ENGINEERING GEOLOGY IN WASHINGTON

Volume I

RICHARD W. GALSTER, Chairman
Centennial Volume Committee
Washington State Section, Association of Engineering Geologists

WASHINGTON DIVISION OF GEOLOGY AND EARTH RESOURCES

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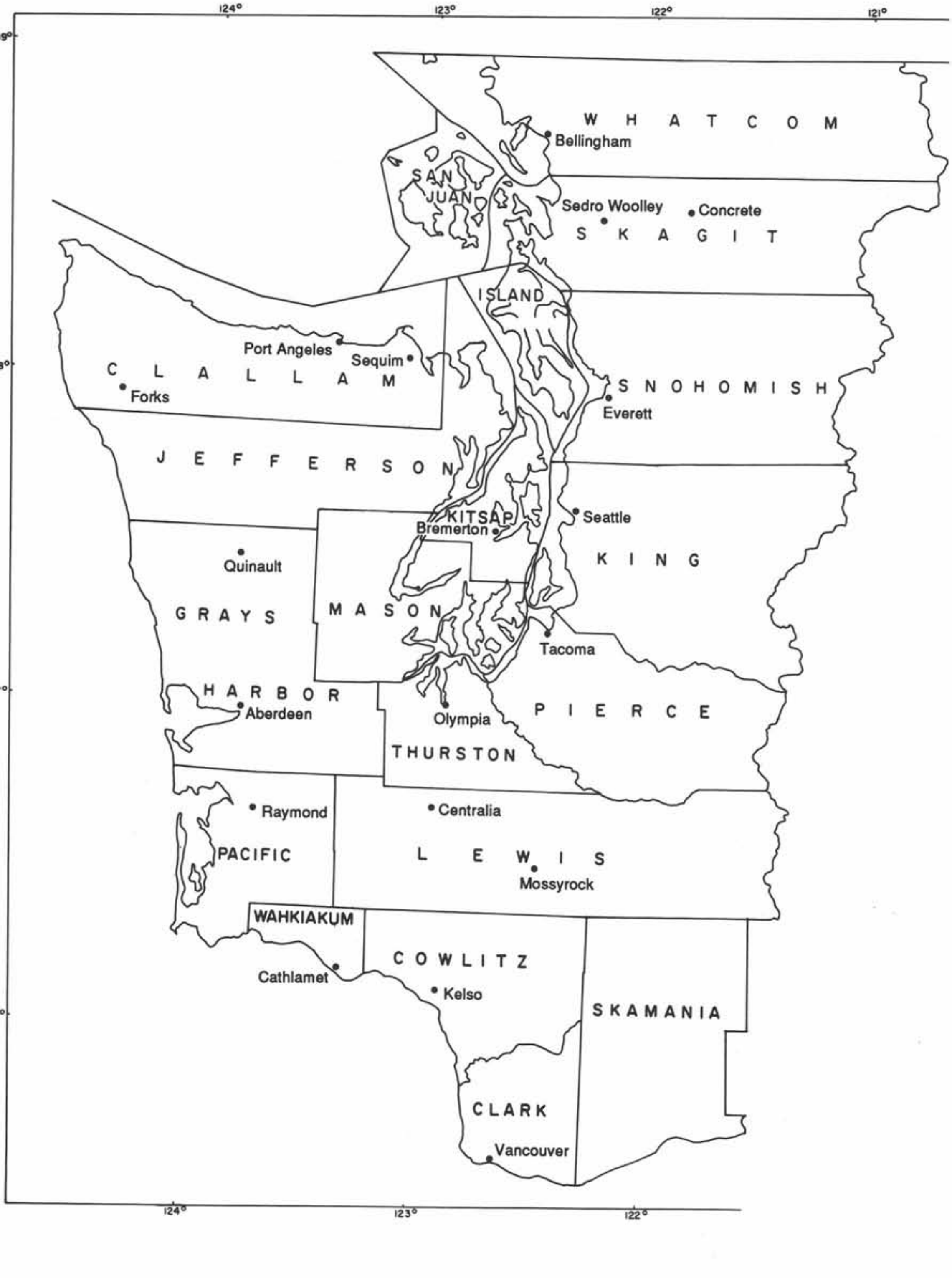
VOLUME II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Dedication

Howard A. Coombs
Dean of Pacific Northwest Engineering Geologists

In the spirit of high regard and warm affection, the Centennial Volume Editorial Committee of the Washington State Section, Association of Engineering Geologists, dedicates these volumes to Howard Abbott Coombs. To those of us who have had the privilege of associating with Howard as students, professional colleagues, and friends, this dedication seems richly deserved and too long delayed by the Pacific Northwest engineering geology community. For those who know only the legend of Howard Coombs, perhaps the breadth of the volumes' contents will attest to the esteem in which he is held by his colleagues.

Howard Coombs was born April 10, 1906, in Dallas, Texas. Following completion of his high school years in Toronto and Chicago, he came to the University of Washington in 1925 as a pre-law student. An early encounter with a beginning geology course caused him to change his major and his career and influenced the careers of his future students. Coombs completed his B.S. degree in geology in 1929 and his M.S. in 1931. During this period he trained as a field assistant to Richard E. Fuller, who was doing his Ph.D. work at Steens Mountain in southeastern Oregon. Coombs also received his earliest indoctrination in the developing field of engineering geology through working with Henry Landes (then State Geologist and department chairman at the University of Washington) investigating the geology of dam sites on the Columbia River for the U.S. Army Corps of Engineers "308 Report".

During the summers of 1931 through 1933, Coombs worked as a ranger in Mount Rainier National Park and mapped the geology of the park. This work was encouraged by an understanding chief ranger, who transferred Coombs from station to station so that the mapping could be completed.

During the academic portions of those years, Coombs served as a teaching assistant at the University of Washington. One of his jobs was to service the monstrous Bosch-Omori seismograph, which had been moved to the basement of Johnson Hall in 1930. The work included smoking the paper and shellacking the records, and it sparked his long interest in seismology. Ultimately he served for 20 years as the Director of the University of Washington Seismological Station and collaborator on seismology for Washington with the U.S. Coast and Geodetic Survey.

While he served as teaching assistant, Coombs showed his individualism and activism by going to the Dean regarding a fracas concerning work loads and hours. Department Chairman Landes retaliated by dismissing the rebel, but in a few days calm returned, and so did Coombs. A greater sharing of the work load resulted. Coombs completed his doctoral thesis, "The geology of Mount Rainier National Park", in 1935 and was awarded his Ph.D. degree, one of the earliest such degrees to be granted by the university. At about this time, the Geology Department separated from the Geography Department, and Coombs was raised to faculty status with the title of Associate; he became an Instructor a year later.

Coomb's move to a faculty position coincided with the beginning of the controversy on the origin of granite, an issue that was to hold the attention of the geological profession for the next two decades. Collaborating with G. E. Goodspeed and R. E. Fuller, Coombs investigated replacement breccias and other petrogenetic heresies. He also continued his interest in the Cascade volcanoes with field studies on Mount Baker. During World War II, he continued to teach, served as a consultant to organizations establishing Navy bases in Washington, Oregon, and Alaska and worked a full shift as a B-17 aircraft inspector at the Boeing Company.

It was during this period that he became the Pacific Northwest eyes and legs for the aging Charles P. Berkey, whose fame as a consultant on dams during the 1930s and 1940s is well known. This led to a growing involvement with dams throughout the Pacific Northwest over the succeeding 45 years. Coombs acted as consultant to the cities of Seattle and Tacoma, to several private and public utilities, a number of private engineering organizations, and federal and state government agencies.

In 1950 Coombs went to Japan as geological advisor to the Supreme Commander, Allied Forces under the AID program. After working with the Japanese on siting 16 dams, he returned to the United States showered with gifts from his appreciative colleagues. He was awarded a Special Service Commendation by Gen. Douglas MacArthur for his work.

In 1952 Coombs became Chairman of the Department of Geology, a position he held for 17 years. He presided over a period of unparalleled growth in faculty, students, and research facilities. During this period he continued to teach and do consulting work, mostly on dams, but also beginning associations with the Weyerhaeuser and Crown-Zellerbach timber companies.

However, neither the administrative tasks of department head nor consulting work took precedence over his teaching duties. Upon relinquishing the department head's position, Coombs' consulting work moved heavily into nuclear power plant siting and construction in Washington and Oregon.

In 1976, after 42 years on the university faculty, Coombs retired to emeritus status but continued his consulting work. In 1976 he was appointed as the geologist member of the U.S.Department of Interior Blue Ribbon Panel to determine the causes of the failure of Teton Dam in Idaho. In 1977 he served as chairman of the special panel investigating the location and characteristics of the 1872 North Cascades earthquake. The eruption of Mount St. Helens in 1980 further increased Coombs' work load; numerous organizations sought his analysis of the volcanic hazards to engineered projects. However, perhaps his greatest contribution during these years has been his personal effort to improve technical communications among engineering geologists in the Pacific Northwest by sharing unpublished reports and data with geologists of various private organizations and government agencies.

Coombs is a fellow of the Geological Society of America (GSA) and served as chairman of that society's Engineering Geology Division in 1971. He was a founding member of the Washington State Section of the Association of Engineering Geologists (AEG). In 1970 he won the AEG publication award for his paper "Leakage through buried channels", which was originally presented at the association's 1968 annual meeting in Seattle. In 1979 he was awarded honorary membership in AEG. He is also a member of the U.S. Committee, International Commission on Large Dams. In 1980 he served as the GSA representative on the National Research Council's Committee on Tunneling Technology.

We are indeed grateful for his presence on and his counsel to the editorial committee. The entire profession has benefitted from his contributions to geology in general and to engineering geology in particular. His reserved, yet enthusiastic and dynamic manner has been appreciated by all who have worked with him.

It is, therefore, most fitting that these volumes be dedicated to Howard A. Coombs.

RWG June 6, 1988

Foreword

The concept that generated these volumes began to take shape in February 1986, and the editorial committee held its first meeting the following month. Keeping the group of engineering geologists together for the life of this project has been no easy task, given the nomadic style of the profession and the pressures of professional work and personal committments. Although several individuals have moved in and out of the committee's work during the past 3 years, those listed below have been the consistent movers throughout the formulation of the volumes.

The compilation, review, and publication of the more than 2,000 pages of typescript and 600 illustrations employed the efforts of more than 100 authors, uncountable word processing operators, drafters, and independent reviewers from a diverse group of organizations.

All of this could not have been accomplished without the assistance of the Washington Division of Geology and Earth Resources. The willingness of Raymond Lasmanis, State Geologist, and J. Eric Schuster, Assistant State Geologist, to publish these volumes is a tribute to their continuing efforts to bring the practical aspects of geology to the citizens of Washington. The committee appreciates the efforts of the Division's geologists and publications staff in preparing the volumes.

The committee also wishes to acknowledge Shannon & Wilson, Inc., which graciously provided facilities for committee meetings in their Seattle office. Lastly we thank the many organizations that provided secretarial and drafting support and those who provided financial grants to assist in publishing these volumes.

(RWG)

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Introduction

Engineering Geology in Washington: Introduction

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PURPOSE AND SCOPE OF VOLUMES

These volumes commemorate the 100th anniversary of Washington statehood (1889-1989). The papers have been compiled by members and colleagues of members of the Washington State Section of the Association of Engineering Geologists, which celebrated its 25th anniversary in 1988. The purpose of this volume is to provide a reference on the practice of engineering geology in this state and a compendium of case histories relating geology to significant engineered projects in the state. Such a reference is valuable to geologists practicing in the field of applied geology, geotechnical engineers, and interested public officials and lay persons.

Engineering geology is not a separate branch of geology but rather the application of all branches to the solution of engineering problems—it is "geology in overalls". It may be defined as the application of geologic data, techniques, and principles to assure that geologic factors affecting the planning, design, construction, operation, and maintenance of engineered projects and structures are appropriately considered. Engineering geology also includes the proper assessment, development, and management of ground water, location and evaluation of natural construction materials, and site-specific evaluation of seismic risk and anticipated seismic motions. All of these factors are generically considered as related to Washington's geology and are presented in a series of papers in Part I. The scope of these discussions is a summary of the present "state-of-the-art" as these factors apply to the practice of engineering geology in Washington, but the papers are not meant to be the final or definitive word on these factors. Part II treats case histories in general terms, but with sufficient detail to promote understanding of the geological problems and their proposed or actual solutions. Certain projects are treated more fully than others because of availability of data. The selection of case histories by no means exhausts the known history of engineering geology problems in this state. The selection does focus on major projects, most of which were constructed during the past half century or so and many of which are well known in both technical and lay literature but have never previously been brought together. Other discussions relate to problems of urban and rural development, including transportation routes, disposal of wastes, conservative development of ground water, and natural resources used in construction. These are important and continuing problems that engineering geologists and our colleagues in the geotechnical engineering community are charged with addressing.

One of the chronic problems of engineering geology and engineering geologists is the general unwillingness of many practitioners to take the time to write and publish the results of their work, a problem common to other applied geology fields, such as mining and petroleum. Project-oriented engineering geology reports are often buried in the files of private companies or government agencies, available only with great effort to those practicing in the profession and to the interested public. It is the purpose of this volume to provide some of this information in print where it may be used as a reference whenever the need should arise.

DEVELOPMENT OF ENGINEERING GEOLOGY IN WASHINGTON

The importance of appropriate geologic assessment for engineered projects in Washington began to be made apparent during the early days of large dam construction. This proceeded apace with development elsewhere in the United States where major construction projects relating to water storage, hydropower, and water transmission were being planned or under construction. Prior to 1930, the geologic assessment of dam sites and tunnel routes was accomplished by a few well-known geology professors from various universities, who served as early consultants, or by civil engineers. In some instances, particularly with lesser projects, no geologic assessments were made. The routing of roads and railroads was largely done with little consideration of geology. Geologic problems were usually conquered by "brute force and awkwardness" with subsequent, often excessive, maintenance problems. Urban construction siting was usually accomplished (and sometimes still is) without proper consideration of foundation conditions or of "hazards" related to geologic processes. Similarly, coastal works were built without geologic considerations, sometimes resulting in excessive maintenance and undesirable effects along the shore.

Perhaps the earliest quasi-engineering geology report for this state was made by Henry Landes (then State Geologist) and Milnor Roberts of the University of Washington in their investigation of the Masonry Dam site on the Cedar River near Seattle. These sage gentlemen warned the City of Seattle in July 1910 of the dangers of leakage through the delta morainal embankment adjacent to the north abutment of the proposed dam. They recommended a program of extensive test drilling, recommendations which were disregarded (Mackin, 1941). The sudden failure of the reservoir in 1918 and the subsequent efforts to control leakage are discussed elsewhere in these volumes. Similarly, the foundation of Elwha Dam near Port Angeles failed during the first reservoir filling in 1912, owing to lack of a proper cut-off to bedrock beneath the structure. Thus, the first two major dam projects in western Washington experienced partial failure for the lack of appreciation of geologic factors. However, by the mid-1920s, changes began to occur, when G. E. Goodspeed at the University of Washington provided consulting geology services to the Great Northern Railroad on construction of the Cascade Tunnel. Kirk Bryan of the U.S. Geological Survey examined the geology of proposed dam sites in the Yakima River Basin for the Reclamation Service. James Gilluly of the U.S. Geological Survey examined several dam sites on the lower Columbia River for the U.S. Army Corps of Engineers. Henry Landes of the University of Washington and a graduate student, Howard Coombs, investigated the geology of many of the Columbia River dam sites for the U.S. Army Corps of Engineers as part of the "308 Report" study during 1930-31, while C. F. Tolman of Stanford University investigated a dam site at Kettle Falls on the Columbia River for Washington Water Power Company.

The foundation failure and collapse of St. Francis Dam in California, in 1928, probably provided more impetus to engineering geology than any other single event in North America (Burwell and Moneymaker, 1950). Shortly thereafter, both the U.S. Army Corps of Engineers and the U.S. Bureau of Reclamation, largely through the encouragement of consultant Charles P. Berkey of Columbia University, began to place geologists on their staffs both in design offices and in the field on construction jobs. One of the earliest of these pioneers was Claire P. Holdredge, an ex-petroleum geologist who, in 1931, became Resident Geologist on the construction of Bonneville Dam. Holdredge later was to become one of the founders and first President of the California Association of Engineering Geologists, the forerunner of the Association of Engineering Geologists (Galster, 1982). Another was Grant Gordon, who arrived early in the construction of Grand Coulee Dam (Neff, 1986). Still another was Allen Cary, a misplaced architect, who moved into a career of engineering geology and soils engineering with the Corps of Engineers during the construction of Mud Mountain Dam during the late 1930s.

During the years of World War II, a considerable amount of engineering geology was done under the guise of military geology. Such efforts included investigations of ground-water supplies, foundation conditions, and evaluations of natural construction materials for military structures. Howard Coombs of the University of Washington continued his part-time career in engineering geology during these years by evaluating sites for the Navy in the Northwest and Alaska and serving as consultant to Seattle and Tacoma on Ross and Mayfield dams, respectively (Barksdale, 1974). At Grand Coulee, Fred Jones began landslide studies and geologic investigations for the irrigation phase of the Columbia Basin Project. However, during the war years most non-military construction was deferred.

The post-war population influx into the Northwest and the resulting construction boom provided the real impetus for geologic evaluation of non-military construction sites. During the next quarter century, the cities of the Northwest expanded dramatically, nearly all the dams on the Columbia and Snake rivers and in western Washington were completed, freeways were built, the Columbia Basin Project was completed, and development of ground-water resources increased. The area's first local truly geotechnical firm, Shannon and Wilson, Inc., was established during the early 1950s, the forerunner of the 25 to 30 to come. While employment of engineering geologists under that label was a rarity, the practice was nonetheless there. Practitioners of engineering geology were employed by various organizations, including the Department of Highways, Water Resources Division (state), U.S. Army Corps of Engineers, Bureau of Reclamation, U.S. Geological Survey, and various geotechnical and ground-water consulting firms. By the early 1960s a need had arisen for more communication between practitioners. Early in 1963, John Fryberger of the Tacoma consulting firm of Robinson and Roberts, Robert Russell of the Washington Department of Water Resources, Allen Cary of the U.S. Army Corps of Engineers, Sigmund Schwarz of Geo Recon, Henry Minch of Metro Engineers, and Howard Coombs of the University of Washington began organizing the group that in August of that year officially became the Washington State Section of the fledgling organization called the Association of Engineering Geologists (AEG). This organization had been spawned 6 yr earlier in California in response to the necessity of practitioner communication and the need for licensing of practitioners during the post-war California population influx and construction boom. The group in Washington was the first to form a formal section outside of California. The Association subsequently held two of their annual meetings (conventions) in Seattle (1968 and 1977), exposing the worldwide profession to the problems and practice of engineering geology in the Pacific Northwest.

GEOLOGIC SETTING AND ITS INFLUENCE ON STATE DEVELOPMENT

General

Any geopolitical division of the Earth's surface divided by a major mountain range *a priori* has some interesting problems. Not only does such a geologic feature influence climate and drainage, but it serves as a commercial barrier as well. The geologic violence, which accreted the western cordillera to North America over the past 150 m.y. or so, has had far-reaching influence on the geologic characteristics and, therefore, on the development of the State of Washington, a distinction held in common with other west coast states and the province of British Columbia. Perhaps the most important result is the relatively large number of geologic provinces represented in the state, providing a great variety of landforms and subsurface conditions rarely found in geopolitical subdivisions of comparable size. This in turn provides a variety of topography, climate, commercial potential, and living situations for both early and modern man.

