_3$	$MgCO_3$	Loss on ignition	CaO	MgO	SiO_2	R_2O_3	P_2O_5
SJ 57-1	Composite -------	100	97.73	0.50	43.25	54.91	0.24	0.72	0.33	0.138

Ownership and development.—The owner of this property is unknown, and there has been no development. Though the limestone is of good quality, the limestone body is too small to be of economic value. Detailed prospecting of this area might locate additional limestone bodies, but it is unlikely that any of commercial size remain undiscovered.

Open Bay Deposit

Location, size, and accessibility.—The Open Bay limestone deposit is in the SW¼SE¼NW¼ sec. 27, T. 36 N., R. 4 W., on the west side of the "Little Henry," or east part of Henry Island, on the east side of the entrance to Open Bay. It consists of several small lenses of limestone, the largest of which is 25 feet long and has a maximum thickness of 4 feet. The limestone outcrops are on the sides of a cliff forming the shores of this part of Henry Island and are accessible by boat.

Geology and description.—The limestone at Open Bay consists of lenticular beds and pods interbedded with ribbon chert, volcanic rocks, and graywacke. The largest limestone bed is only about 4 feet thick and 25 feet in length. It strikes about N. 50° W. and dips 35° NE. The dip of the limestone-bearing rocks steepens northward and reaches 75° on the east side of the island.

The limestone is light gray in color on weathered surfaces and light gray to buff on fresh surfaces. It is dense to crystalline in texture. In thin section, one limestone specimen contained poorly preserved remains of radiolaria and thin shells of a small pelagic pelecypod. No fossils were identifiable, but it is believed that the limestone is Permian in age.

Quality.—This occurrence is too small to be of any economic value and therefore was not sampled for chemical analysis. In hand specimen it appears to have very few impurities and is probably high in calcium content.

Ownership and development.—At one time this area was owned by the Roche Harbor Lime and Cement Company. However, it has recently been platted and sold to private individuals for homesites. There has been no development. The limestone deposit is too small to be of any economic value, and quarrying would be impractical because of an increasing thickness of bedrock overburden down dip.

Henry Island Deposit No. 4

Location, size, and accessibility.—The Henry Island No. 4 limestone deposit is on a peninsula forming the west side of Nelson Bay, on the northeast side of Henry Island in the NW¼NE¼ sec. 22, T. 36 N., R. 4 W. This outcrop is on a low 8- to 10-foot cliff rising from the water. The largest limestone body has a maximum thickness of 5 feet. The area is covered with dense brush and second-growth trees. The limestone outcrops are accessible by boat.

Geology and description. — The deposit consists of a series of lenticular beds and pods of limestone traceable for approximately 200 feet along or near the shore of Nelson Bay. At least two layers of limestone are present, separated by 5 to 6 feet of volcanic rocks and chert. Ribbon chert overlies the limestone. The upper limestone layer is as much as 5 feet thick and is massive and mostly crystalline in texture. The lower layer is dense textured, laminated, and interbedded with small stringers of chert. The limestone strikes N. 30°-40° W. and dips 40°-75° SW. It thickens and thins along strike, and it disappears under water to the north and south.

The limestone is light gray in color on fresh surfaces and weathers to almost white. In thin section the lower, laminated layer is seen to be composed in part of the abundant remains of small thin-shelled pelagic pelecypods. No fossils were identifiable, but it is believed that the organic remains seen in thin section are similar to those found in limestones of Permian age on San Juan Island.

Quality. — Chip samples were taken along the east and west parts of the outcrops. A considerable amount of ribbon chert is interbedded with the limestone and is especially abundant at the east end of the occurrence.

Chemical analyses of Henry Island No. 4 limestone

(Mark Adams, analyst)

Sample no.	Location	Sample length (feet)	$CaCO_3$	$MgCO_3$	Loss on ignition	CaO	MgO	SiO_2	R_2O_3	P_2O_5
SJ 59-1	West end --------	100	98.27	0.33	43.53	55.21	0.16	0.22	0.20	0.144
SJ 59-2	East end ---------	100	82.75	0.35	36.48	46.55	0.17	15.57	0.79	0.096

Ownership and development. — The limestone of this occurrence is owned by Mrs. F. S. Voak, 909 S. Custer Ave., Miles City, Mont. A few tons of limestone was quarried from the west end of the outcrop many years ago. The limestone remaining is too small in amount to be of economic value.

Nelson Bay Deposit

On the geologic map accompanying his report on the geology of the San Juan Islands, McLellan (1927) shows a limestone outcrop on the east side of the entrance to Nelson Bay on the "Little Henry" part of Henry Island. No limestone outcrops were found at this location. A short distance to the east a small limestone pod about 1½ feet long by 1 foot wide was found on the beach at low tide. The former owners of this property, Mr. and Mrs. Frank Bressler, knew of no limestone on this part of the island coast. Small limestone pods only a few inches in size were found associated with volcanic rocks on a small peninsula at the northeast end of the "Little Henry" division of Henry Island.

Pole Island

Pole Island is a tiny island in Mosquito Pass between Henry Island and Bazalgette Point on San Juan Island. A pod of cherty crystalline limestone about 4 feet in diameter is exposed on the south side of this island. Fragments of limestone are found associated with the volcanic rocks that make up most of the island.

Battleship Island

Two small pods of crystalline limestone about 1 foot in length crop out in a shale unit interbedded with volcanic rocks and ribbon chert on the west side of Battleship Island. The island lies directly north of McCracken Point on the north tip of Henry Island and is a state park.

Jones Island

Jones is a small island of about 200 acres situated in the channel between San Juan and Orcas Islands. It is composed of volcanic and sedimentary rocks and contains three small areas of limestone outcrop. At one time the island was used as a fox farm, then it became a Federal wildlife refuge, and is now a state park.

Jones Island Deposit No. 1

Location, size, and accessibility.—The Jones Island No. 1 limestone deposit is on the southeast side of a large bay on the northern coast of Jones Island, in the south part of sec. 11, T. 36 N., R. 3 W. The limestone forms a body lenticular in shape and exposed over an area about 200 feet long and from 20 to 70 feet in width. This deposit appears to be not more than 10 to 20 feet in thickness. The limestone crops out on the beach and is accessible by boat; it is about 8 miles by water north of Friday Harbor. Inland from the shore the island terrain is covered with virgin timber and in places by dense brush. The limestone body is not well exposed.