Washington includes parts or all of seven major geologic provinces as well as smaller parts of several peripheral provinces manifested to a greater extent in adjacent states. These geologic provinces (Figure 1) are characterized by a combination of distinctive rock types

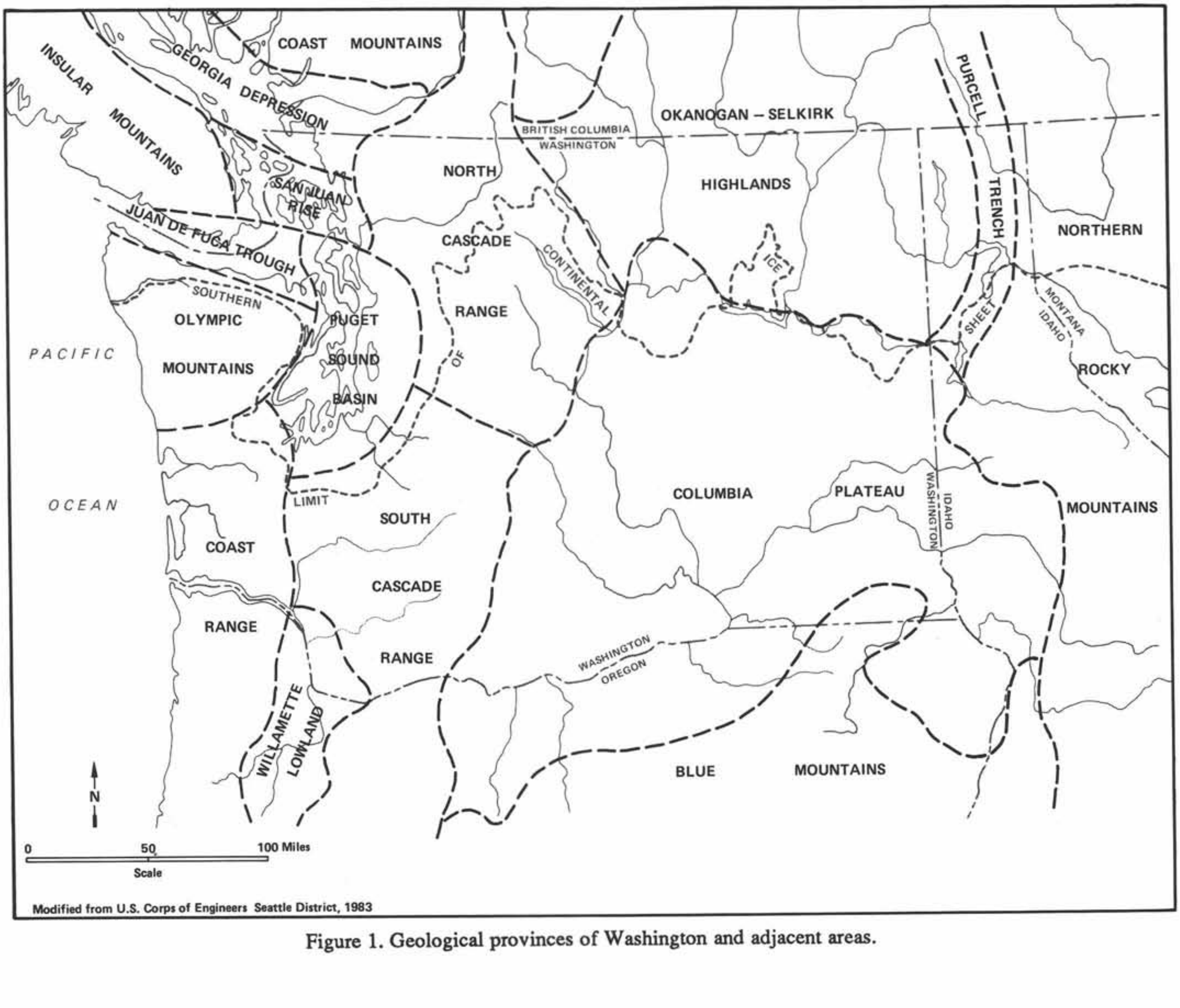

Figure 1. Geological provinces of Washington and adjacent areas.

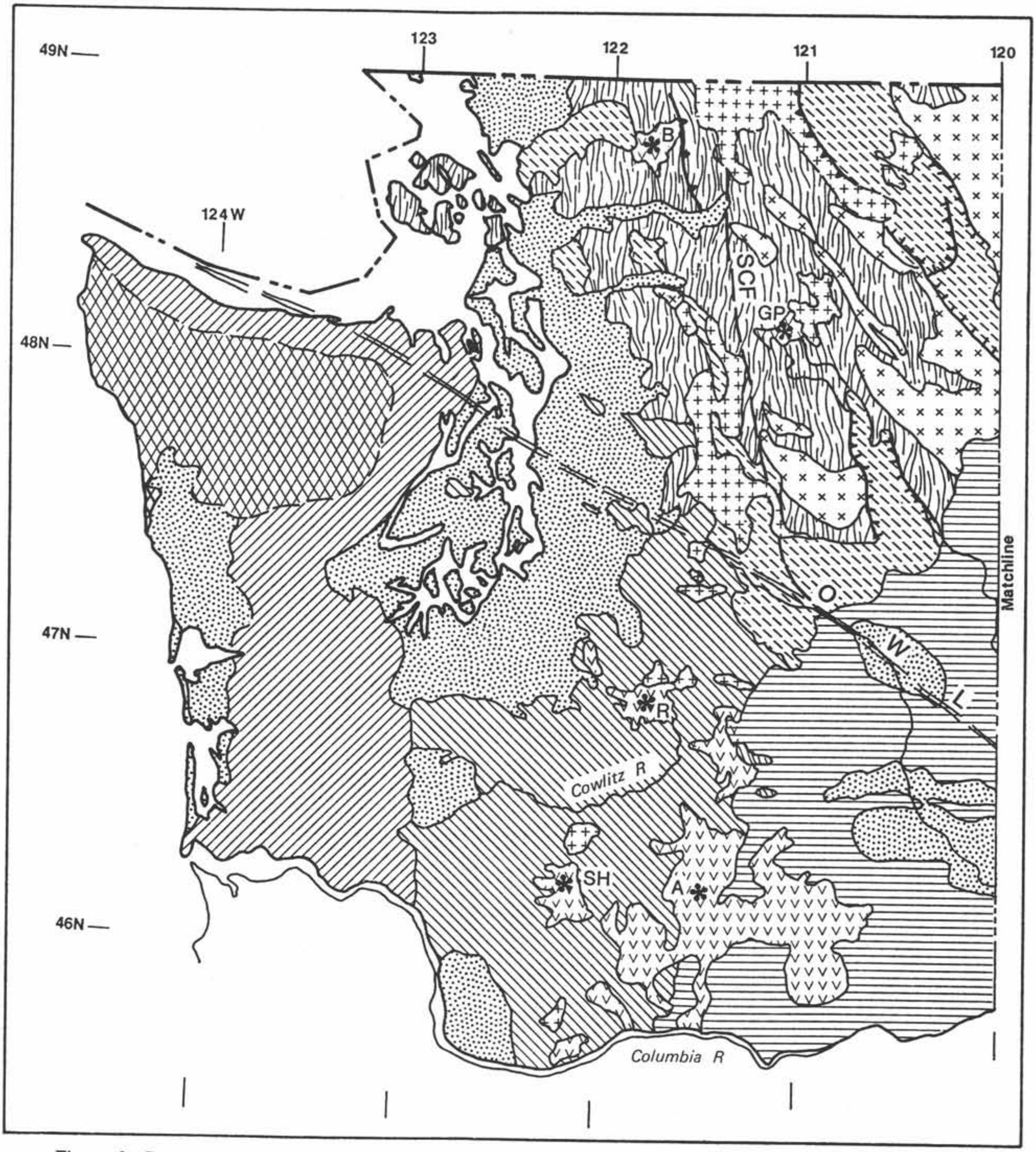

Figure 2. Generalized geologic map of Washington. Olympic-Wallowa lineament approximately located. (After Bennison et al., 1973)

(Figure 2), topography, geologic structure, and erosional characteristics. Each is relatively easy to recognize by both the geologist and casual observer, thus providing a basis for discussion of the state's geology and of its engineering geologic considerations. It is also necessary to discuss to some extent geologic provinces beyond the state borders that have had an impact on the Tertiary-Quaternary history of the state. The northern part of the state was directly affected by a succession of Pleistocene continental ice sheets originating from Canadian ice centers and by numerous mountain glaciers of local origin. These glaciations had a profound influence on the engineering geology aspects of the state as well as on its scenery, influences that commonly extend some distance beyond areas actually glaciated.

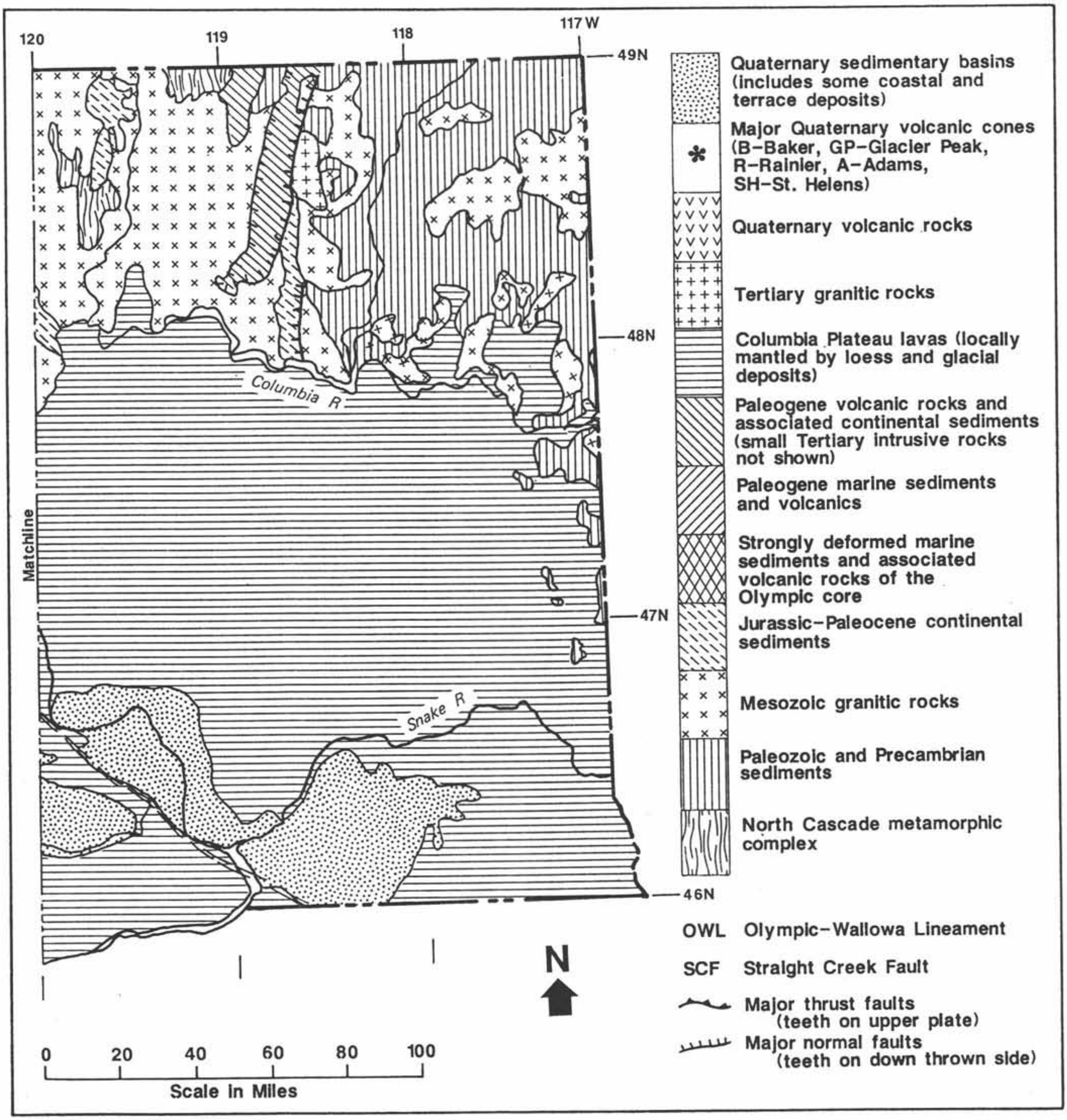

Figure 2. (continued)

Cascade Range

The Cascade Range extends from southern British Columbia on the north into northern California on the south. It effectively separates the moist western part of the state from the dry eastern part, and it has, perhaps, had the greatest influence on the somewhat separate early cultural development of the state. The range is divided into two major segments differing in topography and geology. The division consists of a 10- to 20-mi-wide zone of transverse structure trending west-northwest through which passes the Olympic-Wallowa lineament (OWL) (Raisz, 1945). The South Cascades consist largely of a series of Tertiary andesitic and basaltic lavas, tuffs, and breccias/agglomerates, together with several Tertiary granitic plutons. Three major Quaternary volcanoes (Rainier, Adams, and St. Helens) and a host of minor volcanic cones and fissure eruptive fields rest on the older volcanic rocks. These geologic characteristics continue southward through Oregon and into northern California. Although there are areas of rugged peaks in the South Cascades, the topography is generally more subdued than in the North Cascades, partly a function of the dominance of Tertiary-Quaternary volcanism, of late Tertiary uplift of moderate magnitude, and of generally lesser amounts of alpine glaciation. The result is a mountain range with elevations of 5,500 to 7,000 ft, except for the three major volcanoes that tend to dominate the skyline.

In contrast northward, the North Cascades are of greater antiquity, consisting of a core of Paleozoic-Mesozoic metamorphic rocks, granitic gneiss, schist, hornfels, greenstone, and related rocks, emplaced by major thrust faulting and intruded by Mesozoic and Tertiary plutons. The core rocks are flanked by Cretaceous and Paleogene sediments—sandstone, shale, conglomerate, and coal beds that are especially well preserved in three large and somewhat complex grabens on the east flank of the range. The North Cascades have been, and in some areas still are, heavily glaciated, resulting in a rugged range having elevations of 7,000 to 9,000 ft. Tertiary volcanic rocks are restricted to a narrow north-trending band lying west of an extensive north-trending, strike-slip fault (Straight Creek fault). Pleistocene-Holocene volcanic rocks are limited to the vicinity of Mount Baker and Glacier Peak. These two volcanoes rise 1,000 to 2,000 ft above the general level of the North Cascades and, while easily recognizable, do not tend to dominate the skyline as much as the high volcanoes of the more subdued South Cascades.

The barrier of the entire range is broken only by the Columbia River, which predates the uplift of the range and which provided the initial passageway for early explorers, settlers, and commerce into western Washington and Oregon. The early breaching of the range for human communication north of the Columbia River was by wagon road through Naches Pass in 1853 and by rail through the Stampede Tunnel in 1888, a year ahead of statehood. The range was a somewhat inhospitable area for settlement, except for the lure of minable metals and coal along the range flanks that provided sufficient impetus for those who would "get rich by mining". While the Cascade barrier is now breached by five major highways and two (formerly three) major rail lines, two of the highways are regularly closed during winter snows. The problems of maintaining such land communication routes often extend beyond the normal practice of engineering geology; however, geology has had a major impact on the siting, design, and construction of such transportation routes and their maintenance. Moreover, development of seasonal-use facilities in the Cascade Range requires evaluation of landslide/avalanche potential, flood hazards, and other geologic hazards common to mountainous terrains.

Olympic Mountains

The crudely circular range of rugged peaks that dominates the Olympic Peninsula consists of Tertiary marine sediments and volcanic rocks whose origin is similar to the rocks of the Coast Range to the south. Here, however, the similarity ends, for the difference in tectonic history has produced dramatically different results. Available data suggest that a concentrated plate collision at about 17 Ma shoved the already low-grade metamorphosed sediments and volcanic rocks eastward into a series of arcuate, convex-eastward thrust sheets piled each on top of the other. These low-grade-metamorphosed marine sedimentary rocks presently form the core of the Olympics and the bulk of bedrock along the ocean coast, while the unmetamorphosed sedimentary and volcanic rocks of the same age form the peripheral rocks that dip away from the core on the north, east, and south (Tabor and Cady, 1978). This deformation resulted in the highest (6,000-8,000 ft) coastal range in the contiguous 48 states. Although the Olympic Mountains were an independent ice center during the Pleistocene, none of the valley glaciers reached the present position of the sea. Glacial outwash, however, was deposited extensively on the west side of the range, and mountain glaciers may have preceded or coalesced with continental ice in the Puget Sound Basin on the east. Continental glacial deposits, which underlie the northern and northeastern parts of the province, resulted in a more subdued topography. This factor, together with deep, sheltered harbors, provided attractive areas for early settlement and for exploitation of the timber resources that cover the peripheral foothills. Timber remains the principal industry of the Olympic Peninsula; however, since the creation of Olympic National Park, the tourism has increased markedly. Assessment of flood and slope stability hazards together with availability of natural construction materials are critical items in the siting, construction and maintenance of the highways and roads that service these industries in hilly to mountainous terrains. Coastal geologic processes impact harbor and other coastal developments, and the location and development of ground-water supplies are frequently difficult even in this region of high rainfall owing to the highly complex geology of the Olympic periphery.

Coast Range

The southwestern portion of the state is occupied by a subdued range of forested hills and low mountains (elevations 1,000-2,500 ft) known as the Willapa Hills. These represent a northward extension of similar forested hills and low mountains of the Oregon Coast Range. They are composed of Tertiary marine and estuarine sedimentary and volcanic rocks that have been gently folded and faulted. Because the rocks are deeply weathered, owing to their long exposure to heavy rainfall in a temperate climate and to the absence of Pleistocene glaciation, a thick, iron-rich, reddish residuum mantles much of the province. The coastal areas are dominated by two shallow embayments, Grays Harbor and Willapa Bay, each protected by long barrier beaches formed and nourished by sand moving north from the Columbia River, which exits into the Pacific Ocean at the Oregon-Washington boundary. Both embayments serve as sediment "sinks" for coastal littoral material as well as for the streams entering them. Settlement and development was, and continues to be, based largely on the lush timber resources and to a lesser extent on the shellfish and fishing industries and, more recently, on tourism. Development is largely concentrated on the periphery of the province along the coast and in the Columbia, Chehalis, and lower Cowlitz valleys in areas of easiest access. Early logging activities provided sufficient impetus for a rail line and later a highway across the center of the range connecting the upper Chehalis drainage with the Willapa valley. Commercial development of a thriving cranberry industry is a direct result of the brackish bogs developed during formation of coastal barrier beaches. The thick residuum and widespread weathered bedrock underlying the hill country are subject to many slope stability problems in excavations in spite of the prevailing gentleness of slopes. Low valley and coastal areas require assessment of river and coastal flooding, tsunamis, erosion, and other geologic phenomena prior to siting and construction of facilities. The availability of ground water requires assessment of the fresh water–salt water relation in coastal aquifers, and such assesments are even more difficult in the hill country owing to the absence of glacial outwash.

Puget Sound Basin

Sandwiched between the Olympic Mountains and the Cascade Range is an arcuate, convex-eastward, sea-level basin partly occupied by Puget Sound. The basin's arcuate shape crudely reflects the convexity of the Olympic thrusts, and its origin as a basin probably dates from the same period of deformation. The basin exhibits a paucity of bedrock exposures except along its flanks and along a partly buried bedrock rib of Tertiary sediments and volcanic rocks that extends across the central basin from the Newcastle Hills on the east to the so-called Wildcat Hills of the central Kitsap Peninsula. On the north side of this bedrock spur the thickness of Quaternary sediments exceeds 3,700 ft, the greatest depth of Quaternary sediments known in the Puget Sound Basin (Hall and Othberg, 1974; Yount et al., 1985). The offset of the underlying bedrock also results in the largest gravity gradient in North America, a negative gravity anomaly that lies directly on the Olympic-Wallowa lineament. Quaternary sediment thickness in the southern part of the basin is as great as 2,000 ft, and it ranges from 800 to 2,400 ft in the northern part of the basin.

Much of the floor of the Puget Sound Basin, which is characterized by north-south-trending drumloidal ridges, is underlain by deposits of the several Pleistocene continental ice invasions from the north, mainly till, proglacial sand and gravel, and proglacial lake clay and silt. The intervening valleys are underlain by postglacial alluvium and/or marine deposits, which in turn are underlain by glacial and interglacial materials similar to those on the ridges. The present configuration of the valleys is largely due to the influence of stagnating ice during the waning stages of the last glaciation. Similarly, the many lakes that characterize the uplands are kettles (depressions) left from ice wasting. In the southern portion of the basin, the drumloidal hills are partly or entirely buried by extensive outwash sand and gravel; in the northern section there is a predominance of glaciomarine deposits. Along the flanks of the basin, especially on the eastern and southern sides, ice-marginal drainage produced a profusion of channels, deltas, and terraces on a scale that is rarely found elsewhere in the world.

The combination of deep natural waterways and harbors, together with the moderate topography covered by luxuriant growths of timber, drew the first modern settlers to the basin. The exploitation of timber resources, development of agriculture mainly in the alluvial valleys, availability of abundant water from mountain snow melt, and early discovery of coal along the eastern margin of the basin, coupled with the relative ease of seaport construction, provided the impetus for sustained commercial development. About two-thirds of the state's 4.5 million people live and work in the basin, the geology of which provides relatively low-cost construction, owing to ease of grading and trenching and the availability of sand and gravel for fill and concrete. While the geologic history of the Puget Sound Basin has made it a most hospitable place for human development, it is not without significant geologic problems in terms of foundation conditions, slope stability, flooding, erosion, seismic hazards, and ground-water supply and contamination, items that will be discussed later in these volumes.

San Juan Rise

The northern boundary of the Puget Sound Basin merges imperceptibly into the eastern portion of the Juan de Fuca Trough, but it is separated from the Georgia Depression on the north by a 25-mi-wide band of bedrock hills and mountains bounded on the north and south by major east-trending fault zones. The resulting San Juan Islands and adjacent mainland hills form a bedrock septum between the North Cascades and the Insular Mountains of Vancouver Island. The islands and bedrock hills are only thinly mantled by glacial drift. The core of the septum consists of metamorphosed Paleozoic and Mesozoic volcanic and intrusive rocks together with metamorphosed sediments. These are flanked on the north by Cretaceous to Eocene sandstone, shale, and coal beds, the latter providing the impetus for a coal industry in Whatcom County earlier in this century. The proximity of this area to the Strait of Juan de Fuca and the availability of protected, though shallow, harbors at Bellingham and Anacortes have concentrated commercial development in these areas. Agricultural development has been concentrated on the broad distributary Skagit delta that occupies much of the eastern part of the province. Major geologic problems in this province relate to the somewhat tenuous availability of ground water in the San Juan Islands, flooding on the Skagit delta, and slope stability problems in major excavation areas, both in the bedrock and in the glacial drift mantle. Although there are some coastal erosion problems, they are not extensive owing to the great extent of bedrock exposed in coastal areas.