Geology and description. —The limestone is exposed in an outcrop trending southeast from the beach inland for a distance of about 200 feet. It is also exposed on two tiny peninsulas and a rock island along the shore. The limestone is poorly bedded; its parting planes are a foot or more apart. Black cherty shale is interbedded with it, and along the shore volcanic rocks underlie it. To the south and west the the limestone is in contact with a dense-textured and light-colored dacite that forms a prominent ridge extending southeastward across the island. The limestone outcrop appears to be part of a shallow synclinal structure with gentle dips, so that, despite the fact that the limestone is not more than 20 feet thick, it appears to have a much greater thickness.

The limestone is gray in color and dense in texture. In thin section it is seen to be a brownish-colored lime mud with small indistinct structures that may be fragments of fossils. The age of the limestone is unknown.

At the northwest corner of the outcrop is a solution crevice, and when the tide rises, for a period of about 10 minutes this crevice emits a gurgling noise like that of water running down a drain. Apparently, below the crevice there is a solution cavity that fills and empties with the rise and fall of the tide.

Quality.—The limestone is an impure argillaceous type high in silica.

Chemical analysis of Jones Island No. 1 limestone

(Mark Adams, analyst)

Sample no.	Sample length (feet)	$CaCO_3$	$MgCO_3$	Loss on ignition	CaO	MgO	SiO_2	R_2O_3	P_2O_5
SJ 33-2	20	89.60	0.31	39.54	50.34	0.15	9.12	0.72	0.011

Ownership and development.—The property is owned by the Washington State Parks and Recreation Department. There has been no development, and the limestone body is too small and impure to be of economic value.

References.—McLellan (1927, p. 96, 169), Glover (1936, p. 57).

Jones Island Deposit No. 2

Location, size, and accessibility.—The Jones Island No. 2 deposit is in the SE¼ sec. 11, T. 36 N., R. 3 W., on the northeast coast of Jones Island a little over 1,000 feet almost due east of deposit No. 1. It forms a lenticular bed over 100 feet in length that has a maximum thickness of 14 feet. It is accessible by boat, but the shoreline is rocky and is bordered by cliffs 10 to 50 feet high. Partly submerged rocks lie offshore for several feet.

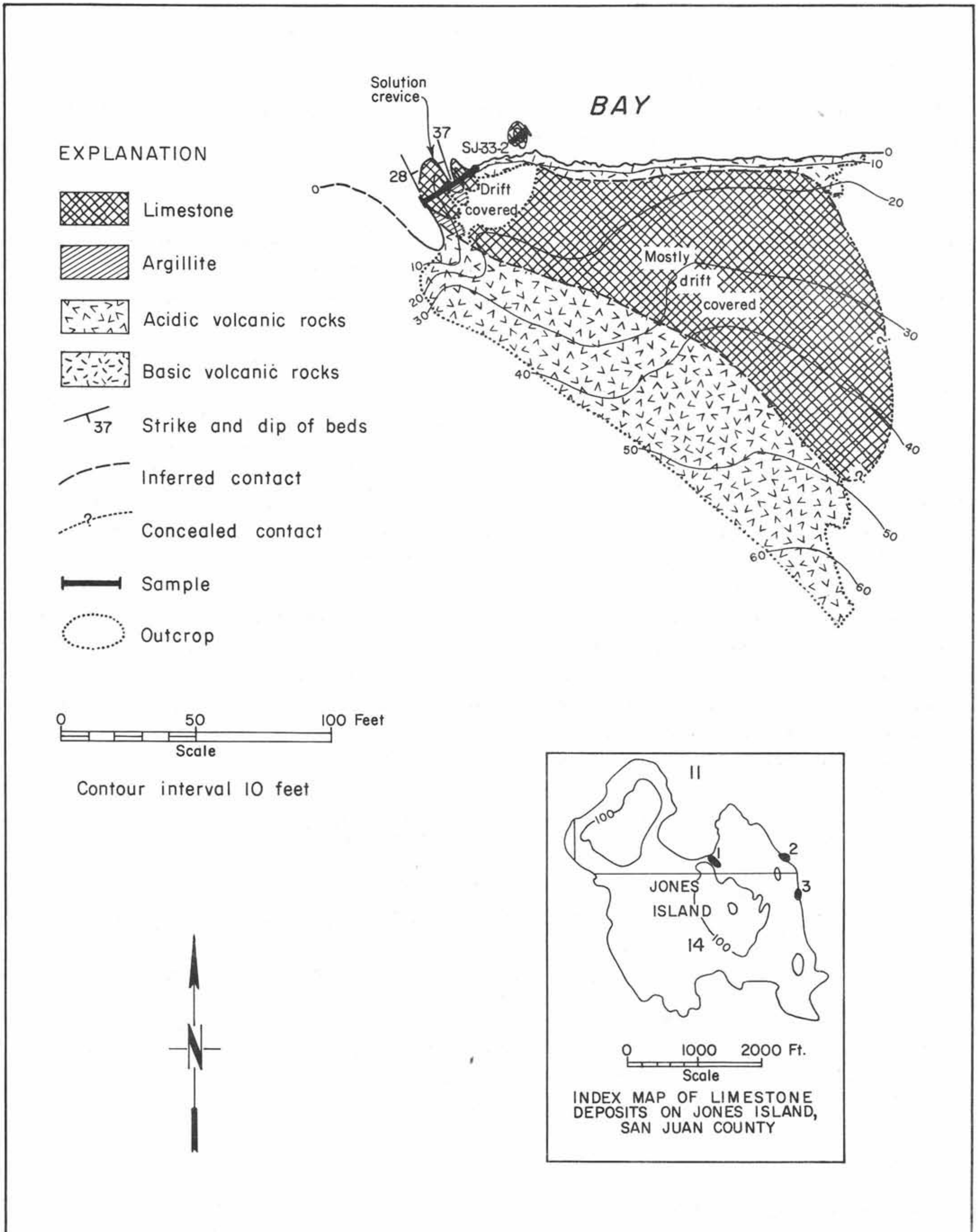


FIGURE 49. — Jones Island deposit No. 1. S½ sec. 11, T. 36 N., R. 3 W., and index map of limestone deposits on Jones Island. Geology by W. R. Danner, C. F. McKillop, and A. M. Rivisto. Compass and tape survey.