Columbia Plateau

The semi-arid Columbia Plateau, occupying about one-third of the state, is Washington's largest geologic province. The entire plateau is underlain by Columbia River basalt lavas, which originated from fissure eruptions in the southeastern corner of Washington and adjacent areas of Oregon and Idaho between 17 and 6 Ma. The lava partly filled a major depression and encroached onto the flanks of the northern Rocky Mountains to the east, the Okanogan-Selkirk Highlands to the north, the Cascade Range on the west, and the Blue Mountains to the south. The lavas diverted the Columbia River against the east flank of the emerging Cascades and impounded lakes in the drainages around the lava field periphery. During maximum outpouring, lava flowed through a low area in the South Cascades and spread out over parts of the Willamette Lowland extending to the present Pacific coast of southwestern Washington and northwestern Oregon. The thickness of the lavas ranges from a few hundred feet near the plateau margins to more than 12,000 ft in the Pasco Basin. It is both the largest in area and most voluminous lava field in North America and, together with its post-eruption history, forms a unique geologic province. The province can be divided into four subprovinces: the Yakima Fold Belt, a series of east-trending anticlinal ridges lying largely, but not entirely, west and north of the Columbia River; the Palouse slope, a gentle southwest-sloping paleoslope largely mantled by eolian silt, occupying the eastern half of the province; the Blue Mountains, a gentle northeast-trending uplift that projects into the southeast corner of the state from Oregon; and the Waterville plateau, a partly glaciated, high plateau occupying the northwestern part of the province.

Around the plateau margins the basalt flows are interbedded with sediments. Pre-lava mountains protrude above the basalt surface only near the northern and eastern margins. Extensive post-lava sedimentation took place in basins (Pasco, Yakima, Kittitas, and Walla Walla) developed in the south-central portion of the plateau during the period of Yakima Fold Belt development, most of which appears to have occurred between 8.3 and 3.3 Ma. Wind erosion and transport of the fine-grained parts of these post-lava sediments apparently produced the great silt dunes of the Palouse subprovince. While only the northern margin of the plateau was glaciated during the Pleistocene, some unique features of the Columbia Plateau are those due to glacial diversion of drainage across its surface and the catastrophic discharge of glacially impounded lakes in northern Idaho and western Montana across the plateau surface (Bretz, 1923; Bretz et al., 1956; Baker, 1973). These events produced the coulees and channeled scablands together with both high- and low-energy fluvial deposits at a scale unique on Earth. This complex geologic history makes geologic interpretation for engineering purposes difficult at best and frequently requires the uninitiated to forego classical geologic concepts.

Much of the plateau was inhospitable to early settlers. The natural aridity of the region restricted early homesteading to areas near the Columbia, Snake, Walla Walla, and Spokane rivers. Settlements concentrated in the vicinity of Walla Walla, close to the moister Blue Mountains, and at Spokane, owing to the availability of water power. Through artificial irrigation, agriculture began to flourish in the Yakima, Kittitas, Pasco, Walla Walla, and Wenatchee valleys during the final decade of the 19th century. Dry land farming of grain has thrived in the Palouse and the Waterville plateau areas. Much of the development of the central plateau, however, waited until after World War II when major irrigation brought by the Columbia Basin Project permitted it to become a truly commercial agricultural entity. The construction of large hydropower dams along the Columbia River and its major tributary, the Snake River, provided the basis for much of the 20th century commercial development in the state. Most of the dams lie within the plateau area or along its margins. In addition to the geological problems involved in the construction of these dams and the Columbia Basin Irrigation Project, numerous ground-water problems have become a matter of study in recent years, both on the upland plateau and in the Pasco Basin, the latter as a result of various nuclear and engineering projects on the Hanford Reservation. Slope stability problems are locally acute around the plateau periphery, where the lavas are intercalated with sediments, and in the post-basalt sediments of the various basins within the Yakima Fold Belt. In recent years, the seismic potential of the western plateau has come under increased scrutiny owing to activities on the Hanford Reservation and increased interest in dam safety.

Okanogan-Selkirk Highlands

A band of ancient, rounded mountains, which range in elevation between 5,000 and 8,000 ft, spans the northeastern part of the state between the Northern Rocky Mountains and the North Cascade Range. They are the southern part of a highland belt that extends northward into British Columbia. A large part of the province is characterized by an extensive belt of granitic crystalline and metamorphic rocks. They are flanked on the east by a thick section of Precambrian to Mesozoic sediments. The crystalline character of the province is interrupted by two north-south-trending sedimentary belts or subprovinces: the Republic graben, which bisects the province and contains a suite of Tertiary volcanic rocks, sediments, and small granitic intrusions; and the intensely folded Permian/Triassic volcanic and sedimentary rocks astride the Okanogan Valley in the western portion of the province. Nearly all of the province, except for a few of the highest peaks, was exposed to Pleistocene continental glaciation so that and many areas within the province are mantled by varied thicknesses of glacial debris. Three major river valleys traverse the province: the Okanogan and Columbia, which flow south, and the Pend Oreille, which flows north (into the Columbia). Glaciofluvial terraces are well developed in these valleys as well as along the Columbia River valley along the highland's southern margin. The highlands support a varied open forest.

Early commercial development in the highlands centered around metal mining, which began during the last two decades of the 19th century and has continued to the present time. Agriculture is restricted to the major valleys and to irrigated parts of some extensive glacial terraces. A modest timber industry is supported by the forested uplands. Most of the geological problems of province center on availability of ground water, flooding in the major river valleys, and slope stability, especially along the Columbia valley. Mine wastes have also attracted considerable study.

Peripheral Provinces

The southeastern corner of the Georgia Depression, a major feature of western British Columbia, extends into northwestern Washington in the form of a broad lowland plain underlain largely by glacial drift and glaciomarine deposits. Principal development has been agricultural, both on the gentle topography of the drift plain and in the shallow alluvial valleys of the Nooksack and Sumas rivers. The proximity of deep water in the adjacent Georgia Strait has led to more recent development of oil port facilities. The few natural harbors, however, are shallow owing to extensive post-glacial infilling from rivers draining into the area from the North Cascades. The geologic problems of this segment of the Georgia Depression are similar to those of the Puget Sound Basin summarized earlier.

Although the bedrock geology of the northern Olympic Range is similar to that of the southern tip of Vancouver Island, separation of these terrains by the Strait of Juan de Fuca requires a separate geologic province from the vantage point of the engineering geologist. The Juan de Fuca Trough is underlain by more than 2,000 ft of Quaternary marine and glacial sediments beneath as much as 100 fathoms of tidal waters, requiring an investigative approach totally different from that for any other province except Puget Sound, which has similar characteristics. While most of the engineering activity has historically involved the periphery of the province, recent efforts to construct undersea pipelines and the oil-spill potential have increased the interest of the engineering geology community in this province.

Two important geologic provinces in Oregon protrude slightly into Washington. The Willamette Lowland, which occupies a prominent position between the Cascade and Coast ranges, includes much of western Clark County. The area is characterized by Quaternary stream terrace and lake deposits underlain by latest Tertiary continental sediments, all of which influence the urbanization of the Vancouver area and the availability of ground water. While Pliocene/Pleistocene volcanic rocks common to the Portland region south of the Columbia River are found along the eastern margin of the province in Washington and provide an important source of rock for construction, they do not dominate the lowland north of the river.

The Blue Mountains protrude into the southeastern corner of the state, forming the forested hills south of Walla Walla. Though underlain entirely by the Columbia River basalt dipping northwest off the more extensive Blue Mountain anticline, the province in Oregon exposes a core of more exotic pre-Tertiary volcanic and sedimentary rocks. It is, therefore, usually considered a province separate from the Columbia Plateau even though the lavas of that province extend over the top of parts of the mountains and have most recently been gently deformed with it. The importance of the province in Washington, from an engineering geology standpoint, is its influence on the ground water beneath the Walla Walla basin (Newcomb, 1961).

REFERENCES CITED* AND ADDITIONAL REFERENCES

*Baker, V. A., 1973, *Paleohydrology and Sedimentology of Lake Missoula Flooding in Eastern Washington*: Geological Society of America, Special Publication 144, Boulder, CO, 79 p.

*Barksdale, J. D., 1974, *Geology at the University of Washington, 1895-1973*: University of Washington Publications in Geological Sciences No. 4, Seattle, WA, 109 p.

*Bennison, A. P.; Renfro, H. B.; and Feray, D. E., 1973, *Geological Highway Map of the Pacific Northwest Region*: American Association of Petroleum Geologists, Tulsa, OK, 1 sheet.

*Bretz, J H., 1923, The channeled scablands of the Columbia Plateau: *Journal of Geology*, Vol. 31, No. 8, pp. 617-649.

*Bretz, J H.; Smith, H. T. U.; and Neff, G. E., 1956, Channeled scabland of Washington–New data and interpretations: *Geological Society of America Bulletin*, Vol. 67, pp. 957-1049.

*Burwell, E. B. and Moneymaker, B. C., 1950, Geology in dam construction, in Paige, S. (editor), *Application of Geology to Engineering Practice*: Geological Society of America, Boulder, CO, pp. 11-43.

*Galster, R. W., 1982, A history of the Association of Engineering Geologists: *Bulletin Association of Engineering Geologists*, Vol. 19, No. 3, pp. 207-249.

*Hall, J. B. and Othberg, K. L., 1974, *Thickness of Unconsolidated Sediments, Puget Lowland, Washington*: Washington Division of Geology and Earth Resources Geologic Map GM-12, Olympia, WA, 3 p., 1 sheet, scale 1:125,000.

Hammond, P. E., 1980, *Reconnaissance Geologic Map and Cross Sections of Southern Washington Cascade Range*: Publications of the Department of Earth Sciences, Portland State University, Portland, OR, 31 p., 2 sheets.

Huntting, M. T.; Bennett, W. A. G.; Livingston, V. E., Jr.; and Moen, W. S., 1961, *Geologic Map of Washington*: Washington Division of Mines and Geology, Olympia, WA, 2 sheets, scale 1:500,000.

*Mackin, J. H., 1941, *A Geologic Interpretation of the Failure of the Cedar Reservoir, Washington*: University of Washington, Engineering Experiment Station Series, Bulletin No. 107, Seattle, WA, 30 p.

McKee, B., 1972, *Cascadia*: McGraw-Hill, Inc., New York, NY, 394 p.

Misch, P., 1966, Tectonic evaluation of the Northern Cascades of Washington State, in *A Symposium on the Tectonic History and Mineral Deposits of the Western Cordillera*, Vancouver, B.C., 1964: Canadian Institute of Mining and Metallurgy, Special Vol. 8, Montreal, PQ, Canada, pp. 101-148.

*Neff, G. E., 1986, Personal communication, Consulting Geologist, Ephrata, WA.

*Newcomb, R. C., 1961, *Storage of Ground Water Behind Subsurface Dams in the Columbia River Basalt, Washington, Oregon, and Idaho*: U.S. Geological Survey Professional Paper 383-A, pp. A1-A15.

*Raisz, E., 1945, The Olympic-Wallowa lineament: *American Journal of Science*, Vol. 243A, pp. 479-485.

*Tabor, R. W. and Cady, W. M., 1978, *Geologic Map of the Olympic Peninsula, Washington*: U.S. Geological Survey Miscellaneous Investigations Series Map I-994, 2 sheets, scale 1:125,000.

*Yount, J. C.; Danbroff, G. R.; and Barats, G. M., 1985, *Map Showing Depth to Bedrock in the Seattle 30' x 60' Quadrangle, Washington*: U.S. Geological Survey Miscellaneous Field Studies Map MF-1692, 1 sheet, scale 1:100,000.

Note – For definitions of technical terms used in these volumes, the reader is referred to the following:

GENERAL REFERENCES

American Society for Testing and Materials, Committee E-8 on Nomenclature and Definitions, 1973, Glossary of ASTM Definitions [2d ed.]: American Society for Testing and Materials, Philadelphia, PA, 540 p.

Bates, R. L. and Jackson, J. A., 1987, Glossary of Geology [3d ed.]: American Geological Institute, 788 p.

Finke, C. W. (editor), 1984, The Encyclopedia of Applied Geology: Van Nostrand Reinhold Co., New York, NY, 832 p.

[McGraw-Hill editors], 1988, McGraw-Hill Dictionary of Scientific and Technical Terms [4th ed.]: McGraw Hill, New York, NY, 2,100 p.

Somerville, S. H. and Paul, M. A., 1983, Dictionary of Geotecnics: Butterworths, Stoneham, ME, 283 p.

Thrush, P. W., and Staff Members, U.S. Bureau of Mines, 1968, A Dictionary of Mining, Mineral, and Related Terms: U.S. Department of the Interior, 1,269 p.

Vollmer, E., 1967, Encyclopedia of Hydraulics, Soil and Foundation Engineering: Elsevier Publishing Co., New York, NY, 398 p.

Part I: Engineering Geology and its Practice in Washington

Geologic Factors Affecting Engineered Facilities

Richard W. Galster, Chapter Editor

Geologic Factors Affecting Engineered Facilities: Introduction

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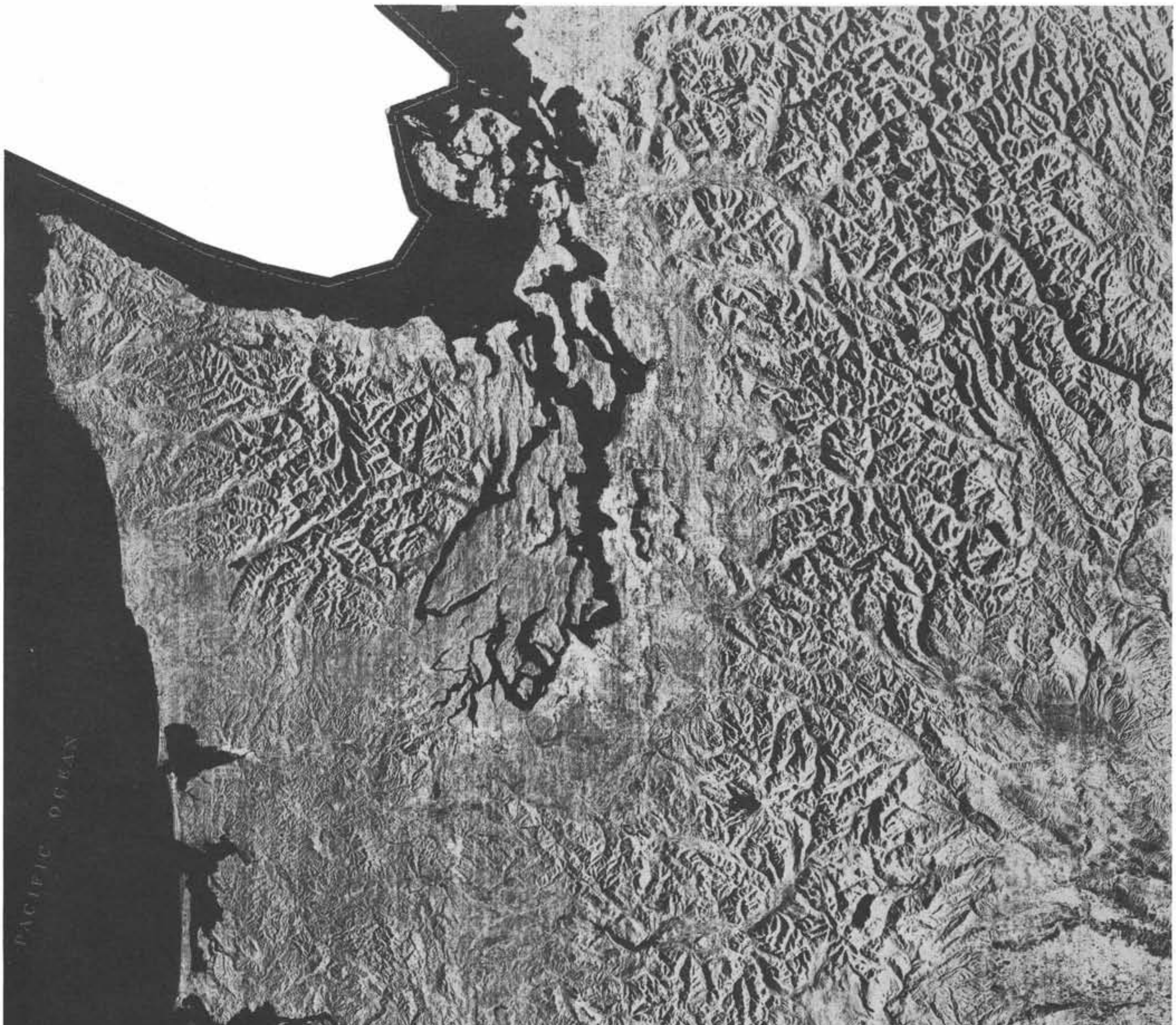
The geologic processes that have fashioned the present topography of the state's various geologic provinces are, in some places, continuing. In other places they have been replaced by different geologic processes. Areas of the Puget Sound Basin, where the primary topography was created by the continental glaciation ending some 12,000 yr ago, are now being modified by streams, coastal erosion, and landsliding. The gentle hill country of southwestern Washington continues to be modified by deep weathering and stream erosion. The mountainous areas of the state are modified by stream erosion, rockslide, and landslide, and, to some extent, glacial activity. The arid Columbia Plateau, no longer subjected to the catastrophic flooding of the glacial period, is slowly being modified by wind erosion, the activity of intermittent streams, and freezing and thawing. Other than erosional and depositional activity adjacent to the Columbia River and other major streams, the plateau has been little modified since the end of the glaciation.

Modification of the landscape by deposition is also important, especially on alluvial plains, certain coastal areas, and adjacent to active volcanic areas. The events of May 18, 1980, at Mount St. Helens attest to such modification most dynamically.

The application of the past and present geologic processes in the geologic setting and the influence of these processes on the design, construction, and operation of the works of man are the basis for engineering geology. In one form or another, all geologic factors influence our habitation of the planet. From an engineering viewpoint, however, some are more important than others.

The term "geologic hazards" has worked its way into both the technical and lay literature, sometimes in the sense of a horrible specter or black cloud hanging over mankind. These so-called hazards are nothing more than normal geologic processes with which we must learn to live—by understanding the processes and working with them instead of fighting them. During the past half-century we have progressed far in understanding the properties of geologic materials, both soil and rock, but we sometimes tend to forget the ongoing geologic processes until a major happening—earthquake, flood, landslide, or volcanic eruption—causes damage to our engineered (and unengineered) works. Many of the problems of these hazards, if not all, can be mitigated by a combination of education and regulation. The papers that follow will perhaps contribute to the former. With education and understanding, appropriate regulation may follow.



Side looking airborne radar (SLAR) image of western Washington; west-looking image compiled by MARS, Inc., Phoenix, AZ and reduced from the original 1:250,000-scale mosaic. Image courtesy of the Seattle District, U.S. Army Corps of Engineers.

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Geotechnical Properties of Geologic Materials

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INTRODUCTION

Engineering geologists and geotechnical engineers are an integral part of the design team for virtually all modern engineering projects that involve site characterization and geotechnical design. Evaluation of alternative project sites or specific site selection usually requires data collection, analysis, and explanation of physical site conditions to other members of a project design team. Because of the need to develop a mutual understanding of geologic conditions and the resulting implications for design criteria, a common understanding of the relations between geologic origin and geotechnical properties is essential. It is imperative that the geologist and engineer work in close cooperation to assure the best product quality.

Traditionally, the geologist's role has focused on identification of the geologic origin and distribution of earth materials. This includes both physical classification and interpretation of the processes of emplacement and modification. The product of a geologist's work within a project design team is often primarily qualitative, usually a map with appropriate descriptions. Such data must be translated into a quantitative form usable in engineering analysis and in design development and evaluation. The translation and quantification of geologic data for engineering purposes occur over a wide range of scales. Discussion of the distribution of geologic materials and processes commonly involves a megascopic scale of feet or miles, while many engineering properties are discussed in microscopic context. A mutual understanding of terms, units, and properties is essential for geologists and engineers to communicate effectively.

This paper relates the geologic characteristics and origin of earth materials commonly found in Washington to certain geotechnical properties. In Tables 1 through 4 descriptive and interpretive properties of soil and rock materials are correlated with their genetic classification.

The information presented in the tables is useful to indicate the general range of values for typical geotechnical properties, but it is no substitute for site-specific laboratory and field information. The tables will be of some direct benefit to students and to geotechnical professionals who are new to the Pacific Northwest; for those with local experience, they will serve mainly as a basis for ongoing argument.

The properties indicated in the tables are those most relevant to geotechnical considerations. The values presented in the tables are based on a compilation of published and unpublished information and do not represent original research. These data have been compiled from field and laboratory tests performed over many years by engineers, geologists, and geophysicists in both the government and private sectors.

Because of the extremely varied nature of geologic materials, the ranges presented in the tables should be considered representative, but not necessarily inclusive of extremes. Where ranges are indicated, we estimate that roughly two-thirds of field or laboratory observations will fall within the indicated ranges. Some geologic categories are not described in the tables; for example, the tables include no discussion of fill materials or landslide deposits because it is the writers' opinion that these materials are too varied to be meaningfully included. Not all pertinent geotechnical properties are listed, and some engineering projects will require information about properties not included in the tables. A design team collectively must evaluate what geological conditions might affect, or be affected by, an engineering project.

DESCRIPTION OF TABLES

Tables 1 through 4 include summaries of descriptive and interpretive properties of soil and rock. The vertical organization of the tables is based on the genetic classification of the materials; descriptive and interpretive properties of general interest for engineering considerations are presented in the horizontal (column) headings. Unified Soil Classification System (USCS) symbols are shown for soil materials, and Unified Rock Classification System (URCS) symbols are indicated for rock

Table 1. Descriptive properties of soil; see Table 5 for classification

Classification: Geologic	Classification: USCS	Grain size	Sorting	Dry density (pcf)	Friction angle (deg)	Cohesion (psf)	Permeability (fpm)	Storage capacity	Seismic velocity (fps x 1000)	Resistivity (ohm-m x 1000)
ALLUVIAL										
High Energy	GW,GP,GM	Med-Coarse	Med-Good	115-130	30-35	0	0.01-10	0.1-0.3 5-7.5 wet	1.5-5 dry 0.2-20 wet	0.3-30 dry
Low Energy	ML,SM,SP, SW	Fine-Med	Med-Good	90-115	15-30	0-500	0.0001-0.1 3.5-6 wet	0.05-0.2 0.001-1 wet	1-4 dry	0.01-10 dry
COLLUVIAL	. . . . Variable . . . . Reflects parent material									
EOLIAN										
Dune Sand	SP	Medium	Very good	90-110	30-35	0	0.01-0.1	0.1-0.3	1-2.5	0.5-100
Loess	ML,SM	Fine	Med-Good	80-100	20-30	500-1000	0.001-0.01	0.05-0.1	0.75-2.5	0.01-2
GLACIAL										
Till	SM,ML	Fine-Med	Poor	120-140	35-45	1000-4000	0-0.001	0-0.01	3.5-10	0.01-5
Outwash	GW,GP,SW, SP,SM	Med-Coarse	Poor-Good	115-130	30-40	0-1000	0.01-10	0.01-0.3 5-8.5 wet	4-6 dry 0.1-5 wet	0.2-10 dry
Glacio-lacustrine	ML,SM,SP	Fine-Med	Good	100-120	15-35	0-3000	0-0.1	0-0.1	2.5-8.5	0.001-2
LACUSTRINE										
Inorganic	ML,SM,MH	Fine	Good	70-100	5-20	0-200	0.0001-0.1	0.05-0.3	1-2.5	0.001-0.5
Organic	OL,PT	Fine-Med	Poor-Good	10-70	0-10	0-200	0.0001-1	0.05-0.8	0.5-1.5	0.001-0.5
MARINE										
High Energy	SW,GW,SP	Med-Coarse	Med-Good	115-130	25-35	0	0.001-1	0.1-0.3	5-6	0-2
Low Energy	ML,SM,MH	Fine-Med	Med-Good	70-115	0-25	0-200	0.0001-0.1	0.05-0.3	2.5-5	0-.05
RESIDUAL	. . . . Variable . . . . Reflects parent material									
VOLCANIC										
Tephra	ML,SM	Fine-Med	Poor-Good	80-120	20-35	0-1000	0.0001-0.1	0.05-0.2	0.5-6	0.5-100
Lahar	SM,SW,GM	Fine-Coarse	Poor	80-130	25-40	0-1000	0.001-0.1	0.05-0.2	3.5-9	0.01-5

Table 2. Interpretive properties of soil; see Table 5 for classification

Classification		Relative erodibility	Excavation difficulty	Moisture sensitivity	Foundation support (psf)	Cut slopes (%)	Seismic hazards	Common uses
Geologic	USCS							
ALLUVIAL								
High Energy	GW,GP,GM	Low	Low	Low	1500-2000	50-65	Low-Med	Aggregate, Fill
Low Energy	ML,SM,SP, SW	Med-High	Low	Med-High	500-1500	25-50	Med-High	Fill
COLLUVIAL	. . . .	Variable			Reflects parent material			
EOLIAN								
Dune Sand	SP	High	Low	Low	500-1000	20-30	Low-Med	Fill, Industrial
Loess	ML,SM	Very high	Low	High	500-1000	25-50	Low-Med	
GLACIAL								
Till	SM,ML	Low-Med	Med-High	High	1500-5000	50-100	Low	Fill
Outwash	GW,GP,SW, SP,SM	Low-Med	Low-Med	Low-Med	1500-3000	50-70	Low	Aggregate, Fill
Glaciolacustrine	ML,SM,SP	Med-High	Med	High	1000-2000	25-50	Med-High	Fill, Industrial
LACUSTRINE	ML,SM,MH, OL,PT	High	Low	High	0-500	0-25	High	PT: Soil additive
MARINE								
High Energy	SW,GW,SP	Medium	Low	Low	1000-2000	25-60	Low-Med	Fill
Low Energy	ML,SM,MH	High	Low	Med-High	0-500	0-25	High	Fill
RESIDUAL	. . . .	Variable			Reflects parent material			
VOLCANIC								
Tephra	ML,SM	Low-High	Low	Low-High	500-1500	20-50	Low-Med	Fill, Industrial
Lahar	SM,GM	Med-High	Low-Med	Low-High	500-1500	25-50	Low-Med	Fill

Table 3. Descriptive properties of rock; see Table 6 for classification

Classification: Geologic	Classification: URCS	Density (pcf)	Compressive strength (kpsi = psi x 1000)	Discontinuities	Permeability	Storage capacity	Seismic velocity (kft/s = x 1000)	Resistivity (kohm-m = ohm-m x 1000)
IGNEOUS								
Intrusive	OAAA-OCEB	150-200	3-30	Joints	Low	Low	12-20	0.5-20
Extrusive	OAAA-ODEE	120-200	1-30	Joints, Flow Features, Voids	Low-High	Low-High	6-18	0.01-5
METAMORPHIC								
High Grade	OAAA-OCED	150-200	3-25	Joints, Foliation	Low	Low	12-20	0.05-20
Low Grade	OBAA-OEEE	150-200	0.5-15	Joints, Foliation	Low	Low	2.5-14	0.001-10
SEDIMENTARY								
Clastic	OBCC-OEEE	130-150	1-15	Joints, Bedding	Low-Med	Low-Med	5-14	0.001-10
Chemical	OBCB-ODEC	140-160	2-15	Joints, Bedding, Voids	Low-High	Low	4-15	0.05-50
Organic	OCCD-ODEE	80-100	0.5-5	Joints, Bedding, Voids	Low-Med	Low	1.5-5.5	0.05-1

Table 4. Interpretive properties of rock; see Table 6 for classification

Classification: Geologic	Classification: URCS	Excavation difficulty	Resistance to weathering	Foundation support	Stability in cuts	Common uses
IGNEOUS						
Intrusive	OAAA-OCEB	High	High	Good	Good	Riprap, Aggregate, Building stone
Extrusive	OAAA-ODEE	Med-High	Med-High	Usually Good	Med-Good	Riprap, Aggregate, Building stone
METAMORPHIC						
High Grade	OAAA-OCED	High	High	Good	Good	Riprap, Aggregate, Building stone, Industrial
Low Grade	OBAA-OEEE	Low-High	Low-Med	Usually Good	Poor-Good	Fill
SEDIMENTARY						
Clastic	OBCC-OEEE	Low-High	Low-Med	Usually Good	Poor-Good	Building stone, Industrial
Chemical	OBCB-ODEC	Med-High	Low-High	Usually Good	Poor-Good	Riprap, Aggregate, Industrial, Building stone
Organic	OCCD-ODEE	Low-Med	Low	Poor	Poor	Fuel

materials. These classification systems are summarized in Tables 5 and 6. A generalized explanation of terms is presented below, but it is not intended to rigorously define either the geologic categories or the geotechnical properties.

EXPLANATION OF TERMS

Soils

- Alluvial: Sediment deposited by streams.
  - High Energy: Generally coarse sediment such as coarse sand, gravel, cobbles, and boulders deposited by fast-moving water.
  - Low Energy: Generally fine-grained soil such as fine sand and silt deposited by slow-moving water.
- Colluvial: Generally heterogeneous soil aggregates transported and deposited by mass wasting processes such as landslides, rockfalls, and avalanches.
- Eolian: Sediment transported and deposited by wind.
  - Dune Sand: Sand-size sediment; typically deposited in dune forms.
  - Loess: Fine-grained sediment; generally fine sand and silt.
- Glacial: Material deposited by or in association with glaciers.
  - Till: Heterogeneous mixture of various particle sizes deposited directly by glacial ice.
  - Outwash: Sediment deposited by high-energy glacial meltwaters.
  - Glaciolacustrine: Sediment deposited in low-energy ice-marginal lake environments.
- Lacustrine: Sediment deposited in lakes.
  - Nonorganic: Sediment composed primarily of silt, sand, and clay.
  - Organic: Peat and other predominantly organic sediment.
- Marine: Sediment deposited in a marine environment.
  - High Energy: Generally coarse-grained material, such as gravel and sand deposited by strong waves or currents.
  - Low Energy: Generally fine-grained material, such as silt and sand.
- Residual: Soil developed in place as the result of weathering or chemical decomposition of parent material.

Table 5. Unified Soil Classification System; from American Society for Testing and Materials, 1985

MAJOR DIVISIONS			GROUP SYMBOL	GROUP NAME
COARSE GRAINED SOILS MORE THAN 50% RETAINED ON NO. 200 SIEVE	GRAVEL MORE THAN 50% OF COARSE FRACTION RETAINED ON NO. 4 SIEVE	CLEAN GRAVEL	GW	WELL-GRADED GRAVEL, FINE TO COARSE GRAVEL
			GP	POORLY-GRADED GRAVEL
		GRAVEL WITH FINES	GM	SILTY GRAVEL
			GC	CLAYEY GRAVEL
	SAND MORE THAN 50% OF COARSE FRACTION PASSES NO. 4 SIEVE	CLEAN SAND	SW	WELL-GRADED SAND, FINE TO COARSE SAND
			SP	POORLY-GRADED SAND
		SAND WITH FINES	SM	SILTY SAND
			SC	CLAYEY SAND
FINE GRAINED SOILS MORE THAN 50% PASSES NO. 200 SIEVE	SILT AND CLAY LIQUID LIMIT LESS THAN 50	INORGANIC	ML	SILT
			CL	CLAY
		ORGANIC	OL	ORGANIC SILT, ORGANIC CLAY
	SILT AND CLAY LIQUID LIMIT 50 OR MORE	INORGANIC	MH	SILT OF HIGH PLASTICITY, ELASTIC SILT
			CH	CLAY OF HIGH PLASTICITY, FAT CLAY
		ORGANIC	OH	ORGANIC CLAY, ORGANIC SILT
HIGHLY ORGANIC SOILS			PT	PEAT

Table 6. Unified Rock Classification System

UNIFIED ROCK CLASSIFICATION SYSTEM					
DEGREE OF WEATHERING	REPRESENTATIVE		A	Micro Fresh State (MFS)	
			B	Visually Fresh State (VFS)	
	ALTERED		C	Stained State (STS)	
	WEATHERED	> GRAVEL SIZE	D	Partly Decomposed State (PDS)	
		< SAND SIZE	E	Completely Decomposed State (CDS)	
ESTIMATED STRENGTH	REACTION TO IMPACT OF 1 LB. BALLPEEN HAMMER		A	"Rebounds" (Elastic) (RQ)	>15000 psi[2] >103 MPa
			B	"Pits" (Tensional) (PQ)	8000–15000 psi[2] 55–103 MPa
			C	"Dents" (Compression) (DQ)	3000–8000 psi[2] 21–55 MPa
			D	"Craters" (Shears) (CQ)	1000–3000 psi[2] 7–21 MPa
	REMOLDING[1]		E	"Moldable" (Friable) (MQ)	<1000 psi[2] <7 MPa
DISCONTINUITIES	VERY LOW PERMEABILITY		A	Solid (Random Breakage) (SRB)	
			B	Solid (Preferred Breakage) (SPB)	
			C	Solid (Latent Planes Of Separation) (LPS)	
	MAY TRANSMIT WATER		D	Nonintersecting Open Planes (2-D)	
			E	Intersecting Open Planes (3-D)	
UNIT WEIGHT			A	Greater Than 160 pcf 2.55 g/cc	
			B	150–160 pcf 2.40–2.55 g/cc	
			C	140–150 pcf 2.25–2.40 g/cc	
			D	130–140 pcf 2.10–2.25 g/cc	
			E	Less Than 130 pcf 2.10 g/cc	

(1) Strength Estimated by Soil Mechanics Techniques

(2) Approximate Unconfined Compressive Strength

SYMBOL NOTATION: AAAA — Weathering, Strength, Discontinuity, Weight

Reference: Williamson (1984)

Note: "0" is used as a position holder

- Volcanic: Deposits derived from volcanoes or other eruptive sources.
  - Tephra: Airborne volcanic ejecta, such as volcanic bombs, cinders, and ash.
  - Lahar: Mudflow composed largely of volcanic debris, or having primarily a volcanic origin.

Bedrock

- Igneous: Rock formed by solidification from a molten state.
  - Intrusive: Rock, such as granite, that solidified from a molten state below the ground surface.
  - Extrusive: Rock, such as basalt, that solidified after reaching the ground surface.
- Metamorphic: Rock derived from pre-existing rock by mineralogical and textural changes.
  - High Grade: Metamorphic rock that has little resemblance to the original parent rock type.
  - Low Grade: Metamorphic rock that is similar to the original parent rock type.
- Sedimentary: Rock deposited as sediment and subsequently lithified.
  - Clastic: Rock, such as shale, sandstone, and conglomerate, formed from fragments of pre-existing rocks.
  - Chemical: Rock, such as limestone, formed by chemical precipitation.
  - Organic: Rock, such as coal, formed largely or exclusively from organic material.

Descriptive Properties

- *USCS*: Unified Soil Classification System (American Society for Testing and Materials, 1985, D 2487).
- *URCS*: Unified Rock Classification System (Williamson, 1984).
- *Grain Size*: The general category of particle sizes corresponding to terms used in the USCS.
- *Sorting*: Segregation by grain sizes. "Poor" means a wide range of grain sizes, such as silty sandy gravel; "good" means a narrow range of grain sizes, such as sand. No specific percentages are implied.
- *Dry Density*: Dry weight in pounds per cubic foot.
- *Friction Angle*: Angle of internal shearing resistance (Φ) expressed in degrees.
- *Cohesion*: That part of the shear strength of soil or rock which does not depend on interparticle friction.
- *Permeability* (Hydraulic Conductivity): The ease with which water will move through soil interstices, expressed in feet per minute. For rock, variation is so great that it is expressed in the tables in dimensionless relative terms only. Negligible permeability is expressed as 0.
- *Storage Capacity* (Specific Yield): The volume of water that will drain from a unit volume of an unconfined aquifer.
- *Seismic Velocity*: Compressional seismic wave velocity in thousands of feet per second.
- *Resistivity*: Electrical resistance to direct current expressed in terms of thousands of ohm-meters.
- *Compressive Strength*: Load per unit area under which an unconfined block of rock fails (unconfined compressive strength), expressed in pounds per square inch.
- *Discontinuities*: Surfaces or voids that interrupt otherwise homogeneous rock masses.

Interpretive Properties

- *Relative Erodibility*: Susceptibility to erosion in terms of sediment yield per unit area.
- *Excavation Difficulty*: The relative difficulty of excavation by heavy equipment.
- *Moisture Sensitivity*: Susceptibility to significant changes in physical properties due to changes in water content. In general, sensitivity increases with increasing silt or clay content.
- *Foundation Support*: Typical allowable bearing value for shallow spread foundations, expressed in pounds per square foot. Assumes conventional cast-in-place concrete footings with embedment adequate for frost protection. Expressed in dimensionless relative terms only for rock.
- *Cut Slopes* (Soil): Typical maximum inclination for permanent cut slopes less than 15 ft in height. Assumes no destabilizing factors such as adverse structural/stratigraphic or ground-water conditions.
- *Stability in Cut Slopes* (Rock): Relative stability of permanent cut slopes. Assumes no destabilizing factors such as adverse structural/stratigraphic or ground-water conditions.
- *Seismic Hazards*: Relative association with earthquake-induced damage.
- *Common Uses*: Typical applications of economic importance.
- *Resistance to Weathering*: Relative resistance to mechanical or chemical deterioration.

DISCUSSION

Descriptive Properties

- The Unified Soil Classification System (USCS) does not recognize particles larger than 3 in. in diameter. Common usage extends it to materials including cobbles (3-12 in.) and boulders (greater than 12 in.).
- Cohesion is the result of soil structure and/or cementation. Some finite cohesion is generally present in loess due to its unique granular structure and the common occurrence of minor cementation. Cohesion in till is a result of ice consolidation and a wide range of particle sizes, including a significant fraction of silt.
- Permeability differences reflect variations in gradation between geologic materials. Very high permeability is associated with high-energy alluvial deposits or glacial outwash where coarse, open-work gravel is common. Permeability in these deposits can vary greatly over short horizontal and vertical distances. Extremely low permeability is associated with poorly to moderately sorted materials that are ice-consolidated and contain a substantial fraction of silt and clay.
- Storage capacity reflects the volume of void space and the content of silt or clay within a soil deposit. Storage capacity is very small for poorly sorted or ice-consolidated, fine-grained materials such as till and glaciolacustrine deposits.
- Seismic velocities in soil can be affected by water content. Coarse-grained soils display significantly higher velocities when water-saturated. Less velocity increase is associated with finer grained soils. The electrical resistivity of soil and rock decreases with water content. Geophysical values are differentiated between wet and dry conditions where differences are significant and data are available.

Interpretive Properties

- Erodibility is closely related to slope, vegetative cover, water concentration, and numerous other factors in addition to geologic characteristics.
- Excavation difficulty is discussed in more detail in handbooks published by Caterpillar, Inc. (1987a, b). Note that the table entries for this category refer to unrestricted excavation. Restricted excavations such as trenches are normally more difficult than open cuts. Substantial variations from the indicated values should be expected on the basis of site-specific factors.
- Satisfactory foundation performance includes consideration of numerous factors in addition to the indicated bearing values. These factors include settlement performance, general stability, and effects of and on adjacent manmade or natural features.
- The design of safe cut slopes must consider site-specific details of soil and water conditions and their relation to risk. For example, a maintenance risk is much less significant than a life-threatening risk. Therefore, rather than relying on physical properties, slope design will commonly be dictated by risk.
- Seismic hazards can be manifested in the form of ground shaking, liquefaction, ground rupture or displacement (for example, landslides induced by seismic shaking). The extent to which the indicated geologic classifications are associated with seismic hazards is expressed in relative terms.
- Moisture sensitivity varies considerably within each geologic classification. For example, low-energy alluvial deposits characterized by clean, free-draining sand are not particularly sensitive to moisture, whereas low-energy alluvial soils containing a substantial fraction of silt are extremely sensitive to moisture. Although not included as a specific interpretive category for rock, moisture sensitivity can also be important. The moisture sensitivity of rock is generally proportional to the amount of clay or silt produced by mechanical or chemical decomposition.

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REFERENCES

American Society for Testing and Materials, 1985, D 2487-83, Classification of Soils for Engineering Purposes: *Annual Book of ASTM Standards*, Vol. 04.08, pp. 395-408.

Caterpillar Inc., 1987a, *Caterpillar Performance Handbook*, Edition 18: Caterpillar Inc., Peoria, IL, 768 p.

Caterpillar Inc., 1987b, *Caterpillar Performance Handbook, Hydraulic Excavators*: Caterpillar Inc., Peoria, IL, 176 p.

Williamson, D. A., 1984, Unified Rock Classification System: *Bulletin of the Association of Engineering Geologists*, Vol. 21, No. 3, pp. 345-354.

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Natural Construction Materials

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INTRODUCTION

Construction operations create large demands for bulk, nonmetallic, mineral materials. Every time a bridge is built, a roadway paved, or a building constructed, large quantities of bulk materials are used, most commonly in the form of stone, sand, and gravel. The demand for these products has resulted in active mining operations of various sizes throughout Washington State. Influences of past glaciations have provided Washington with a unique geologic environment that contains a rich endowment of large, accessible, sand and gravel deposits. Therefore, the primary commodity from surface mining operations in Washington is, collectively, sand and gravel. Crushed and riprap stone is mined in lesser quantities, but it still is in great demand.

This paper is limited to the discussion of production of sand and gravel resources and riprap and crushed stone. Production of building and decorative stone, items once in considerable demand in Washington, has recently declined to relatively insignificant levels. This is primarily due to increased use of uncut stone by builders. For those interested in building stones of Washington, an excellent reference is "Building Stone of Washington" (Moen, 1967).