Geology and description.—The limestone is a lenticular body interbedded with volcanic rocks. Its southernmost exposure, on the top of the beach cliff, is a group of small pods of limestone in volcanic rocks. North of these its outcrop parallels the shore as a thin-bedded and contorted limestone and tuff sequence. Farther north, the limestone becomes a single massive bed that thickens to a maximum of about 14 feet. It then bends to the northwest and thins out a few feet inland. The limestone appears to be bounded in part by a fault or shear zone along its north side. Its total length is just over 100 feet.

The limestone is light gray in color and crystalline in texture. A few poorly preserved fossils were found, including horn corals, colonial corals, and bryozoan fragments. They appear similar to Devonian fossils found on Orcas Island but are not well enough preserved to be definitely identified.

Quality.—The limestone bed was sampled by chips taken along strike and is high in calcium.

Chemical analysis of Jones Island No. 2 limestone

(Mark Adams, analyst)

Sample no.	Location	Sample length (feet)	$CaCO_3$	$MgCO_3$	Loss on ignition	CaO	MgO	SiO_2	R_2O_3	P_2O_5
SJ 33-1	Top of cliff	14	97.52	0.89	43.46	54.79	0.43	0.71	0.45	0.037

Ownership and development.—The property is owned by the Washington State Parks and Recreation Department. The limestone body is too small to be of any economic value. Blocks of limestone on the beach below the outcrop indicate that the deposit may have been blasted at one time, but no quarry was developed.

References.—McLellan (1927, p. 96, 169), Glover (1936, p. 57).

Jones Island Deposit No. 3

Location, size, and accessibility.—The Jones Island No. 3 limestone deposit is in the NE¼ sec. 14, T. 36 N., R. 3 W., on the east coast of Jones Island, about 800 feet south of Jones Island Deposit No. 2. It consists of two small limestone outcrops. The southernmost of these is about 1½ to 3 feet thick and is exposed for about 10 feet trending inland from the beach. A few feet to the north, protruding from the beach gravels, is a ridge of limestone about 12 feet long, 6 feet wide, and 3 to 4 feet high. The limestone of this area is accessible by boat, but the shore is rocky and consists of cliffs as high as 30 feet. The offshore area is studded with partly submerged rocks.

Geology and description.—The southernmost exposure consists of a crystalline gray limestone similar in appearance to the Jones Island No. 2 deposit to the north. It forms a narrow bed, standing almost vertical, striking southwestward inland from the shore. Where large blocks of the limestone have fallen onto the beach and water has polished the limestone surface, numerous poorly preserved colonial corals, horn corals, and small crinoid columnals are visible. These fossils are believed to be of Devonian age.

The northern exposure consists of crumpled, thin-bedded, clastic-textured, blue-gray limestone. It also is standing nearly vertical. As its outcrop is entirely surrounded by beach gravels, its extent is unknown.

Quality.—Because of the small size of these exposures, no samples were taken from them.

Ownership and development.—The limestone is owned by the Washington State Parks and Recreation Department. There has been no development of the occurrence, which is too small to be of economic value.

Limestone on Other Parts of Jones Island

The area between the limestone outcrops at the bay on the north coast of Jones Island and the outcrops on the east coast was searched for evidence of possible continuations or connections of the limestone outcrops as shown on the geologic map by McLellan (1927). No outcrops, sinkholes, or other indications of the presence of limestone were found. A valley along strike between deposits No. 1 and No. 2 is covered with glacial drift, soil, and dense vegetation.

The west coast of Jones Island is composed mostly of volcanic rocks and a few small areas of interbedded sedimentary rocks that include gray limestone beds up to about 2 inches in thickness and seldom more than 1 foot in length. No limestone outcrops were found that could be related to those indicated on the McLellan geologic map as being on the west side of the bay at the north end of Jones Island or along the west coast.

Cliff Island

Cliff Island is a small island in the Wasp Island group that lies between the western parts of Orcas and Shaw Islands. It is about 1,500 feet long and up to 500 feet wide. It consists primarily of volcanic flows, some with pillow structure, dipping southward and striking almost east-west.

Cliff Island Deposit

Location, size, and accessibility.—The Cliff Island limestone deposit is on the north shore of Cliff Island in the N½ sec. 25, T. 36 N., R. 3 W. It consists of two lenticular limestone beds, one about 500 feet long and less than 20 feet in maximum width, and a second about 400 feet long, also less than 20 feet in maximum width. The outcrops are in shore cliffs accessible by boat. This limestone is 2½ miles by water south of Deer Harbor, Orcas Island. The shoreline is mostly a rock cliff, and there are submerged rocks and thick kelp beds immediately offshore to the north.

Geology and description.—The limestone is composed of at least two lenticular limestone bodies interbedded in a sequence of pillow basalts, tuffs, breccias, and ribbon cherts. This sequence dips southward at angles of 25° to 70° and strikes from east-west to N. 30° E. The easternmost limestone bed is cut off to the east by a fault. Small limestone pods, usually only a few square inches in area, are interbedded with the volcanic rocks. A similar limestone pod can be seen on the west coast of Nob Island, about 450 feet northwest of Cliff Island. It is interbedded with a sequence of altered diabasic and silicic porphyritic-textured volcanic rocks.

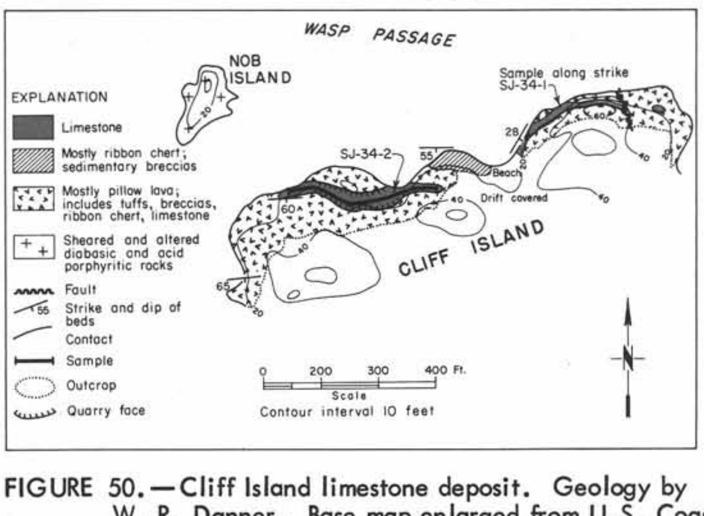


FIGURE 50.—Cliff Island limestone deposit. Geology by W. R. Danner. Base map enlarged from U.S. Coast and Geodetic Survey of 1949, Friday Harbor quadrangle.

The combination of indentations of the north shore of Cliff Island and the southward dips of the beds causes the limestone to crop out at sea level or below at one place and on the top or face of the shore cliffs at another. The limestone dips steeply underneath volcanic rock overburden and has a true maximum thickness of less than 20 feet. In parts of the volcanic rock section, limestone fills spaces around the margins of the basalt pillows and is a cement in breccia beds.

The limestone is light gray in color and mostly crystalline in texture. In thin section, limestone from the north end of the island is seen to consist of either a lime mud cut by calcite veinlets or a partially recrystallized oölite. Limestone interbedded in the pillow lava flows exposed at the west end of the island contains filament-like structures believed to be the shells of small pelagic pelecypods. The age of the limestone is unknown but is thought to be Permian.

Quality.—The limestone is high in calcium.

Chemical analyses of Cliff Island limestone

(Mark Adams, analyst)

Sample no.	Location	Sample length (feet)	$CaCO_3$	$MgCO_3$	Loss on ignition	CaO	MgO	SiO_2	R_2O_3	P_2O_5
SJ 34-1	East outcrop -----	400	99.00	0.39	43.19	55.62	0.19	0.38	0.19	0.001
SJ 34-2	West outcrop -----	500	98.97	0.54	43.80	55.60	0.26	0.22	0.09	0.037

Ownership and development.—The island is owned by Charles Arnt, of Orcas Island, Wash., and Hollywood, Calif. It was formerly owned by Manufacturers Mineral Company, of Seattle, who developed a quarry on the limestone and in 1960 sold the island. A quarry at the northwest side of the island was excavated down almost to high-tide level. Because of the bedrock overburden and the small size of the limestone bed, the remainder of the outcrop is not considered to be of economic value. The limestone was first quarried some time between 1888 and 1894, and was shipped to a paper mill at Lowell, near Everett, by a Mr. Tift. However, the main operation took place about 1947 or 1948.

References.—McLellan (1927, p. 95, 169), Glover (1936, p. 57), Green (1948, p. 27).

Crane Island

Crane Island is the largest island in the Wasp Island group and is a little more than 221 acres in area. It is composed predominantly of a southward-dipping assemblage of ribbon cherts and argillites that, on a small peninsula at the southwestern tip of the island, are overlain by volcanic rocks and limestone.

Crane Island Deposit

Location, size, and accessibility.—The Crane Island limestone deposit is either in the NW¼ sec. 30 or the SW¼ sec. 19, T. 36 N., R. 2 W., on a small peninsula on the southwest side of Crane Island bordering on Wasp Passage. It consists of a lenticular bed of limestone cropping out in an east-west direction across the peninsula. Its exposed width is between 20 and 75 feet, its length is between 175 and 200 feet, and its vertical exposure is as much as 12 feet. The limestone crops out at sea level on both sides of the peninsula and is accessible by boat. It lies about 2,000 feet northeast of Cliff Island and is about 2¼ miles south by water from Deer Harbor, Orcas Island.

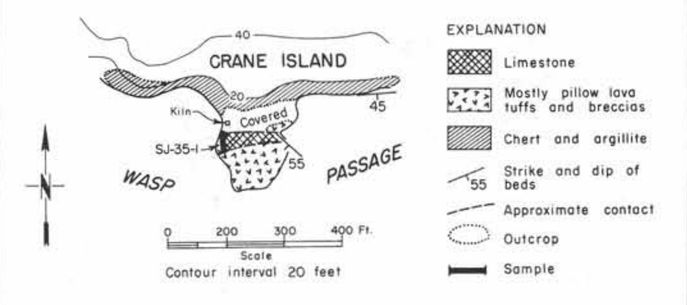


FIGURE 51.—Crane Island limestone deposit. NW¼ sec. 30, T. 36 N., R. 2 W. Geology by W. R. Danner. Base map enlarged from U.S. Coast and Geodetic Survey of 1949, Friday Harbor quadrangle.

Geology and description.—It is thought that the limestone of Crane Island is a continuation of the lenticular limestone beds exposed along the north side of Cliff Island, 2,000 feet to the southwest. On each island a sequence consisting of dark-red to black pillow

FIGURE 52.—Crane Island limestone deposit. West end, view looking east from off shore.

basalts overlies the limestone, and a sequence composed predominantly of chert and argillite underlies it. The lower contact on Crane Island is mostly covered with drift and soil. Where the limestone is exposed in a beach cliff on the east side of the small southwest peninsula of Crane Island, it appears to form a lens in volcanic flows and tuffaceous sedimentary rocks and has a variable dip to the south. On the beach cliff at the west side of the peninsula the limestone is greatly contorted, and in places it strikes almost north-south and dips to the west.

The limestone is light gray to brownish gray in color and is mostly crystalline in texture. Outcrops on the west side of the peninsula are well bedded in layers from 1 to 3 inches in thickness. When examined in thin section, much of the bedded limestone is seen to be oölitic in texture. When freshly broken, it emits a bituminous odor.

Quality.—This limestone is high in calcium and shows only a few stringers of carbonaceous material as visible impurities.

Chemical analysis of Crane Island limestone

(Mark Adams, analyst)

Sample no.	Location	Sample length (feet)	$CaCO_3$	$MgCO_3$	Loss on ignition	CaO	MgO	SiO_2	R_2O_3	P_2O_5
SJ 35-1	West side outcrop	75	99.43	0.21	43.79	55.86	0.10	0.23	0.14	0.029

Ownership and development.—In 1959 Crane Island was being subdivided into lots for summer-home sites. The present owner of the limestone is unknown. There is no evidence of a quarry on the outcrop, but a few small exploration trenches are visible where the limestone is covered with drift and soil. The ruins of a very small limekiln can still be seen on the beach north of the west end of the limestone outcrop. The occurrence contains less than 10,000 tons of limestone and is considered to be too small to have economic value.

References.—McLellan (1927, p. 95, 169), Northern Pacific Railway Co. (1941, unpublished notes, p. 14).

Shaw Island

Shaw Island is the fifth in size of the islands in San Juan County and is a little less than 8 square miles in area. It is composed predominantly of ribbon chert, argillite, and graywacke and has minor amounts of interbedded volcanic rocks. At least four small areas of limestone outcrop are known, and at least one of these was quarried at one time.