SAND AND GRAVEL

General

Washington's sand and gravel mining industry directly employs more than 1,200 people in about 230 active gravel mining operations throughout the state (U.S. Bureau of Mines, unpublished 1987 data). Fifty-four percent of the employees work for 27 of the larger sand and gravel producers (or 12 percent of the principal producers). Western Washington, primarily San Juan, Snohomish, King, Pierce, Thurston, Kitsap, Mason, Lewis, and Clark counties, is the location of 23 of these principal producers. King and Pierce counties are the largest producers; 12 of the principal producers are located within these two counties.

Production of sand and gravel is directly related to the construction industry and therefore generally reflects the overall health of the economy of the state (Figure 1). Production peaked in 1979 at 24.3 million short tons mined and a value of about $59.4 million. Following this peak, production fell to about 15.4 million short tons during the economic downturn which bottomed in 1982; at that time the value was near $43.1 million. Production then began increasing once again, and in 1986 there were 26.3 million short tons mined with a value estimated near $76.4 million. The production of sand and gravel is expected to be near record levels at least until 1990 (Bettesworth, 1987).

This record use for sand and gravel resources is due to an increasing population and to several large projects, such as the Interstate Highway 90 construction. However, as the population and demand for sand and gravel increase, a serious supply problem may develop. Many sand and gravel producers are finding that urbanization is limiting expansion of their existing operations by creating adverse zoning and by public demands for minimizing environmental impacts. Additionally, several producers have found that the geology of their land holdings does not concur with their original reserve estimates. This combination of factors results in many producers now realizing that the life expectancy of their present operations is less than 10 yr.

The same urbanization that creates increased demand and encroachment onto existing reserves also creates problems in locating new sources of sand and gravel. Therefore, new sources of developable sand and gravel will most likely be outside these urban areas. The intent of this discussion is to show what constitutes developable sand and gravel mining resources, what has been done to identify sources of sand and gravel, and the current state of the sand and gravel industry in relation to future supplies.

Previous Studies

Studies of sand and gravel deposits in Washington date back to 1918 when John Opperman discussed sand and gravel in the glacial drift in the Puget Sound region. This paper was followed in 1919 by a discussion of resources of sand and gravel for road building in Washington (Leighton, 1919). The Washington State

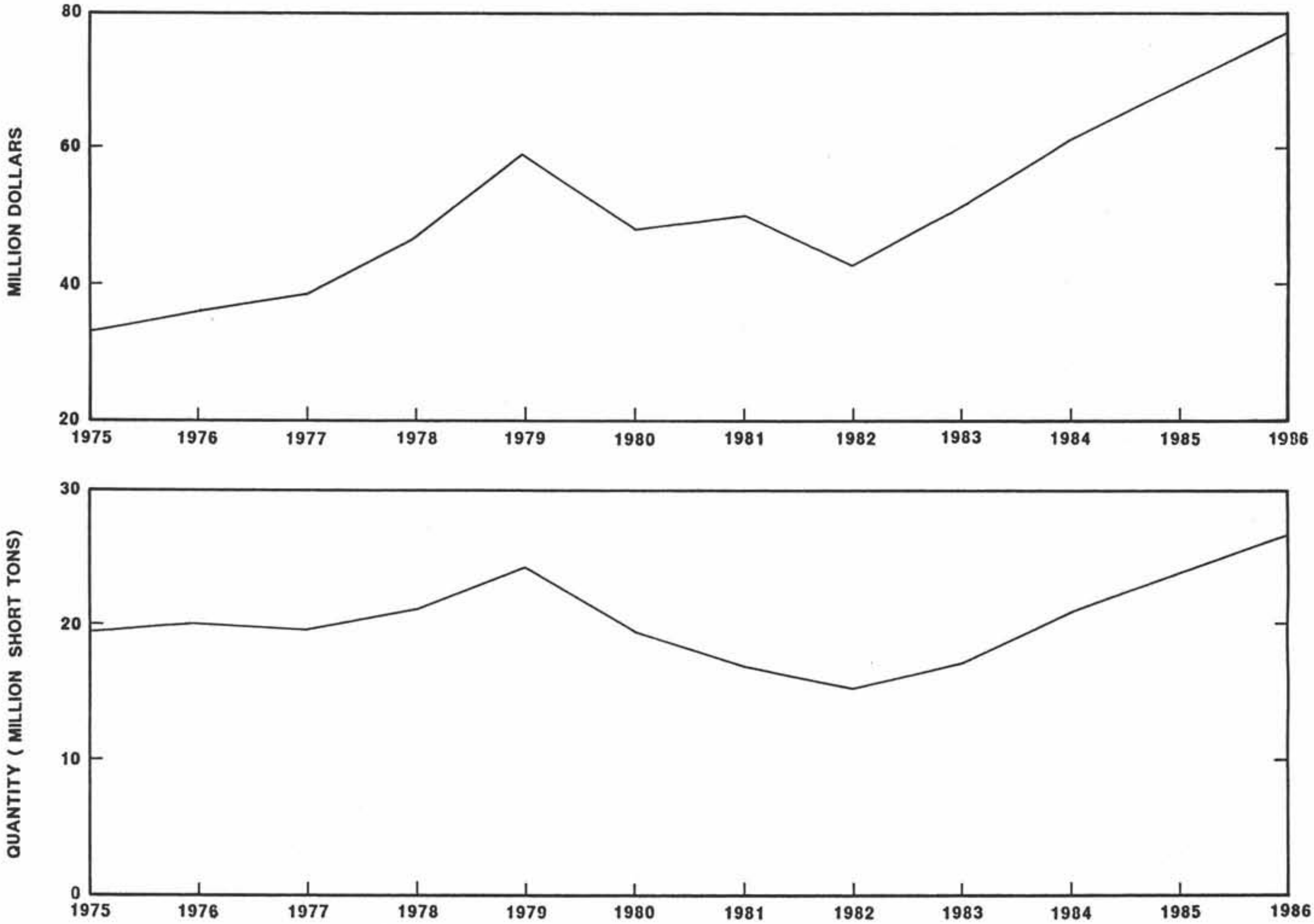

Figure 1. Production values for sand and gravel. From U.S. Bureau of Mines Minerals Yearbook, 1975-1986.

Department of Ecology (WDOE) (1977-1980), in a section of its coastal zone atlases, identified sand and gravel deposits that have marine access. More localized studies were performed for Pierce County (Gence, 1934), King County (Kroft, 1972), Clark County (Fiksdal, 1975), Spokane County (Powers, 1976), and in the Snohomish River basin (Dunne, 1979). There have also been many studies performed for individual gravel companies and land owners. These studies have generally been privileged information and therefore could not be used when considering remaining reserves. However, some of these studies are beginning to be issued in environmental impact statements. As more of the information becomes available, it will provide increased knowledge about actual reserves remaining in the state.

Information in the available public reports is generally outdated relative to current mapping techniques and environmental laws. Also, these reports may give a false sense of remaining reserves. See, for example, the estimate of 3 billion cy of remaining reserves in King County (Kroft, 1972). At the current rate of consumption, such a volume estimate would imply that King County would be able to supply the entire state's needs for the next 200 yr. As will be discussed herein, this estimate is no longer valid.

Economic Gravel Resource Characteristics

For a given sand and gravel deposit to be considered economic, it must have three main characteristics. These are (1) high quality and quantity; (2) good accessibility and proximity to markets; and (3) lack of significant environmental impacts during extraction operations.

Quality and Quantity Considerations

The quality of a deposit is primarily determined by the particle size distribution of the sand and gravel and the percentage of fines (minus 200 sieve size–or silt and clay). Fines are considered detrimental in a sand and gravel deposit primarily because of their adverse effects on the strength, workability, and durability of concrete and asphaltic concrete pavement. Sand and gravel deposits that contain significant percentages of fines and are thus unsuitable for concrete or asphaltic concrete production can in many instances be used as structural fill. However, this use may be limited to emplacement in dry weather because adequate compaction is difficult, if not impossible, to attain when such material is overly wet. Generally, if a deposit contains more than 10 percent fines, or if the deposit contains significant lenses or beds of silt and/or clay, it is precluded from consideration as an economic source of sand and gravel. This is mainly due to the cost of washing the fines out of the sand and gravel (which requires large quantities of water) and the unproductive areas required for settling ponds.

If a particular deposit is anticipated for use in concrete or asphaltic concrete pavement, the size gradation of the sand, as well as the ratio of sand to gravel, become quality considerations. Well-graded sand increases the strength, durability, and workability of the final product. Gap-graded (poorly sorted) sand deposits usually require significant blending, which increases the cost of production and may increase the quantities of waste sand remaining from the dominant grain sizes. Commercially desirable deposits must also contain a significant quantity of gravel-size aggregate. The closer the deposit is to attaining a ratio of 60 percent gravel to 40 percent sand, the less the aggregate needs to be handled and generally the higher the profits realized.

The lithologic and mineralogic properties of the sand and gravel are also important considerations when evaluating the quality of a particular deposit. In Washington, basalt, granite, diorite, gabbro, quartzite, and some andesite are the most durable for use in concrete and asphaltic concrete pavement. Weaker lithologic types are generally derived from Eocene or younger sedimentary rocks, foliated metamorphic rocks, and low-density volcanic rocks. In addition, the older the gravel deposit, the greater the likelihood that the minerals in the granite, diorite, and andesite have weathered to clays. This causes the density of the gravels to be reduced and durability of the final product to be lower, and it may also require additional water in a concrete mixture to maintain workability. If deposits containing these gravels are used, a less desirable final product is usually the result.

Many lithologic types tend to react chemically with the highly alkaline cement component of concrete. Volcanic glass or other cryptocrystalline minerals are considered detrimental in concrete products. Also, the volcanic rock types derived from the large Cascade volcanoes tend to react in concrete. Utmost care should be exercised when using a deposit of sand and gravel that is composed of significant quantities of these rock types.

The final considerations for determining if a deposit is a high-quality sand and gravel resource are the volume of the minable deposit, its overall thickness, and the thickness and characteristics of the overburden. Generally, a sand and gravel producer requires a deposit that has sufficient volume to last longer than 10 yr. Also, whereas many deposits are quite large, their average thickness is less than desirable. Thin deposits require the purchase and zoning of additional acreage and periodic and costly movement of mining equipment. A deposit less than 50 feet thick usually is not economically attractive except to the smallest producers.

The thickness and physical characteristics of the overburden can have significant detrimental economic effects on a particular sand and gravel deposit. Overburden is defined as a deposit containing appreciable fines (minus 200 sieve size or silt and clay) and organic materials. These materials must be scraped off the minable deposit and stockpiled for later use in reclamation of the site. Overburden thickness less than 15 feet is usually desirable. However, if the overburden (excluding organic layers) contains a significant percentage of gravel and overlies an otherwise high-quality sand and gravel deposit, thicker layers of overburden may not be severely detrimental to the overall profitability of the project.

Accessibility and Proximity to Market

A second important characteristic sought when evaluating whether a sand and gravel resource can be economically mined is related to the accessibility of the deposit and its proximity to markets. The need for road building, road upgrading, and bridge building to move pit materials may significantly reduce the economic viability of the deposit. Also, the cost of land hauling (which currently ranges from $0.20 to $0.25 per ton-mile) renders land deposits that are distant from markets potentially uneconomical. In contrast to land hauling, the most economical method of transportation is barging on navigable waterways (approximately $1.50/ton in the southern part of Puget Sound). Considering that the Pacific Northwest's largest markets (Tacoma, Seattle, Everett, and Vancouver, Washington, Portland, Oregon, and Vancouver, British Columbia) all have port facilities, high-quality sand and gravel deposits on or near navigable waterways are those most attractive for profitable mining operations.

Environmental Impacts

The third main characteristic of a high-quality deposit deals with the environmental impacts (real or perceived) of operating a sand and gravel pit. It is almost certain that new permits for sand and gravel extraction will require environmental impact statements. These environmental impact statements will need to address, specifically and in detail, noise, dust, increased truck traffic, visual impacts, drainage (including downstream siltation), possible stream or river degradation (if the proposed operation is in or near an active river channel), and impacts on ground water.

Of the noted potential impacts, noise, dust, and drainage can usually be economically mitigated, if properly identified. Visual impacts can be mitigated if the deposit is large enough or is developed so as to minimize visual impacts. Although potential mining in an active river channel has attractive "renewable resource" characteristics, downstream degradation significantly limits the amount of gravel extraction in these systems. This may consequently limit the economic importance of these deposits or, in sensitive drainage basins, prevent extraction altogether.

Increased truck traffic and potentially adverse impacts on ground water regimes may create environmental concerns that override any economic considerations for a particular sand and gravel mining operation.

Geology of Sand and Gravel Deposits

The vast majority of the sand and gravel mined in Washington is confined to three broad geologic units. These are (1) deposits associated with the advance of ice during the Fraser Glaciation, (2) outwash deposits associated with the recession or maximum stands of ice of the Fraser Glaciation, and (3) Recent or historic river deposits. Older glacial deposits are also locally mined. However, owing to reduction of particle quality by weathering, the use of this aggregate is usually limited to borrow sources for non-structural fill.

Advance deposits of the Vashon Stade of the Fraser Glaciation are currently being mined for use as concrete and asphaltic concrete pavement aggregate near Everett and near Tacoma. In both locations, the overlying till unit (overburden) is relatively thin and is underlain by a thick sequence of high-quality, deltaic deposits of sand and gravel. Also of economic consideration, the till unit in these areas contains less silt and clay than does typical till throughout the Puget Lowland.

Vashon recessional or ice-maximum outwash sand and gravel deposits and glacial-lake flood deposits (in eastern Washington) are the most important geologic units in terms of economic considerations and of total volume previously excavated and currently being extracted in the State of Washington. These outwash deposits can be further subdivided into outwash delta deposits, outwash channel deposits, and kame deposits. The outwash delta deposits (which include those at the present mining operations near Issaquah, Steilacoom, and Friday Harbor) are the most economically important of the recessional deposits. This is primarily due to the ease of mining, thickness (usually greater than 100 ft), and consistency of the deposits. An estimated 60 to 70 percent of the total sand and gravel mined in the state is from outwash delta deposits. Outwash channel deposits have much more varied lithology, containing abundant cobbles, sand, and silt beds. The thickness of channel deposits is usually less than 100 ft, and the deposits are more difficult to mine due to the usual absence of an exposed face prior to mining. Kame deposits also have highly varied lithology and generally lap onto older deposits, resulting in significant and rapid changes in deposit thickness.

Pleistocene and Recent river channels are also mined throughout the state. Some of the larger mining operations are in the prehistoric Columbia River channels and tributaries and on older terraces of the Chehalis and Yakima rivers. These types of deposits are generally limited in thickness and vary in consistency in both horizontal and vertical directions.

The gravel bars deposited by modern rivers are also extensively mined throughout the state, particularly where other types of deposits are not available or have been exhausted. Volumes of minable material are generally limited; however, they have the potential of being renewed during storm and flood events. Environmental concerns may limit the mining of these deposits to times of the year when the water level is lowest and no fish runs are occurring. Yearly mining of gravel bars may result in degradation of the downstream channel (Dunne et al., 1980), such as adverse impacts to bridges, fish habitats, and water quality. In addition, mining in modern river beds can result in rapid changes in river courses and can create adverse erosion during relatively minor river events as in the case of the Yakima River near Union Gap (Dunne et al., 1980). In this instance, two deep gravel pits were excavated in the flood plain, and each pit was protected by sand and gravel dikes. In 1971, a small flood breached the upper dike, and the flood waters flowed into the first pit. Outflow from this pit then eroded the roadbed of Interstate Highway 82 and flowed into the second pit, subsequently breaching a downstream dike as well. As a result, the Yakima River shifted more than 3,000 ft laterally during one flood event.

Mining Recent river gravel bars may soon be regulated to such an extent that profitable mining of these deposits may not be possible. Therefore, these deposits probably should not be considered when determining future reserves of economical sand and gravel resources.

Future Sand and Gravel Supplies

When considering future sand and gravel supplies, knowledge of the geology of existing mining operations and the locations or areal extent of similar geologic environments is imperative. Evaluations should also distinguish between inland deposits and sand and gravel resources that have access to navigable waters.

Marine-Based Deposits

A recessional outwash delta of Vashon age is being mined near Friday Harbor in San Juan County. The deposit exhibits south-dipping foreset beds, and collapsed sedimentary structures are in evidence in the northern part of the deposit. These features and the fact that the deposit is on an island bounded by deep marine channels, which provide east and west limitations, suggests that the river that was responsible for its deposition was flowing directly off the glacier itself. A similar deposit is present on the southernmost peninsula of San Juan Island near Cattle Point. However, the major portion of this deposit is within a national historic park and, therefore, cannot be considered as a future supply of sand and gravel. The geologic environment that resulted in these two above-sea-level deposits also is in evidence farther south, approximately 150 ft below sea level. This submarine deposit may, at some time in the future, be considered as a potential sand and gravel source if submarine mining techniques prove to be economical and environmentally sound.

A Vashon-age recessional delta that has navigable-water access is currently being mined near Steilacoom (Figure 2). This delta was deposited in a Pleistocene lake created when the glacier retreated toward the north but still blocked the northward drainage through the Strait of Juan de Fuca. The Coastal Zone Atlas of Washington (WDOE, 1977-1980) identifies a similar deposit a few miles south of the Steilacoom delta. No volume estimates or quality evaluations were made on this deposit by the WDOE. Thus, the potential for this delta to provide a future source of sand and gravel is not known.

The Friday Harbor and Steilacoom sand and gravel pits are currently the only two active operations with navigable-water access in the Puget Sound region. Past sand and gravel mining has occurred on Maury Island (Figure 2), and some of this material was barged to Seattle/Tacoma markets. This sand and gravel was deposited during the advance of the Vashon glacier and at present has some quality limitations. However, Maury Island should still be considered as a potential future source, depending on market conditions, primarily due to its past mining history and navigable-water access.

A draft environmental impact statement (Associated Sand and Gravel, Inc., 1981) identifies the Hamma Hamma River delta as an economic source of sand and gravel. This recessional delta, which is located on the west side of Hood Canal, has navigable-water access. Mining of this deposit has been very limited to date, and marine loading facilities have not yet been provided.

A large recessional sand and gravel deposit of Vashon age is located near the center of Whidbey Island. This deposit is of sufficient quantity and quality to be considered as a future economical source provided that it could be transported to a marine loading facility for shipping to area markets.

Other sand and gravel prospects that were identified in the WDOE Coastal Zone Atlases (Mason and Clallam counties) include three recessional deltas, one located about 2 mi east of Port Angeles and two located on Hood Canal—the Lilliwaup Bay and Potlatch Bay prospects (Figure 2). On the basis of available topographic data, the Port Angeles prospect may be thin; however, drill log information is not yet available to supplement the topographic data. Both Hood Canal prospects are in part residentially developed. Thus, the Hamma Hamma delta is the only new marine-based deposit that has been publicly identified as a future economic source of sand and gravel, although environmental questions may inhibit or prevent major extraction activity.

The mining operations at Friday Harbor and Steilacoom are rapidly depleting their deposits. Without new marine-based sand and gravel sources coming on line, barging to the large market areas may cease when these deposits are exhausted. A large cost increase for sand and gravel and for the products in which they are used may be expected at that time.

Land-Based Deposits

Future sand and gravel deposits have been studied only in King, Pierce, Clark, and parts of Spokane counties. The following discussion will focus on King County because of its importance to the economy of Washington and the fact that the most detailed study of sand and gravel reserves to date was made for this county.

Kroft (1972) describes three classes of potential sand and gravel reserves totaling about 3 billion cy in King County: (1) Class A deposits are primarily deltas deposited during the recession of the Fraser glacier(s); (2) Class B deposits are those in modern river valleys, such as the Duwamish River valley; and (3) Class C deposits are primarily recessional, meltwater channel deposits, also from the last glaciation.

Recent residential and commercial development, generally poor deposit quality, and environmental concerns have prevented any new significant development of sand and gravel mining operations in modern river valleys. Therefore, Kroft's Class B deposits should no longer be considered as potential sources of large quantities of economic-grade sand and gravel.

In order for a sand and gravel deposit to be considered economic for development as a potential source of concrete-quality aggregate, it should be more than 50 ft thick, contain less than 10 percent fines, have a total volume equal to a minimum of 10 years' consumption, have potential environmental impacts that are easy and economical to mitigate, and be minable in such a fashion that the operation is not readily visible to the general public. In addition, residential subdivisions should not be nearby, and the potential site should not have adverse zoning constraints. On the basis of these criteria, very few of Kroft's Class C deposits should be considered available for development except as very small or temporary borrow pits. Therefore, the Class A deposits (Vashon-age recessional deltas), as referred to by Kroft, are the only potential sources of sand and gravel currently eligible for consideration as quality aggregate. These deposits and their 1988 status are listed on Table 1.