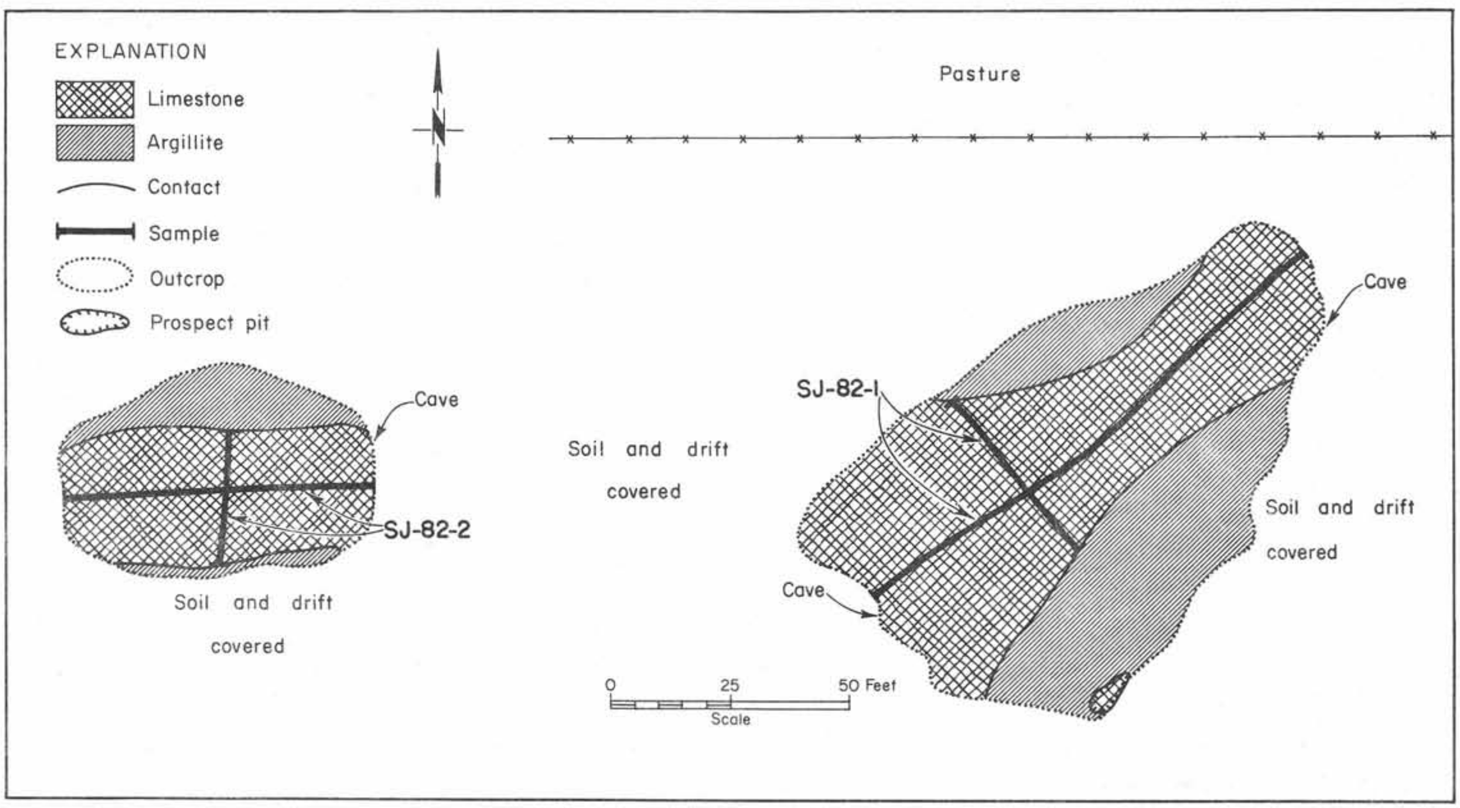


FIGURE 53.—Yansen limestone deposit, Shaw Island. SE¼NW¼ sec. 29, T. 36 N., R. 2 W. Geology by W. R. Danner, C. L. Smith, E. A. Adams, and C. F. Royse, Jr. Compass and tape survey.

Yansen Deposit

Location, size, and accessibility.—The Yansen limestone deposit is in the SE¼NW¼ sec. 29, T. 36 N., R. 2 W., in the northwestern interior of Shaw Island, at an altitude of about 200 feet. It consists of two low moundlike limestone outcrops, one of which is about 60 feet long and 30 feet in maximum width, and the other, about 115 feet long and from 20 to 50 feet in width. The greatest vertical extent is about 14 feet. The occurrence is accessible by about 3½ miles of graveled road from Shaw Landing, or is about 1 mile by road from the west coast of the island. The limestone lies in a dense brush-covered area about 100 feet west of a gravel-surfaced road and 20 to 60 feet south of a pasture.

Geology and description.—Two lenticular (?) beds of limestone crop out as low rounded knolls in a thickly vegetated area of low relief. Glacial drift and soil surround and partly cover the outcrops. Argillite is in contact with the limestone on the north and south sides of the mounds and crops out at several places in the vicinity. The limestone strikes from nearly east-west to northeast-southwest and dips to the southeast. It is light gray to bluish gray in color and crystalline in texture. Bedding is not not readily apparent. Small caves lead into the limestone, one at the east end and one at the west end of the eastern mound, and one at the east end of the western mound. A partly filled prospect pit about 6 feet deep was found at the south edge of the eastern outcrop; limestone is exposed in the bottom of it.

Quality.—The limestone of these two outcrops is of high quality. Halliday (1963) explored the caves rather thoroughly and found masses of "noncalcareous" material beneath the surface of both mounds. This material does not show in any of the surface exposures.

Chemical analyses of Yansen limestone

(Mark Adams, analyst)

Sample no.	Location	Sample length (feet)	$CaCO_3$	$MgCO_3$	Loss on ignition	CaO	MgO	SiO_2	R_2O_3	P_2O_5
SJ 82-1	East outcrop -----	Composite	98.18	0.418	43.45	55.16	0.20	0.43	0.13	0.008
SJ 82-2	West outcrop ----	Composite	98.45	0.52	43.24	55.31	0.25	0.18	0.61	0.063

Ownership and development.—The property is owned by Donald Yansen, who lives about ½ mile to the northeast and who runs the store at Shaw Landing. There has been no development, although apparently the area was prospected at one time. The small size of the outcrops makes them uneconomic, but since the quality of the limestone is good, it might be worth while to determine, by drilling or stripping, the actual extent of limestone under cover and to determine whether the two outcrops are connected. The occurrence might furnish a few thousand tons of good-quality limestone.