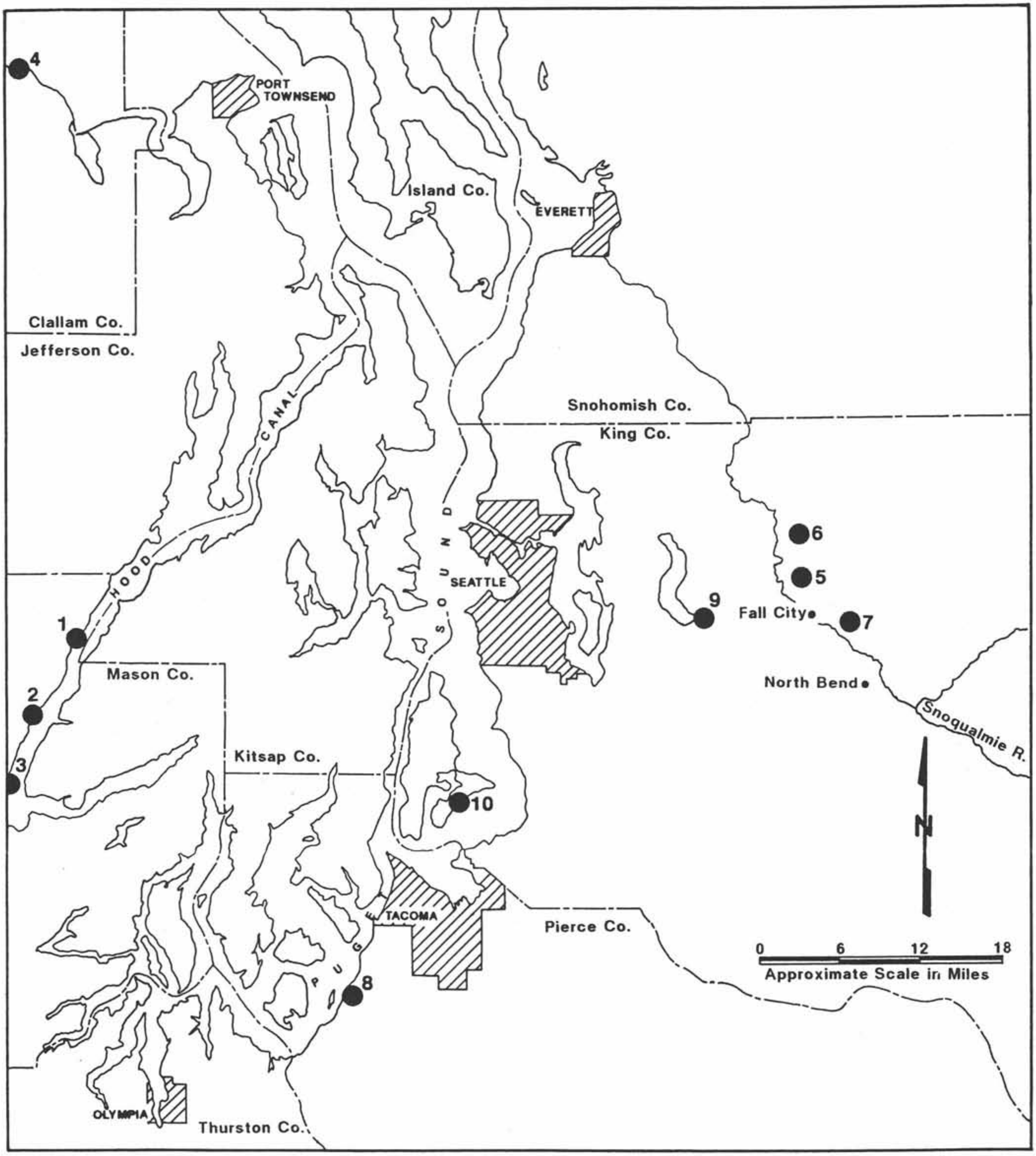

Figure 2. Index map of sand and gravel deposits in the Puget Sound area. 1. Hamma Hamma prospect, 2. Lilliwaup Bay prospect, 3. Potlatch Bay prospect, 4. Port Angeles prospect, 5. Griffin Creek prospect, 6, Tolt River prospect, 7. Tokul Creek prospect, 8. Steilacoom delta, 9. Issaquah delta, 10. Maury Island deposit.

Table 1. Reported volume and current status of Class A deposits, King County

Delta	Reported volume (million cy)	Current status
Auburn	43	Currently being mined
Cedar Grove	2	Nearly exhausted
Cherry Creek	66	Residential development
Harris Creek	67	Nearly exhausted
Holder Creek	4	Exhausted
Griffin Creek	540	Undeveloped
Inglewood	13	Residential development
Issaquah	200	Nearly exhausted
Redmond	32	Nearly exhausted
Snoqualmie Falls	16	New mapping indicates no viable resource
Tibbits Creek	4.5	Residential development
Tokul Creek	240	Small portions are residential development
Tolt River	23	Half the delta is in residential development

Review of Table 1 indicates that the Griffin Creek, Tokul Creek, and Tolt River deltas (Figure 2) are the only remaining large sources of sand and gravel that were identified by Kroft. It would appear from the table that the Griffin Creek delta is the largest of the three. However, recent mapping by the U.S. Geological Survey (Tabor et al., 1982) has indicated that the area thought by Kroft to represent a delta deposit actually is one of shallow, ice-marginal channel deposits. Kroft's reported volume of 540 million cy is therefore interpreted to be about 400 million cy too high. Although not as large as previously thought, the Griffin Creek delta still should be considered a potential economic source of sand and gravel. The Tolt River delta may be too small to be developed by a large sand and gravel operator. In addition, a significant percentage of the aggregate is in various stages of decay, which may make it unsuitable for concrete-quality aggregate. The Tokul Creek delta is one of the few known remaining sources of sand and gravel in northwest King County of sufficient volume and attractive sand/gravel/silt ratios to be considered economical for development.

From the above data, it becomes clear that of the 3 billion cy of sand and gravel thought to be available for production in 1972 (Kroft, 1972), less than 500 million cy can be currently considered as available for development for concrete-quality aggregate. The vast majority of this sand and gravel lies in three deltas, all along the east flanks of the Snoqualmie River valley (Figure 2). The Tokul Creek delta is the closest of the three to a major east-west transportation route (Interstate Highway 90).

Additional economic sources of sand and gravel not identified by Kroft may be available within King County. Some of these deposits are undoubtedly known to members of the sand and gravel mining industry through confidential studies. However, until these deposits are publicly identified, assessing their availability as future sources of sand and gravel is difficult.

The sand and gravel mining industry, through the Washington Aggregates and Concrete Association, is currently working with King County to identify and maintain favorable zoning so that sand and gravel resources may be available for future use. Such zoning is only valid if updated sand and gravel resource assessments are employed, not only in King County, but also in other counties where the resource is considered of economic importance.

ROCK QUARRIES

General

Bulk construction materials quarried in Washington are generally of three main types: (1) limestone, for use in cement; (2) dimension stone; and (3) crushed stone. Crushed stone and limestone, in terms of value and quantity mined, are the most important. Dimension or building stone quarries have substantially reduced operations since 1982, when an estimated 14,000 short tons valued at nearly $2 million were mined (U.S. Bureau of Mines, 1983).

Recent trends are toward the use of unfinished natural stone and crushed stone. The uses generally include riprap, roadway construction, rockeries, and landscape rocks. This industry directly employs more than 600 people (U.S. Bureau of Mines, unpublished 1987 data) and, in the most recent year (1985) for which production figures were available for crushed rock, $32 million were added to the state's economy (Figure 3).

Owing to the economic importance of unfinished natural stone and crushed stone to the economy, this paper will focus on quarries that mine stone for these categories. The discussion will include methods of determining rock quality, geologic considerations, and economic evaluation of prospects.

Rock Quality

A rock to be used as crushed stone for roadway construction must meet specific laboratory criteria for fineness and mechanical and chemical weathering in order to be utilized for any state, county or public works project. The Washington State Department of Transportation (WSDOT) and the American Society for Testing

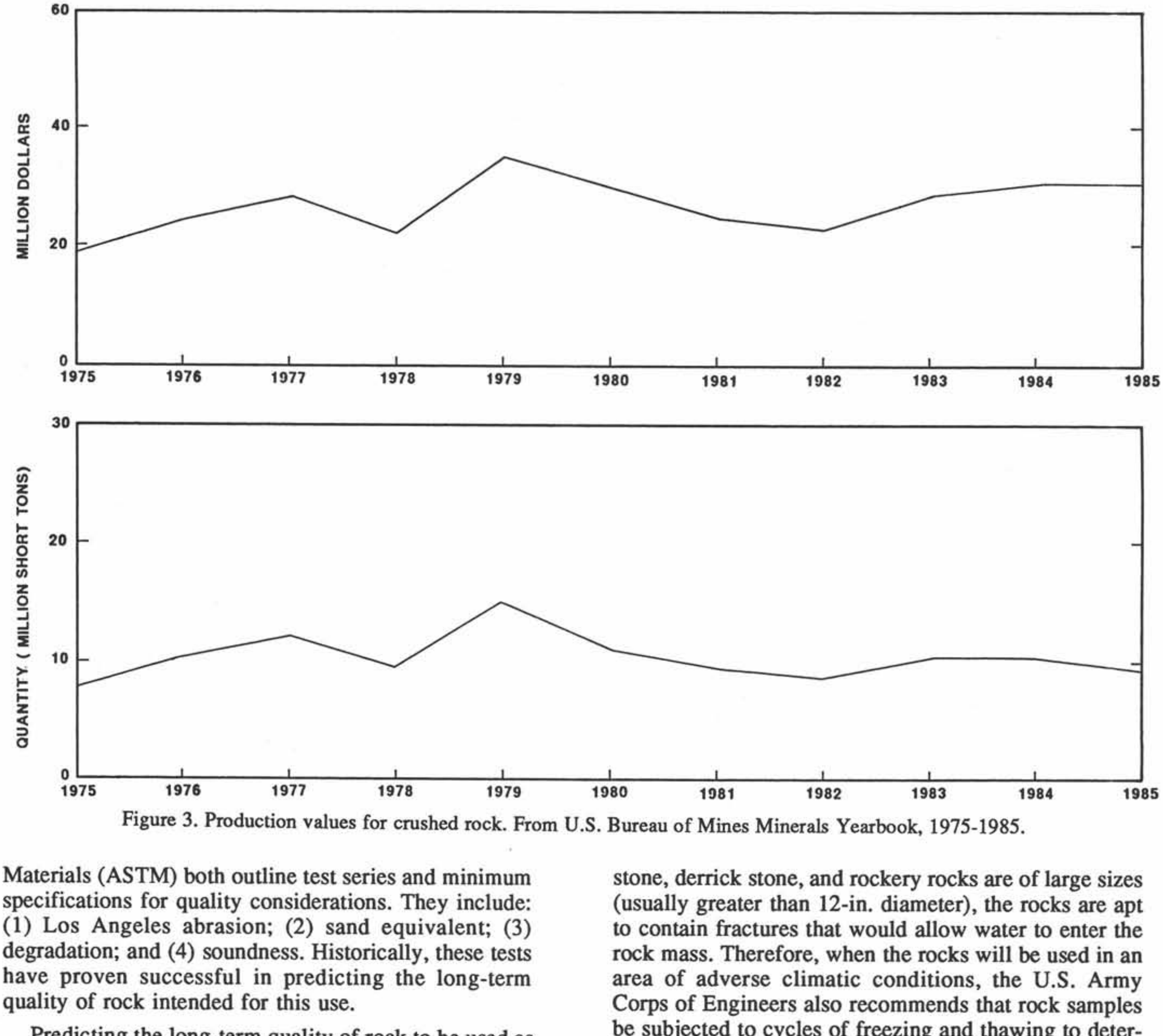

Figure 3. Production values for crushed rock. From U.S. Bureau of Mines Minerals Yearbook, 1975-1985.

Materials (ASTM) both outline test series and minimum specifications for quality considerations. They include: (1) Los Angeles abrasion; (2) sand equivalent; (3) degradation; and (4) soundness. Historically, these tests have proven successful in predicting the long-term quality of rock intended for this use.

Predicting the long-term quality of rock to be used as riprap, jetty stone, derrick stone, or rockery rock has been less successful than for the smaller (up to 1-1/2-in. diameter) crushed stone for roadway construction. Rocks anticipated for these uses also need to be capable of withstanding mechanical and chemical breakdown. However, the tests presently in use (as described above for crushed stone) have not demonstrated total reliability for predicting rock quality for this intended use. Therefore, although research is still being performed in this area, the U.S. Army Corps of Engineers has developed a test series, based on their many years of observation, that appears to be more reliable for predicting rock quality of these larger size products. These laboratory tests include the following: (1) specific gravity; (2) percent absorption; and (3) ethylene glycol accelerated expansion. In addition, since the riprap, jetty stone, derrick stone, and rockery rocks are of large sizes (usually greater than 12-in. diameter), the rocks are apt to contain fractures that would allow water to enter the rock mass. Therefore, when the rocks will be used in an area of adverse climatic conditions, the U.S. Army Corps of Engineers also recommends that rock samples be subjected to cycles of freezing and thawing to determine their susceptibility to this type of mechanical weathering.

In Washington, certain types of rock, especially andesites and foliated metamorphic rocks, have a history of sudden and significant deterioration even after as many as 15 yr of satisfactory field use. This characteristic may not be indicated by either of the above-mentioned laboratory test programs. Therefore, although used mainly for evaluating concrete aggregate, a thorough petrographic analysis, performed by a geologist experienced in the industry, may be important for predicting this behavior. A petrographic analysis can accurately determine the rock type, its origin, and relative abundance of various mineral components. Knowing the mineralogy of a particular rock type is useful for predicting how it will weather. Texture and porosity of the rock type can also be determined by the petrographic analysis and used to predict its weathering behavior. Understanding the pore system (whether it is visible to the naked eye or a micropore system) can aid in determining the susceptibility of the rock to freeze-thaw action. A good petrographic examination will also detect planes of weakness not visible to the naked eye, composition of fracture and vein fillings, and properties such as foliation, schistosity, and present degree of weathering. All of these characteristics are important in predicting the long-term performance of the rock for its intended use.

Geologic Considerations

Throughout Washington, the rocks that are used as riprap, jetty stone, derrick stone, rockery rock, or crushed stone include granite, basalt, diorite, some andesites, nonfoliated metamorphic rock types, and Cretaceous or older sedimentary rock types, such as graywacke, limestone, and argillite. Tertiary sedimentary rocks in this area are generally poorly indurated, of light weight, and subject to rapid mechanical and/or chemical weathering. In addition, a significant quantity of the andesitic rocks and foliated metamorphic rocks tends to disintegrate and may chemically weather faster than other igneous or metamorphic rock types.

Economic Considerations

In order for a quarry to be a profitable operation for the owner, factors other than actual quality of the rock must be examined. These include accessibility, proximity to market, nearby development, thickness and ease of excavation of overburden, fracture patterns, and ratio of large to small stone.

Accessibility and Proximity to Market

Products from rock quarries are significantly less valuable than other mined mineral commodities. Therefore, an economically viable operation requires that a quarry be located close to markets and in areas that do not require large financial investments for road and bridge construction. If startup costs or transportation costs are too high, the final products usually cannot be priced high enough for the operation to be profitable, and the quarry operation will eventually cease functioning. For this reason, many small, formerly active quarry operations can be found throughout the state. However, it must also be realized that some of these quarries were opened for a specific project, which has been completed, and the quarries are no longer needed.

Nearby Development

All hard-rock quarries require blasting in order to detach the stone from the face of the outcrop. For some old quarries that have been abandoned for years and in which attempts to re-establish operations are initiated, operators find that advancing development has placed residential and/or commercial structures in close proximity to the quarry site. This can result in a denial of operating permits owing to the nuisance and/or possible safety concerns related to both blasting and increased truck traffic. Alternatively, opening of new quarries in areas that have nearby residential/commercial development may involve years of effort and substantial sums of money in overcoming environmental and safety issues. Even if the operating permits are obtained, the financial burden imposed by completing the regulatory and legal process and by providing the probable required mitigating measures seriously impacts the ability of the quarry to be profitable. Therefore, the location of the proposed quarry with respect to developed areas may be one of the most important considerations when examining the economic viability of the operation.

Overburden

Any mining operation, such as an open quarry, must be seriously concerned with the quantity of overburden that is to be removed prior to commencing the quarrying. In a hard-rock quarry, overburden is defined as any material that overlies the rock to be quarried. Overburden may consist of soil, decomposed or highly weathered rock, other varieties of rock, unconsolidated sedimentary material (alluvium or colluvium), or glacial sediments.

Generally, a quarry operation in Washington will not be economically viable if the overburden is in excess of 15 ft thick. This is due to the relative abundance of high-quality rock that results in a low value per ton for the rock products. Therefore, the cost of removing excess overburden may exceed the value of the rock to be quarried. Exceptions are quarry operations established solely for nearby, large, short-term, construction projects, such as dams, power plants, and freeways, and quarry operations in high-quality rock that serve large metropolitan markets. Even under these ideal conditions, the amount and type of overburden can severely impact the profitability of the quarry.

Fracture Patterns (Ratio of Large to Small Stones)

A final consideration in order for a quarry operation to be profitable is the fracture pattern of the deposit and the resulting ratio of rockery/riprap-size rock to rock suitable for producing crushed stone. Experience in these operations indicates that a source must produce at least 30 percent large stone (1 to 8 man size for rockery and riprap use). This is due to the higher cost associated with producing crushed stone and the greater economic return per ton of the larger rock sizes. There are exceptions to this percentage rule, such as in quarries established solely for producing crushed stone for roadway base, concrete, and asphaltic concrete pavement for isolated, large-scale construction projects. If the immediate need for these products cannot be served by other quarry operations, then an individual quarry or series of small quarries will be established to serve the need.

CONCLUSIONS

This paper has discussed a number of factors, including current environmental concerns, that have reduced what once was thought to be a nearly inexhaustible sand and gravel resource to one for which proper identification and resource protection is becoming critical. There are large gaps in our present knowledge of existing sand and gravel resources. This lack of currently appropriate data must be rectified, especially in the counties of greatest market demand: Snohomish, King, Pierce, Thurston and Spokane counties. The potential resources with marine access must also be re-evaluated by geologists who have the industrial experience and environmental knowledge. In addition, the industry itself must become more involved with county planners in identification and protection of these economically important resources.

The future of rock quarries is much the same as for sand and gravel. Proper planning and resource identification must be accomplished in order to protect the availability of the high-quality resources. Also due to a recent series of law suits against quarry operators for rock failures, it is increasingly apparent that additional studies to determine the long-term quality aspects of quarry rock must be undertaken and the results applied immediately.

REFERENCES

Associated Sand and Gravel, Inc., 1981, *Sand and gravel excavation and barge loading facility, Hamma Hamma site*: Draft Environmental Impact Statement, Mason County Planning Department, Mason County, WA, 134 p.

Bettesworth, R. D., 1987, *Forecast 1988*: Rock Products, Vol. 90, No. 12, p. 53.

Dunne, T., 1979, *Sediment transport and gravel resources in the Snohomish River basin*: Report to Snohomish County Physical Planning Office, Everett, WA, 97 p.

Dunne, T.; Dietrich, W. E.: Humphrey, N. F.; and Tubbs, D. W., 1980, Geologic and geomorphic implications for gravel supply. In Cassidy, J. T.,: *Proceedings from the Conference on Salmon-Spawning Gravel–A renewable resource in the Pacific Northwest*: Washington Water Research Center Report 39. pp. 75-100.

Fiksdal, A. J., 1975, *Sand and gravel in Clark County*: Washington Division of Geology and Earth Resources Open File Report 75-11, Olympia, WA, 2 p., 1 plate.

Gence, L., 1934, *The sand and gravel deposits of King and Pierce counties, Washington* [B.S. thesis]: University of Washington, Seattle, WA, 55 p.

Kroft, D. J., 1972, *Sand and gravel deposits in western King County, Washington* [M.S. thesis]: University of Washington, Seattle, WA, 62 p.

Leighton, M. M., 1919, *The road building sands and gravels of Washington*: Washington Geological Survey Bulletin 22, Olympia, WA, 307 p.

Moen, W. S., 1967, *Building stone of Washington*: Washington Division of Mines and Geology Bulletin 55, Olympia, WA, 85 p.

Opperman, C. J., 1918, *Sand and gravel of Puget Sound glacial drift* [B.S. thesis]: University of Washington, Seattle, WA, 31 p.

Powers, M. W., 1976, *Sand and gravel deposits in parts of the Spokane (SE and SW) quadrangles, Washington* [M.S. thesis]: Eastern Washington State College, Cheney, WA, 52 p., 3 plates.

Tabor, R. W.; Frizzell, V. A. Jr.; Booth, D. B.; Whetten, J. T.; Waitt, R. B.; and Zartman, R. E., 1982, *Preliminary geologic map of the Skykomish River 1:100,000 quadrangle, Washington*: U.S. Geological Survey Open-File Report 82-747, 31 p., 1 plate, scale 1:100,000.

U.S. Bureau of Mines, 1975-1986, *The Mineral Industry of Washington: U.S. Bureau of Mines Minerals Yearbook*: U.S. Bureau of Mines.