Reference.—Halliday (1963, p. 62-65).

Biendle Deposit

Location, size, and accessibility.—The Biendle deposit is in the NW¼SW¼ sec. 29, T. 36 N., R. 2 W., in a low roadcut and in the roadbed on the south side of a new section of county road in the northwestern part of Shaw Island. It consists of a poorly exposed limestone lens about 6 feet wide east-west and 6 to 11 feet long. It can be reached by about 4½ miles of graveled road from Shaw Landing or by about ½ mile of road from the west coast of the island. The altitude is between 150 and 200 feet above sea level.

Geology and description. — The occurrence consists of a small lens of crystalline gray limestone interbedded in a massive to poorly bedded argillite and cherty argillite sequence. Argillite appears to completely enclose the limestone outcrop, most of which is in the roadbed. The limestone was uncovered when this part of the county road was straightened, and possibly a large part of the lens was removed at that time. It is thought that this occurrence is the one indicated on the geologic map of McLellan (1927) in this part of Shaw Island, as no other limestone could be located. The age is unknown.

Quality. — The limestone is of good quality but contains silica as a minor impurity.

Chemical analysis of Biendle limestone

(Mark Adams, analyst)

Sample no.	Sample length (feet)	$CaCO_3$	$MgCO_3$	Loss on ignition	CaO	MgO	SiO_2	R_2O_3	P_2O_5
SJ 83-1	Composite	97.06	0.20	42.55	54.53	0.10	1.99	0.46	0.064

Ownership and development. — The limestone is on the county road right-of-way, but before the road was straightened the deposit was on property reported to be owned by a Mr. Biendle. The deposit is too small to be of any economic value.

Reference. — McLellan (1927, p. 169, geologic map).

Lutz Quarry

Location, size, and accessibility. — The Lutz limestone occurrence is at an altitude of about 100 feet above sea level in the NE¼ sec. 30, T. 36 N., R. 2 W., on the northwest part of Shaw Island just southwest of a bend in the county road leading to Neck Point. The occurrence consists of remnants of limestone on the south side of an abandoned quarry 100 feet long east-west, 10 to 25 feet wide, and 10 to 20 feet in vertical exposure. It is accessible by about 5 miles of good graveled road from Shaw Landing. It is about ¼ mile from the west coast of the island, in an area covered with dense brush and second-growth trees.

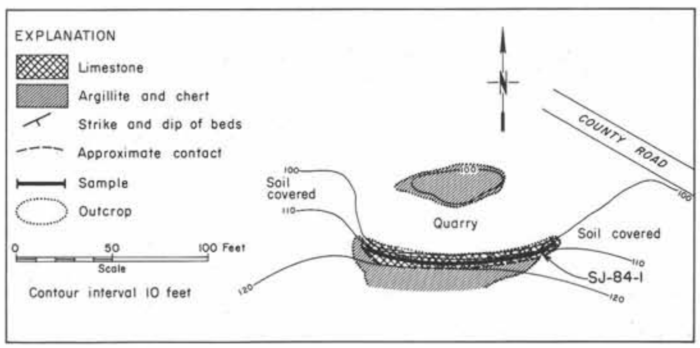


FIGURE 54. — Lutz limestone deposit, Shaw Island. NE¼ sec. 30, T. 36 N., R. 2 W. Geology by W. R. Danner, C. L. Smith, E. A. Adams, and C. F. Royse, Jr. Compass and tape survey.

Geology and description. — The occurrence consists of a small crystalline-textured gray limestone lens interbedded in a sequence of dark-gray to black argillites. The deposit strikes almost east-west and dips steeply to the south. Most of the limestone has been removed by quarrying. All that remains of the north quarry wall is a small knob of argillite. The south quarry wall is cut into a hill of argillite, and the remainder of the limestone lens dips steeply south into it.

Chemical analysis of Lutz limestone

(Mark Adams, analyst)

Sample no.	Sample length (feet)	$CaCO_3$	$MgCO_3$	Loss on ignition	CaO	MgO	SiO_2	R_2O_3	P_2O_5
SJ 84-1	100	95.17	0.58	41.83	53.47	0.28	3.37	0.52	0.032

Quality.—Limestone remaining in the quarry is high in silica.

Ownership and development.—The quarry is on the property of Mrs. Marion Lutz, who lives ¼ mile to the south. A small quarry was established on this limestone in the 1890's by a Mr. Tift. Railroad tracks were laid from the quarry to tidewater for transportation of the limestone, and it was shipped to a paper mill at Lowell, near Everett. The quarry has been abandoned for many years and is now overgrown with vegetation. The limestone is exhausted, and the occurrence is of no economic value.

West Coast of Shaw Island Area

Location, size, and accessibility.—Several small lenses and pods of limestone crop out in the SE¼SE¼ sec. 30 and the NW¼ sec. 32, T. 36 N., R. 2 W., on beach cliffs and the hillside above the west coast of Shaw Island north of Parks Bay. The largest limestone body is about 30 feet long and 3 to 4 feet thick. The area is accessible by boat or by a private beach road that is about 5 miles by a county graveled road from Shaw Landing.

Geology and description.—The occurrence consists of a group of small limestone pods and lenses, most of which are only a few square feet in area. They crop out in the beach cliffs in sec. 32 and in the hillside above the beach and also in the beach cliffs in sec. 30. The most southerly outcrop is on the west side of the small peninsula on the northeast side of Parks Bay. About 500 feet to the north are other small limestone bodies exposed along the shore. The largest is about 10 feet long and has a maximum width of 3 feet. The limestone is interbedded with tuffaceous sedimentary rocks and ribbon cherts. When freshly broken, the limestone has a bituminous odor. The limestone-bearing rocks strike almost north-south and dip to the east.

Above the beach on the hillside in sec. 30 are outcrops of chert, argillite, and volcanic rocks that also contain limestone pods. Most of these are only 1 or 2 feet thick, but some are up to 4 or 5 feet in thickness. The limestone is light gray in color, crystalline in texture, and contains thin interbeds of argillite. No fossils were found. These beds strike almost north-south and dip gently into the hillside to the northeast. An attitude measured on a beach outcrop had a strike of N. 70° W. and a dip of 50° NE.