Washington Department of Ecology, 1977-1980, *Coastal Zone Atlas of Washington*: Washington Department of Ecology, 12 vol.

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Foundation and Excavation Conditions in Washington

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INTRODUCTION

The foundation and excavation conditions in Washington have primarily been determined by glacial erosion and deposition, young and mountainous topography, volcanism, and postglacial deposition. Rock is exposed or covered with a thin veneer of glacial or postglacial soil over much of the state, with notable exceptions being the fairly thick sequences of Quaternary sediments in the Puget Sound Basin, areas along the coast of the Olympic Peninsula, and internal basin areas of eastern Washington. Roughly one-half to two-thirds of the state is underlain by Tertiary basalts and andesites. The remaining portion has exposures of primarily Mesozoic or younger sedimentary, metamorphic, and intrusive granitic rock types.

Of the state's major cities west of the Cascade Range, Seattle, Tacoma, Bellevue, Everett, and Olympia are all essentially founded on a variety of glacial soil materials. Of the remaining major Washington cities, only Bellingham, Bremerton, and Spokane are partly founded in areas with abundant rock outcrops and have bedrock as a foundation, tunneling, and cut slope material. The remainder, including Vancouver, Yakima, Wenatchee, Mt. Vernon, Kennewick, Richland, and Walla Walla are founded on alluvium, terrace deposits, or glacial alluvium

This paper divides and discusses soils according to glacial and nonglacial origins and rocks according to major rock categories. Soil descriptions in the following discussion are generally in compliance with the Unified Soil Classification system (USC), and densities are related to the Standard Penetration Test (SPT).

GLACIAL SOILS

General

Glacial soils in Washington were deposited during the four major recognized glaciations which covered the northern part of the state. Soils discussed herein are in those areas inundated by the continental ice sheets in Puget Sound basin and central and eastern Washington. Alpine glacial deposits are also present in the state but are not as commonly encountered, although they are a factor at a few dam sites and major mountain highway passes. In areas adjacent to the foothills of the Cascades and the Olympics, the alternating times of deposition of continental and alpine glaciations produced a complex sequence of interbedded deposits.

Glacially derived soils have widely varying grain-size and composition characteristics that may change dramatically over very short distances. Of equal importance with regard to engineering properties is whether the soil has been overridden and consolidated (densified) by the weight of glacial ice.

The following discussion of glacial soils is therefore divided between soils that were overridden or overconsolidated (glacially consolidated) and those that were not overridden (normally consolidated). Except for soil removed by erosion, normally consolidated soils have not had any more weight (overburden pressure) on them than they presently experience. Glacial soils which were originally normally consolidated may, of course, be overridden by successive glacial advances, resulting in overconsolidated soils.

Glacially consolidated soils include tills, proglacial outwash sands and gravels, and proglacial lacustrine clays and silts, as well as soils from previous interglacial episodes. As a general rule, glacially consolidated soils are hard or dense. Normally consolidated glacial soils include glaciomarine drift, depression fillings, and recessional outwash deposited at the close of the last glaciation. These soils are loose to medium dense or soft to stiff, except where desiccation has hardened the cohesive soils.

Glacially Overridden Sediments

Till

The most widespread surficial glacial deposit, as indicated on geologic maps, is lodgement till because it was the product of the last glacial ice advance. Till is the basal load carried and "smeared" along the sole of the glacial ice. It can be locally reworked by subglacial streams. Several till layers are found in some areas of Washington. Till is usually quite thin in alpine areas, but it accumulated to thicknesses of 20 to 30 ft in some areas of the Puget Sound basin. It is found throughout the glaciated area in the northern part of the state, but may constitute a discontinuous cover due to differential deposition or subsequent erosion. Unit names for some of these deposits in western Washington are Vashon till, Possession Drift, and Orting Drift.

In general, lodgement till is a dense to very dense, gray, unsorted, gravelly, silty sand or sandy silt, locally clayey, with scattered or agglomerated cobbles and boulders. It is commonly referred to as "hardpan" as it has the appearance and texture of concrete in some places, and it is particularly dense at Indian Island (southeast of Port Townsend) and at the Seattle-Tacoma International Airport. Till is a diamict and, as such, varies in grain-size distributions, depending on parent rock and deposition process. A key distinguishing feature of Washington tills, compared to other parts of the United States, is its predominantly granular nature (Olmsted, 1969).

Foundation conditions in till are excellent, offering some of the highest allowable bearing pressures for soil. In very dense till, allowable bearing pressures are usually 6 to 8 tsf and can be as high as 12 tsf under ideal conditions. Conventional spread footings are usually cast on top of or slightly into unweathered till, and deep pile foundations usually use this stratum for end bearing where it underlies soft or loose recessional or postglacial soils. Penetration of piles into till is limited, except with a steel H or open pipe pile with reinforced driving shoes.

While till is very difficult to excavate and commonly requires the use of heavy rippers, it stands nearly vertical in the sidewalls of an excavation and requires minimal shoring. Vertical cuts as high as 40 to 50 ft are known to be stable for years, with only minor bluff regression due to spalling from freeze-thaw action. Erosion protection, such as rocks or concrete walls, is used in many places to prevent the slow regression of steep till faces (Gifford and Kirkland, 1978).

During tunneling, till is hard to penetrate but stands up well and does not squeeze. One of the major considerations when tunneling through till is the abundant and erratically spaced cobbles and boulders. In choosing a tunneling method for this type of soil, provision for removal of cobbles and boulders is a key factor.

Because it is relatively impervious (permeability values of 10^{-5} to 10^{-8} cm/sec), till acts as a perching layer (aquiclude) such that excavations in soils overlying till commonly need to be temporarily dewatered. Although not widespread, pervious, less silty zones in the till can be water-bearing but are not readily recharged.

Outwash

Glacial outwash that has been subsequently overridden by ice is found in the same areas as the tills discussed above. Some geologic unit names applied in the Puget Sound basin are Esperance Sand and Colvos Sand. In many places, overridden outwash is in sharp contact with and directly underlying a till stratum. In general, these deposits are dense to very dense, brown or gray, clean to silty, fine to coarse sand and are commonly gravelly. In some areas, thin layers of silt are interbedded in the sands.

Foundations in these sands are generally conventional spread footings, with allowable bearing pressures of 2 to 4 tsf. Where the sands are very clean, the soil needs to be kept moist by wetting to maintain its apparent cohesion (tension created by water molecules). Very little settlement is experienced by structures founded in this type of soil, provided that the sand is not disturbed by excavation.

In general, excavation of the outwash is easy with power equipment, except where it has been cemented by precipitated iron oxide. Where the sands are silty, sideslopes of excavations will stand quite steeply, but where the sands are clean, excavation walls will cave and ravel back to a 1 H to 1 V slope, necessitating a trench box or other shoring for safety and to control the trench width. The same sorts of conditions apply to tunneling in outwash sand in that, although easily excavated, it often ravels or runs, as experienced in the Chambers Creek sewer interceptor tunnel near Tacoma (Douglas et al., 1985). Tunneling may be accomplished with a full-face wheel excavator; however, provisions need to be made to remove cobbles and boulders, which may be agglomerated.

Because glacial outwash deposits are pervious (permeabilities ranging from 10^{-1} to 10^{-4} cm/sec), they are profoundly affected by the ground-water table. Many of these deposits are water-bearing and require dewatering for foundations, shoring, or tunnel excavations. The sidewalls of any type of excavation in water-bearing sand will flow, cave, and collapse without support. Outwash sand is easily dewatered, except where it is finer grained and many require specialized techniques.

Glaciolacustrine Deposits

Glaciolacustrine deposits that have been overridden occur in the same general areas as till and glacial outwash deposits. Some common names of units are Lawton Clay and Kitsap Clay member. In general, the units are very stiff to hard, clayey silt or silty clay and have varying degrees of plasticity. Most of these cohesive soils are of low plasticity (Laprade, 1982; Sherif, 1966). They consist mostly of illite, having been the products of glacial abrasion (glacial flour); where the units are weathered, montmorillonite was created (Mullineaux et al., 1964). The clays and silts vary from massive (no discernible bedding) to laminated, and some contain numerous fractures and joints. The fractures and joints are generally thought to be the result of stress relief of a brittle material upon removal of the weight of glacial ice. Boulders as large as 10 ft in diameter have been encountered in this fine-grained soil.

Conventional spread footings in these clays/silts are commonly used, with allowable bearing pressures ranging from 1 to 3 tsf. The clays are susceptible to slaking and slight swelling. Therefore, they should be kept dry to minimize reduction in bearing capacity when they become wet.

These glaciolacustrine soils can be fairly easily excavated with a backhoe or dozer to a very steep angle temporarily. However, it is not uncommon for a sideslope to suddenly "pop-out" along pre-existing joints. The joints are not usually noticeable in the face of the excavation, and such a condition can be costly and hazardous for workers. For these reasons, deep vertical cuts in these clayey soils are usually shored or temporarily restrained with a trench box. Deep cuts made for basements of high-rise buildings or highways in urban areas usually need to be retained temporarily and/or permanently with soldier pile cantilever walls or tieback shoring (Abbott and Strazer, 1974; Andrews et al., 1966; Grant et al., 1984; Palladino, 1971; Palladino and Peck, 1972; Wilson and Johnson, 1964).

Where tunnels are dug in this soil the sidewalls and crown will often stand temporarily, but subsequent minor raveling or block fallouts require that support be placed promptly. Excavation can be performed with a tunnel boring machine (TBM) or with a digger tool, depending on the amount of concretions, drop stones, or clastic debris. Minor swelling of these clays in the presence of free water may indicate the need for reinforced concrete in the tunnel invert. Nearly the entire route of the Mt. Baker Ridge tunnel, for Interstate Highway 90 in Seattle, was completed in silt and/or clay, for which a digger shield was used (Parker and Robinson, 1983; Robinson et al., 1987; Sherif and Strazer, 1973).

In general, the glaciolacustrine clays and silts are relatively impermeable; coefficients of permeability are 10^{-6} to 10^{-8} cm/sec. However, any water in these soils is generally carried in the joints and fractures and will weep out of these discontinuities where they are exposed in an excavation face.

Significant water pressure can develop in these cracks and is a contributing factor to "pop-outs" on clay slopes. Where pervious sands overlie the clay, the clay acts as an aquiclude and ground water is perched atop the unit. Interceptor drainage trenches for site dewatering need to notch down into the clay stratum in order to effectively drain overlying granular soils.

Many of the naturally occurring landslides in western Washington slip along the upper contact of clay where it underlies pervious sand strata (Tubbs, 1975). Landslides also commonly occur in these clays in response to even minor excavations.

Normally Consolidated Glacial Soils

Glaciomarine Drift

Glaciomarine drift (GMD) is a heterogeneous and varied mixture of the full range of grain sizes from clay to boulders. Because its major constituent is usually clay and its appearance is similar to that of lodgement till, it is frequently referred to as clayey till. In surface exposures where it has become dried and hardened or where it has been overridden by successive glacial advances, it is very difficult to differentiate from lodgement till (Easterbrook, 1964). It is found extensively throughout the northern part of Puget Sound, such as on Whidbey Island, at Bellingham, and in the San Juan Islands area. Due to its method of deposition by ice rafting, subaqueous flows, or meltwater-fan building, grain-size content can vary over very short distances, and concentrations of intermixed sands and gravels are not uncommon. In the Anacortes area, where the deposit is ubiquitous, the upper 15 to 20 ft of the GMD has become hardened by desiccation and is softer with increasing depth—the opposite of most natural soil deposits.

Foundation requirements in GMD vary considerably depending on the structural loads and the footprint of the structure. For lightly loaded structures, such as residences and small commercial structures, foundations in the desiccated soil are suitable at bearing pressures of 1 to 2 tsf because the pressure effects of the structure do not reach deep enough to stress the softer underlying materials. Heavy or large-area buildings (i.e., warehouses or industrial structures) may stress the deeper, softer soils, and ground settlements could ensue. For these situations, stress analysis can be performed to evaluate the depth of stress effects in order to estimate settlement. Where the structure is too heavy or where settlements are likely to be prohibitively large, the structure may need to be supported by end-bearing piles to an appropriate underlying deposit (if within reasonable depth). Predrilling through the upper, hardened, desiccated clay may be required, especially when displacement-type piles are used.

For excavation purposes, GMD is relatively easy to remove. However, it is generally plastic and is sticky when worked with a backhoe or dozer. Due to its cohesive nature, the walls of excavations will stand very steeply temporarily; however, they will squeeze. The softer, wetter soils will present more squeezing conditions than the desiccated soils.

Tunneling is difficult in this ground because of its soft, sticky nature. The most promising method of tunneling is generally pipe jacking. Again, provisions need to be made for hand removal of boulders, which are commonly encountered in GMD.

Because it is essentially a clay, GMD is relatively impermeable; permeabilities range from 10^{-5} to 10^{-8} cm/sec. Granular layers or pockets contain free water. However, significant recharge is unlikely. Even with extensive exploration, the prediction of the location of water-bearing lenses or areas in GMD is impossible.

Recessional Outwash

Granular glacial outwash that was deposited as the last glacial ice receded and was therefore not overridden by the ice is termed recessional outwash. It is found sporadically throughout the glaciated region and is generally red-brown or brown, silty sand and sandy silt with scattered gravel. It is usually thin, on the order of 2 to 10 ft thick. In some areas, such as delta deposits on the margins of the Puget Sound basin and in high-velocity flood deposits (Steilacoom Gravel), the recessional outwash is considerably thicker and much coarser. Because it was not overconsolidated by the weight of glacial ice, it is loose to medium dense and can vary markedly in relative density over short distances.

Due to its loose to medium dense nature, recessional outwash is easily excavated with backhoes or dozers; trenches require shoring. Tunneling or pipe jacking through this ground can make rapid advance rates, but continuous temporary and permanent support is required.

Where the recessional outwash is medium dense, it may be suitable for light residential or commercial foundation loads of about 1 tsf. Nonetheless, loose soils need to be removed and replaced with structural fill that is densified by vibration, or the structure should be supported by piles bearing in dense soil below. Structures built upon loose recessional sands can experience settlement of 3 to 6 percent of the layer thickness (Boirum and Gifford, 1986). These soils are amenable to soil improvement techniques such as dynamic compaction, a method in which a large weight is dropped from a crane boom. Dynamic compaction was successfully used for the foundation soils for the new Madigan Hospital at Fort Lewis (U.S. Army Corps of Engineers, unpublished data).

All of the above characteristics can be markedly altered by the presence of ground water, which is commonly perched on the immediately underlying till. Where the till stratum is missing, recessional outwash may overlie advance outwash or even sediments of a previous glaciation. The recessional sands may tend to pump or flow in open excavations or tunnels unless adequately dewatered. Dewatering for construction purposes can be accomplished with well-points, sumps, or interceptor trenches, depending on the topography and type of construction.

Depression Fillings

Following the recession or ablation of glacial ice, the ground surface was hummocky and irregular. Natural processes of erosion and deposition over the past 10,000 to 13,000 yr have resulted in topographic change. Vegetative growth in enclosed water-filled basins resulted in the development of peat bogs. These types of deposits consist of fibrous sphagnum peat, silty peat, and peaty silt (muck). Soft clays and silts also filled many depressed areas.

Where peaty deposits contain much fibrous material, excavations will usually stand vertically. On the other hand, where the soils are predominantly soft silt, the muck may flow and make excavation very difficult, even with the use of a trench box for support. Depression-filling soft clays or pure silts, where not desiccated, may also be subject to flowing during excavation, requiring the use of a trench box to keep the trench open and provide safety for workers. Soft, wet, highly plastic clay can be more time consuming to move because it sticks to excavation and hauling equipment.

Where foundations are planned in areas which contain these soils, the soft organic materials and clayey soil must be removed because foundations will suffer either bearing-capacity failures or, more likely, severe settlements. Settlements of as much as 30 to 50 percent of the thickness of a peat layer have been experienced by structures founded on these soils. Removal and replacement by structural fill or pile support in competent soil below the unsuitable strata are necessary (Druebert and Yamane, 1980). In the case of low-volume roads, geofabrics can be used to spread the loads and prevent mixing of the soft natural ground and overlying fill (Mohney and Steward, 1982). Preloading, commonly combined with wick drains or stone columns, has also been successfully used to prepare these soils for foundation loads.

Because depression-filling soils are near-surface deposits, tunnels are not normally driven in these materials. Pipe jacking for utility access through these soils is fairly common. Except in the case of fibrous peat, the pipe casing must be kept ahead of the auger in order to prevent collapse of ground and potentially harmful ground settlement.

NONGLACIAL SOILS

Residual Soils

Most of those areas in Washington that have not been glaciated or otherwise mantled by glacial outwash are underlain by Tertiary sedimentary and volcanic rocks that have had 10 to 50 Ma to develop residual soils. Predominant residual soil types are clays and silts. In areas where basalts have been weathered, terra rosa, a deep red-brown clay, has developed. In areas of siltstone, sandstone, and claystone, residual soils are clayey residuums that grade downward into their parent materials. The upper several feet of these soils are generally completely fine grained and free of clasts; closer to the top of bedrock, chunks of the native bedrock become larger, fresher, and more numerous. Although glacial erosion usually removed residual soils, there are some places where residuum lies between bedrock and overlying glacial soils, for example, on the Western Washington University campus in Bellingham. Some examples of rocks which have developed significant thicknesses of residual soil are the Skookumchuck Formation near Centralia, the Montesano Formation in the Grays Harbor area, the Ohanapecosh Formation in south-central Washington, the Troutdale Formation in southwest Washington, and the Columbia River basalts. Residuum thickness varies from 5 to 10 ft on the Columbia River basalts in southwestern Washington to 15 to 50 ft on other sedimentary rocks.

Granitic rocks may locally have a thick residual layer consisting of decomposed sand commonly referred to as grus. Grus forms from the decomposition of the feldspar and mica and the relatively resistant silica portion of the granite.

In residual soils, foundation criteria can vary considerably. Light-weight structures can usually be founded in the upper 5 ft of these soils; additional excavation or even pile support may be required for heavy structures. The unit weight, shear strength, and bearing capacity of residuum generally all increase with depth. Allowable bearing capacity in the near-surface clays may only be 1 tsf, whereas that of the hard soils near the top of unweathered rock may exceed 5 tsf. Because the top of the unweathered rock surface may be quite irregular, thorough exploration and/or many probes are necessary for safely siting heavily loaded structures. Differential founding of a structure on soft soil and hard rock should be avoided.

Excavation in residual soils is usually relatively easy because they are not hard, but the difficulty of digging increases with depth as the bedrock surface is approached and more rubble and ledges of less weathered rockare encountered. Likewise, because of the cohesive nature of the soil, trenches and cuts tend to stand very steeply unless wet, pervious zones are present.

Most tunneling through rock involves at least portal excavation in residual or colluvial soils. In several instances, such as the Renton effluent transfer system sewer tunnels, portions of the tunnels passed into and out of rock and residual soils. Because many residual soils preserve relict textures of the original rock, including fractures and shear zones, they may prove to be considerably more difficult to tunnel through than the harder rock materials.

Furthermore, since material strengths may vary laterally and vertically from a few hundred to several thousand pounds per square inch over very short distances, rapid adjustments in excavation and support techniques are required in these soils.

Because residual soils are usually clayey there is very little ground water in them. Ground water is commonly found at the contact between the residuum and the bedrock surface.

Alluvial Soils

Alluvial soils, which were formed on the deposits of modern rivers, are found in all of Washington's major river valleys. The downstream reaches of these valleys are the areas most commonly developed, and sediment transport capacities dictate that finer grained alluvium is usually encountered by major industrial works in the lower reaches. These alluvial deposits consist of fine sand, silty fine sand, fine sandy silt, and non-plastic silt. Due to shifting of depositional channels, individual beds of uniform grain size are rarely laterally continuous over large areas, and interfingering of different soil units is common. These deposits can be loose and soft to depths of 100 to 200 ft, bottoming, for instance, in dense gravels in Grays Harbor or in very dense glacial soils in the Nooksack River valley.

Due to the loose nature of these alluvial soils, they are subject to significant settlements due to structural loads, dewatering, or seismic shaking. Therefore, ground modification or pile support is generally necessary for all but the lightest of structures. Ground modification consists of pre-loading, stone columns, soil densification, or dynamic compaction. Pre-loading has historically been the most widely used of these methods (Bestwick and Kirkland, 1967; Gurtowski and Kirkland, 1979; Mikkelson and Bestwick, 1976; Rippe and Shroeder, 1976), but ground densification by stone columns or probe vibration is becoming more popular because of its cost effectiveness where soil conditions are conducive to rearrangement by vibration. All of these methods require detailed engineering studies, and some are proprietary.

The most common method of foundation support for structures on deep alluvial soils is piles (Boirum et al., 1980; Crowser and Hansen, 1975; Crowser and Schuster, 1973; Gurtowski and Wu, 1984; Yamane and Wu, 1983). Bearing can be both by end bearing or friction, depending on the magnitude of the loads, allowable settlements, depth to dense or hard ground, and availability of pile types. Because of the looseness of these deposits, piles drive relatively easily until significant friction is built up or a bearing stratum is encountered. Some common types of piles used in alluvial soils are timber, concrete, close-end steel pipe, and step tapered (all displacement piles). The driving of piles tends to densify loose alluvial sands so that it is harder to drive each successive pile driven in a group (Boirum et al., 1980).