Quality.—Most of the limestone is high in calcium.

Chemical analyses of West Coast Shaw Island limestone

(Mark Adams, analyst)

Sample no.	Location	Sample length (feet)	$CaCO_3$	$MgCO_3$	Loss on ignition	CaO	MgO	SiO_2	R_2O_3	P_2O_5
SJ 85-1	Lens on hillside --	30	97.54	0.43	42.82	54.80	0.21	1.22	0.30	0.068
SJ 85-2	North pods ------	Composite	98.45	0.04	43.33	55.31	0.02	0.34	0.61	0.193
SJ 91-1	South beach -----	Composite	96.44	0.45	41.42	54.18	0.22	3.77	0.97	0.013

Ownership and development.—The area is subdivided into small lots with summer homes. Owners of the different small outcrops were not determined. No development is in evidence, although it is possible that a few blocks of limestone were quarried from the southernmost outcrop on the beach many years ago. All the limestone bodies seen are too small to be of economic value.

Reference.—McLellan (1927, p. 169).

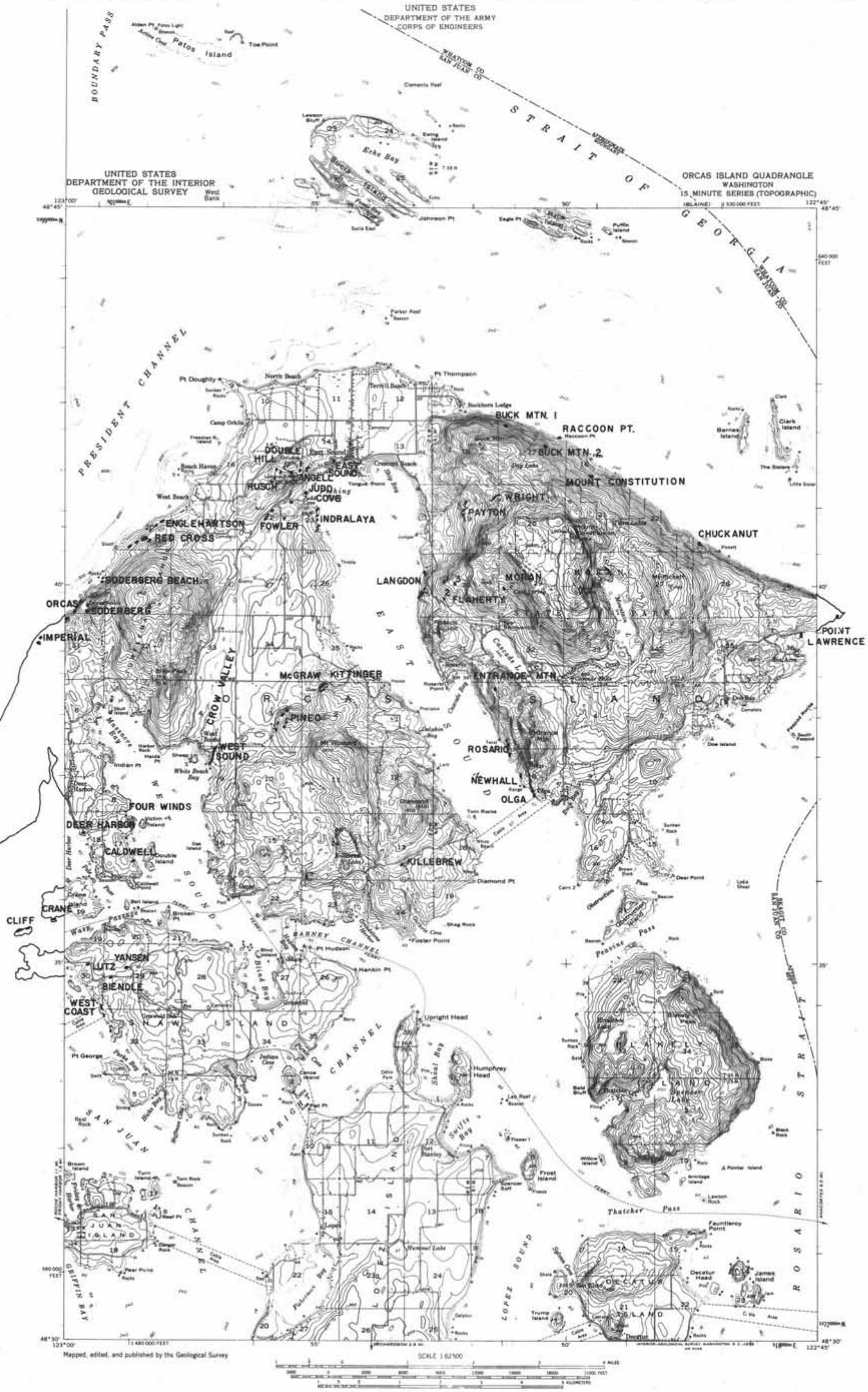


FIGURE 55. — Index map of the limestone deposits of Shaw and Orcas Islands.

Orcas Island

Orcas Island, comprising an area of almost 57 square miles, is the largest island of the San Juan group. Devonian, Pennsylvanian, and Permian sedimentary and volcanic rock sequences are exposed over about two-thirds of the surface of the island and contain many small bodies of high-calcium limestone. At least 30 of these have been quarried at various times, but only 3 have been active in recent years, and they are nearing exhaustion. None of the limestone bodies on the island, developed or undeveloped, now contains more than 50,000 tons, and most of them contain only a few thousand tons of limestone.

Red Cross Quarry

Location, size, and accessibility.—The Red Cross limestone "ledge," as it is sometimes called, is in the SE$\frac{1}{4}$ sec. 20, T. 37 N., R. 2 W., on the west coast of Orcas Island at the northwest end of the Turtleback Range. It consists of four small outcrops and one large limestone lens about 300 feet long and 115 feet in maximum width. About 50,000 tons of limestone remains in the larger body, which has been quarried. One of the smaller outcrops, if assumed to have a depth of at least 30 feet, may contain 30,000 tons. The quarry is accessible by about 1 mile of wagon road starting at the W. G. Englehartson farm, on the West Beach road, and is approximately 4 miles by road from East Sound. The other limestone outcrops are accessible by 850 to 1,050 feet of rough jeep road from the quarry. The altitude of the largest limestone body is about 300 feet above sea level. A dense growth of young trees and brush covers the terrain. A few small open rocky areas occur locally.

Geology and description.—The Red Cross occurrence consists of a group of limestone lenses in a sequence of volcanic rocks, graywackes, shales, and sandstones of Devonian age. The largest lens formed a prominent knob about 90 feet high before it was quarried. It is about 300 feet long and 75 to 115 feet wide. On the north and south it is bounded in part by faults, the extensions of which cut it off at its west end. The limestone disappears under glacial drift to the east, and this drift boundary may also be its approximate contact with adjacent bedrock. An apparently normal contact along the south side of the limestone strikes northeast and dips steeply to the south. The northern bounding fault trends northeast-southwest and dips about 50° SW. The southern bounding fault strikes northwestward and dips about 65° NE. The dips on both faults are variable. Part of the northern border of the limestone lies along a fault zone that is 20 feet or more in width and contains broken blocks of limestone in a gouge matrix. North of the fault zone lie soft black shales and sandstones that crumble easily upon weathering. Farther north and to the southwest, volcanic rocks with interbedded lenses of graywacke crop out, and they are also well exposed in sea cliffs a short distance west of the quarry. To the northwest, roadcuts on the quarry access road are in dark-brown calcareous and concretionary shales.

The limestone is gray in color and is partially dolomitized. It is also partially recrystallized and contains small irregular masses of chert or jasperoid. Near its contacts it is argillaceous. Fossils, although not abundant, occur throughout the limestone and consist mostly of corals, brachiopods, calcareous algae, encrusting foraminifers, and stromatoporoids. Fossil genera so far identified include: Thamnopora, Stringocephalus, Rothpletzella, and Wetheredella; they indicate a late middle Devonian age for the limestone.

About 500 feet south of the quarry are three small limestone outcrops apparently representing individual lenses in volcanic rocks, although their contacts are not well exposed. The first outcrop (Red Cross No. 2) is 20 feet long and about 10 feet wide. It is exposed on the west side of a jeep road. A larger outcrop (Red Cross No. 3) is 70 feet farther south. It is on the east side of the jeep road and may extend under the roadbed. This outcrop is about 30 feet long and 20 feet wide. The limestone in both outcrops is similar in appearance to that of the quarry and contains fossil corals. Red Cross No. 4, about 60 feet south of No. 3, is the largest, forming a small brush-covered knoll. This outcrop is about 45 feet long and 35 feet wide. It contains some argillaceous layers and appears to be more crystalline in texture than the other outcrops.

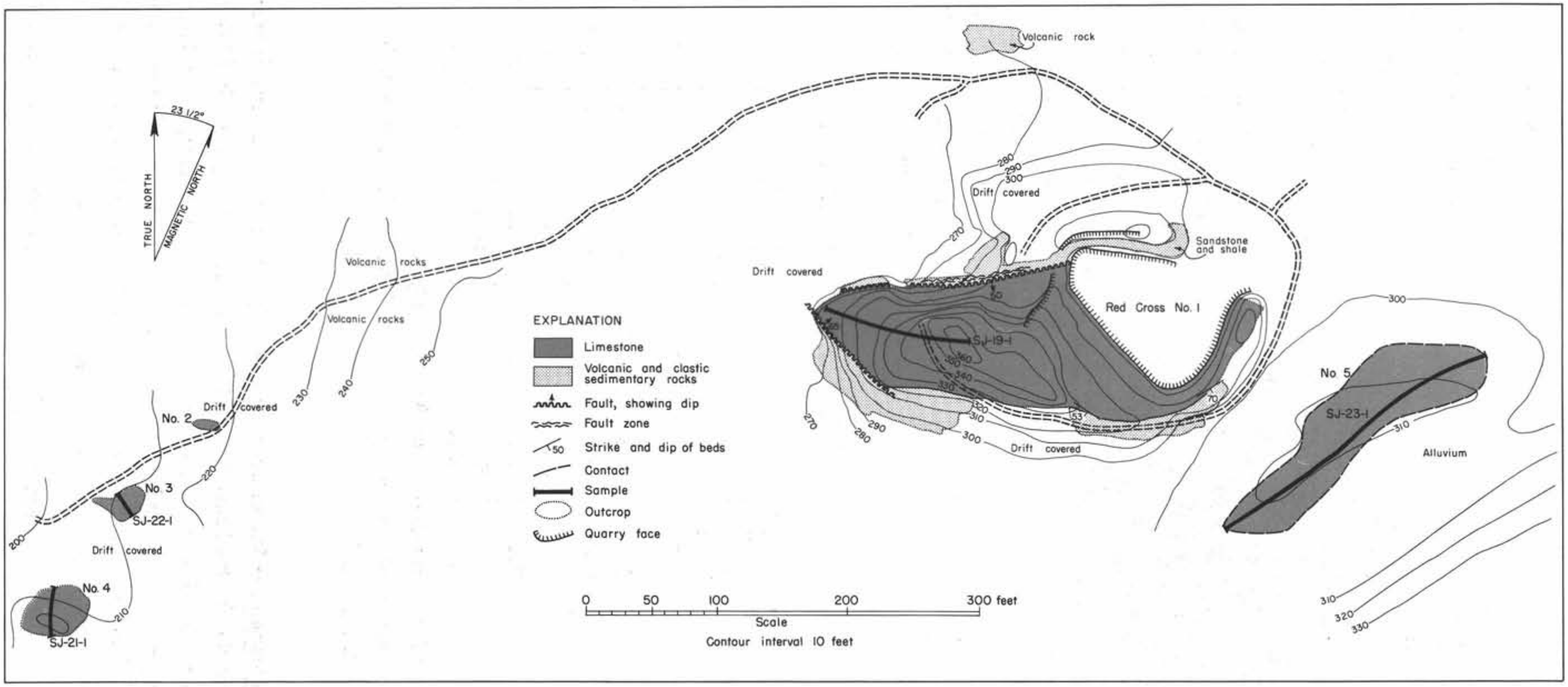


FIGURE 56.—Red Cross Deposit. SE$\frac{1}{4}$ sec. 20, T. 37 N., R. 2 W. Geology by W. R. Danner, C. F. McKillop, and A. M. Rivisto. Plane table and compass and tape survey.