Excavations are easily dug in alluvial soils. However, the sidewalls will cave or flow, requiring prior dewatering and/or shoring. Where sediments are too soft to stand, pre-loading can be performed, possibly aided by wick or stone column drains, and excavation can follow a few months later (Sharp, 1987). For utility tunnels, pipe jacking is feasible, and the pipe needs to be kept ahead of the auger to prevent running or flowing ground and associated settlements. Even with good ground control, settlements of several inches may occur above 10-ft-diameter tunnels due to soil squeezing into the advancing heading. When jacking in loose or soft soils, the pipe generally tends to dive.

Because these soils usually occur in existing river valleys, a high ground-water table is normal, and excavations require dewatering by pumped wells, sumps, or well points. However, due to the loose, compressible nature of these soils, dewatering may result in appreciable settlements over a large area in sandy soils. Conversely, the effectiveness of dewatering may be limited where the soils are clayey or very silty.

Eolian Soils

Coastal Sand

Along the Pacific coast wind-blown sand is widespread, but it is not everywhere still in the dune form. This type of dune deposit consists of cross-bedded silty fine sand and fine sand that is generally loose to medium dense and increases in density with depth. These soils are suitable for structures with allowable bearing pressures of about 1 tsf or less. Buildings that are more heavily loaded require excavation and recompaction or replacement with imported soil or, alternatively, pile support by friction piles.

Excavation is very easy in these sands, and trench sidewalls will stand near-vertical where apparent cohesion is present in moist soil. However, where the ground-water table is high, the sidewalls will cave or even flow, and when dry, the eolian sands will ravel. Dewatering is generally easily accomplished for excavations, either by well points or sumps.

Loess

Wind-blown silt covers large areas of eastern Washington, especially in the Palouse region, hence the soil's well-known name, "Palouse soil". It is a very uniformly graded silt and very fine sand. Due to slow accumulation and the presence of more or less continuous grass cover, vertical root holes are a prominent feature of this soil. The root holes, left by the decay of the organic matter, create a vertical porosity 100 to 1,000 times greater than that in the horizontal direction. As a result, vertical drainage can be very rapid and prevents the soil from becoming saturated (Olson, 1979).

Although the dry unit weight is low (about 90 to 95 pcf), the strength of the soil is good. Allowable bearing pressures near the surface are 1 to 1.5 tsf and 2 to 2.5 tsf at depth. Palouse loess is not typical of other loess elsewhere in the world in that it is not susceptible to collapsing, even during saturation, so that foundations can usually be placed in the loess without pile support (Lobdell, 1981).

Temporary excavations can be made 20 to 30 ft vertically where the soil is moist to dry. Saturation by a rising ground-water table or surface water can cause the slope to fail or regress. Permanent slope cuts are usually made at 1.5 H to 1 V (Olson, 1987).

Colluvial Soils

Colluvium is the rind of loose to medium-dense soil which drapes the sides and toes of slopes throughout the state. It was emplaced by gravity, and grain size can vary from clay and silt to boulder-size clasts. The mode of deposition ranges from very slow creep (the imperceptible movement of only millimeters per year) to catastrophic landslides. Because it has been reworked by gravity, it has no discernible layering, except where multiple layers of landslide debris are distinguishable. On steep slopes (greater than 40°) the colluvial rind is generally very thin, whereas near the toe of the hillside, where slope angles are 10° to 20°, the thickness can be considerable. The relative rate of slope movement can sometimes be approximated by measuring the amount of bowing of trees.

Colluvium is not generally suited for foundations due to its loose nature and its tendency to move downslope. Foundations are placed below the mobile soil layer. Excavations require shoring or other suitable support. Where excavations are made parallel to the contour of a hillside, open excavations should have short lengths (10 to 20 ft) to prevent caving of the uphill sidewall and subsequent landsliding by headward progression uphill.

Because of the looseness of the colluvial soil, it is generally more pervious than the underlying soil, so that ground water is often perched at that contact.

SEDIMENTARY ROCKS

Sedimentary rocks occur primarily along the west side of the Cascades, around the Olympic Peninsula, and intermingled with metamorphic rocks across the northern quarter of the state from the coast to the Washington-Idaho border. Sedimentary rocks around the Olympic Peninsula and west of the Cascades are mostly of Tertiary age and include sandstone, conglomerate, siltstone, claystone, shale, argillite, graywacke, and economic thicknesses of coal all interspersed with volcanic rocks. Sedimentary rocks in the Northern Cascades and northeastern Washington range in age from Precambrian through Cretaceous and consist of a wide variety of altered or slightly metamorphosed sedimentary rocks including limestone, dolomite, conglomerate, shale, graywacke, claystone, siltstone, argillite, and coal.

Because of the wide variety of sedimentary rock types and ages, there is a very large range of rock material and rock mass properties. The Paleozoic rocks tend to be relatively hard, slightly to moderately metamorphosed, and moderately to highly fractured and to possess well-developed joint sets and irregularly spaced shear zones.

Tertiary rock types tend to be moderately to slightly jointed, although highly fractured, sheared, and faulted units have been encountered near Centralia and along the Cascades and around the Olympic Peninsula. These younger sedimentary rocks tend to have varied strengths, ranging in some instances from a dense to hard soil consistency through very hard rock, commonly over distances of a few hundred feet. Local mineralization near Tertiary intrusive dikes and sills generally results in rock material that ranges from being easily rippable to requiring blasting over distances as short as 100 ft.

Most of the sedimentary rock types, except the decomposed or altered clayey or silty varieties, are useful as fill material. The soft, almost soil-like sandstones of the Miocene Montesano Formation have been quarried for foundation fill in the Grays Harbor area, as has the Eocene Skookumchuck Formation near Centralia.

Foundation requirements vary widely in response to the variations in material properties. Some Tertiary rock types are soft enough to be treated as dense or hard sands and have bearing capacities on the order of 2 to 5 tsf. The pre-Tertiary units tend to be stronger and may be designed for bearing capacities on the order of 5 to 20 tsf. Spread footings are the most widely used foundations on sedimentary rock materials, although piles have been socketed into rock for bridge foundations.

A few of Washington's many dams are founded in sedimentary rock units. The Boundary and Sullivan dams in the far northeast corner of the state are founded in Cambrian limestone, dolomite, quartzite, and phyllite. Several dams, fully or partially founded in sedimentary rock, have experienced significant reservoir or foundation leakage. At Lower Baker Dam an estimated 150 cfs of water leaked, at a reservoir head of 230 ft, through cracks and open fissures in the limestone abutments. Extensive and repeated grouting was required to seal the leaks.

The partially completed and now mothballed Satsop nuclear plant is nearly completely founded in soft sandstones of the Miocene Astoria Formation (Tillson, 1977). The unconstructed Skagit nuclear plant was located at the boundary of the Shuksan thrust plate where soft sandstones of the Eocene Chuckanut Formation are in contact with pre-late Triassic Darrington Phyllite and Shuksan Greenschist.

Major underground facilities in these sedimentary rocks are not common. The underground powerhouse at Boundary Dam is an exception. However, numerous utility and railroad tunnels have been excavated through some of the Tertiary units, primarily in the western quarter of the state, in Seattle, Everett, Bellingham, Chehalis, and Aberdeen. These tunnels have encountered extremely varied conditions even in a single rock unit, and rock material strengths ranged over short distances from that of very lightly cemented dense sand (150 psi) to very hard rock with strengths greater than 15,000 psi. These increased strengths may be due to silicification near dikes and sills in the Tertiary sedimentary rocks. Due to these variations in rock strength, tunneling has been complicated by the need for a wide range of equipment and excavation procedures.

There is also a long history of underground coal mining in the Eocene Chuckanut and Skookumchuck formations , and in the Puget Group west of the Cascades from Bellingham in the north through the Black Diamond area to Centralia in the south, and in the Roslyn Formation in the Cle Elum and Roslyn areas in the central part of the state (Beikman et al., 1984). Some of the underground mines in these areas were taken to depths in excess of 2,000 ft using conventional coal mining techniques. None of these underground mines are currently in operation. Many of the abandoned underground workings pose a problem to urban development, resulting in subsidence over areas ranging from a city lot to several acres, particularly around abandoned shafts (Smith, 1975).

Excavations in sedimentary rocks for highways, quarries, dam abutments, and surface coal mines have resulted in some very large cut slopes. Some of the more pronounced highway cuts in the Tertiary deposits are located around the Olympic Peninsula, in the Kelso area, between Olympia and Hoquiam, and near Bellingham. Large highway cuts have also been excavated in the Paleozoic quartzites, limestones, and shales in the northeast corner of the state near Boundary Dam. The height and angle of many of these cut slopes have been partially a function of the orientations of joints, bedding planes, the presence of shear or fracture zones, and the strength of the rock material. Cuts as high as 100 ft have been made in the Tertiary sandstone near Hoquiam at slopes of 50° to 60°. Cuts to 70° or 80° and to 100 ft high have been excavated in the Eocene Chuckanut sandstone near Bellingham. Scattered block or wedge failures have occurred in such cuts, resulting in blocked highway and railroad alignments in this area.

Significant slopes have been cut for the open-pit coal mining operation near Centralia. The surface mines commonly exceed depths of 200 ft, and slopes of 60° to 70° are not uncommon. The coal is mined from the Eocene Skookumchuck Formation, which consists of massive to thinly bedded sandstone, siltstone, shale, and economic beds of coal as much as 50 ft thick. The stability of the high walls is largely a function of the relatively weak rock materials and numerous throughgoing faults and joint sets, which result in frequent highwall failures (Miller and Hilts, 1970).

Ground water plays a significant role in all types of excavations and foundations in sedimentary rocks. The younger Tertiary deposits, such as the Skookumchuck Formation and Puget Group, all tend to include water sensitive lithologies. Many of the sandstones, shales, and claystones of these units slake and deteriorate in the presence of free water. Water also tends to aggravate cut slope stability problems by deteriorating the rock materials and exerting seepage forces and ice pressures in joints. At the Centralia mine, ground water in confined aquifers below the coal layers has caused heave in the bottoms of some of the cuts and massive slides of spoil materials on saturated bottom clays (Miller and Hilts, 1970).

VOLCANIC ROCKS

Roughly one-half to two-thirds of Washington is covered by Tertiary basalts. Much of the basalt is concentrated as Miocene flood basalts of the Columbia Plateau. Surface erosion of these flows formed the coulees and plateau scablands of eastern Washington.

Eocene through Holocene basalts, andesites, and volcaniclastic rocks flank the various active and semi-dormant volcanic peaks along the west side of the Cascades, including, north to south, Mount Baker, Glacier Peak, Mount Rainier, Mount St. Helens, and Mount Adams.

Late Mesozoic and early Tertiary flow and pillow basalts and andesites occur in the Olympic Peninsula, while Carboniferous altered andesites, basalts, and diabase with minor tuff, greenstone, and spilitic volcanic rocks occur in the northern Cascades. Even with this preponderance of volcanic rocks, only two of Washington's major cities, Spokane and Bremerton, are actually partially founded on this rock type; significant numbers of basalt exposures are apparent throughout the cities. Most other cities located within the Columbia Plateau, such as the Tri-Cities (Richland, Kennewick, and Pasco), Wenatchee, Walla Walla, Yakima, Ellensburg, Moses Lake, and Pullman, are founded on alluvium and colluvium which locally thickly mantle the basalts. The south ends of Seattle and Bellevue also have exposures of sedimentary and volcanic rocks, which impact highway cuts, isolated building foundations, and utility construction.

Individual andesite and basalt flows vary widely in thickness, lateral extent, and continuity. Flow thicknesses range from a few feet to several hundreds of feet. The thickness of the greatest accumulation of flows is estimated at about 10,000 ft in the Columbia Plateau. Basalts are both vesicular and non-vesicular, and flows may have columnar, random, or platy joints. Due to variations in texture, composition, and depth of weathering or chemical alteration, volcanic rocks range in strength from less than 1,000 psi to more than 25,000 psi.

Sedimentary interbeds between flows consist of sand, gravel, tuff, silt, and clay. Interbeds range in thickness from a few inches to several tens of feet. Many of the interbeds are water bearing and have been used as major water sources for agriculture and municipalities. The scoriaceous or highly fractured flow tops are also commonly water bearing.

Excavation of the volcanic rocks generally requires blasting, although locally they may be rippable due to the presence of closely spaced fractures or their low strength. Miocene basalts generally require blasting for excavation and are typically excellent for carrying high foundation loads. Foundations in these rocks are commonly designed for 8 to 20 tsf for bridges, buildings, and dams. Design loads in excess of 100 tsf may be theoretically feasible for these units, but such high structural loads are not known to have been required or used.

Many of Washington's major hydroelectric dams have been constructed at least partially in volcanic bedrock. These include: on the Columbia River, the Priest Rapids, Wanapum, McNary, John Day, The Dalles, and Rock Island dams; the Dry Falls and Long Lake dams near Grand Coulee; Summer Falls and Quincy Chute in the central part of the basin; and the Lower Monumental, Little Goose, and Lower Granite dams on the Snake River in southeast Washington.

In western Washington several smaller dams have been constructed on volcanic rocks near Mount Rainier and Mount St. Helens. These include the Packwood, Alder, Mud Mountain, Cedar Falls, Mossyrock, Ariel, Yale, and Swift Creek dams. Many of these dams have required steep abutment excavations on the order of 100 to 200 ft high. Some of these excavations are retained and reinforced with rock bolts.

Associated structures for the dams, such as inlet and outlet tunnels, have also been constructed successfully in these volcanic rock types, although water-bearing interbeds or flow tops and intensely fractured zones have posed major construction problems. Most of these tunnels were initially supported with rock bolts or steel ribs and subsequently lined with concrete for improved flow characteristics.

Several major underground facilities have been or are planned for construction in basalt. The first U.S. underground hydroelectric plant was constructed in basalt at Snoqualmie Falls in the central Cascade Range (Galster and Olmsted, 1977). This hydroelectric plant includes a 40-ft-wide x 30-ft-high x 200-ft-long unlined and unreinforced underground chamber that was excavated in randomly jointed, blocky basalt. More recently, numerous studies have been performed to evaluate several deep basalt flow horizons beneath the Hanford nuclear reservation as repository sites for hazardous and nuclear waste. Such a repository would consist of several miles of 20- to 30-ft-diameter tunnels and caverns constructed for the transport and placement of nuclear waste cannisters.

Basalt provides a fairly good tunneling medium for both conventional drill-and-blast tunneling and TBM-driven tunnels. Several railroad and highway tunnels have been constructed through Miocene basalts along the Columbia River. These tunnels have been driven primarily by drill-and-blast techniques, and many are essentially unsupported and unlined. Some are partially lined to prevent progressive deterioration of interbeds or ravelling.

The 8,500-ft-long, 11-ft-diameter drainage tunnel used to lower Spirit Lake at the foot of Mount St. Helens was constructed using a TBM (O'Brien, 1987; Sager et al., 1985); support is provided by spot to patterned rock bolts and sections of ribs and lagging in highly fractured or sheared ground. The 29-ft-diameter x 9,950-ft-long, horseshoe-shaped Bacon Siphon Tunnel near Grand Coulee Dam, which has a water-carrying capacity of 12,050 cfs (Bartell, 1977), was excavated by drill-and-blast methods and temporarily supported with ribs and lagging; a permanent concrete lining was emplaced for hydraulic reasons.

Excavated slopes in volcanic materials tend to be stable. Although Miocene basalt is commonly columnar or randomly jointed, it is usually of good quality and requires little or no support, depending on tightness of the joints. In some instances, rock bolting may be required to support isolated columns or blocks. In areas around the Olympic Peninsula, in the North Cascades, and in portions of western Washington, the normal columnar or random jointing of the older basalts has been overprinted by regional joint systems. This makes some slopes in these areas prone to block or wedge movements that may be controlled by spot or pattern bolting or require shallower cut slopes.

Ground water may be a consideration in the design of foundations, tunnels, or slopes in the volcanic rocks. Some volcanic rocks are so tight and relatively unjointed as to be almost impermeable and fairly dry, whereas other volcanic flows may be so heavily fractured and jointed that they also are water sources. As noted earlier, interflow layers or flow tops commonly carry copious amounts of water and may be used for potable and commercial water sources. Water passing through volcanic interbeds and flow tops has been observed to cause serious slope instabilities in the Cascades and has resulted in very high inflows, encountered abruptly, in advancing tunnels.

CRYSTALLINE ROCKS

Crystalline igneous rocks are scattered, primarily as major batholiths across the northern one-third of the state from the Puget Sound Basin to the Washington-Idaho border. These Mesozoic and Tertiary intrusive bodies occupy an area equal to about one-tenth of the state. Most of these intrusive rocks consist of quartz diorite, quartz monzonite, granodiorite, and trondhjemite, all falling under the general category of granitic rock. Major batholiths are the Snoqualmie and Index batholiths in the North Cascades and the Mount Stuart, Chelan, Okanogan, and Colville batholiths, located from west to east across northern Washington.

Other localized intrusive bodies are Tertiary granites and andesitic or basaltic dikes around Mount Rainier, Mount St. Helens, and Mount Baker and at many places throughout the North Cascades. The granites tend to be quite hard, having unconfined strengths ranging from about 10,000 to 25,000 psi. The intrusive rocks are slightly to heavily jointed and locally sheared or fractured; this results in large variations in mass behavior for foundations, slopes, and underground excavations. Weathering depths are generally on the order of a few feet, especially where glacial scouring has exposed these rocks, but localized deep weathering to several tens of feet may occur across shear or fracture zones.

Due in part to their tendency to resist erosion and form rugged topography, combined with their very low permeability and high strength, Mesozoic granitic batholiths form the abutments and foundations of several of the state's major dams, including the Lake Chelan Dam which forms a 50-mi-long lake in the midst of the Chelan batholith. The Wells, Chief Joseph, and Grand Coulee dams, all located along the Columbia River skirting the southern edge of the Okanogan and Colville batholiths, are founded at least partially on granitic rock where the river has eroded down through a relatively thin basaltic cover.

Because of the rugged topography in areas underlain by granitic rocks, highways and railroads passing through these rocks have required the construction of several tunnels. The 7.8-mi-long Great Northern Railroad Tunnel constructed in 1928 beneath the crest of the Cascades at Stevens Pass is currently the second longest railroad tunnel in the western hemisphere. The tunnel is constructed through Mesozoic granitic rocks of the Mount Stuart batholith. The railroad tunnel was excavated by drill-and-blast methods and is only partially supported. The tunnel is still in operation and in good condition. Numerous smaller highway tunnels have been constructed along the North Cascades Highway (State Route 20) where it passes through the southern end of the Chilliwack batholith, as well as along highways through the Mount Stuart, Chelan, Okanogan, and Colville batholiths.

Due to the high strength, massive character, and generally widely spaced joints in crystalline rock, cuts have been excavated on near-vertical slopes to heights in excess of 200 ft with little or no support. Many of these cuts have stood for more than 50 yr with only minor ravelling and weathering or isolated block or wedge failures. However, unfavorable joint orientations and spacings, commonly related to exfoliation, have required locally reduced slopes of 1 H to 1 V. Smooth wall blasting is particularly effective for reducing slope ravelling and minimizing overbreak in these rocks.

Ground water plays a relatively minor role in the stability of these granitic rocks in foundation, underground, and slope excavations. Generally, ground-water inflows in foundation and underground excavations are minimal. The formation of ice wedges around and behind blocks in cut slopes may contribute to isolated rock block failures, particularly in the mountainous areas in which these granitic rocks generally occur.

METAMORPHIC ROCKS

Roughly 30 percent of the northern one-third of the state, or approximately one- to two-tenths of the state, consists of metamorphic rocks. The metamorphic rocks are interfingered with and grade into the granitic intrusive bodies and sedimentary rocks extending from the San Juan Islands through the North Cascades and Okanogan Highland to the Washington-Idaho border. Metamorphic rocks include very low grade quartzites, slates, and phyllites, primarily in the Pend Oreille area north of Spokane. Low- to high-grade metamorphic rocks present around the batholiths range from greenschist, phyllite, and slate at the low-grade end, up through intermediate-grade schist, amphibolite, marble, and quartzite to high-grade migmatitic biotite and quartz diorite, trondhjemite, and hornblende gneiss.

Due to their varied lithology, metamorphic rocks have extremely varied rock mass properties. In general, these rocks tend to be moderately to highly jointed and to include numerous fracture and shear zones which disrupt their continuity and lower their mass strength. Rock mass strengths for the various metamorphic lithologies are commonly controlled by the rock fabric (including foliation and schistocity) and may range from as low as 200 psi for some of the biotite and graphitic schists and phyllites to more than 20,000 psi for the migmatized granitic gneisses.

Excavation requirements for the metamorphic rocks are correspondingly varied; most of these rock types require heavy blasting for efficient excavation. Locally, weathered schists and phyllites may be excavated by rippers, but this is generally not the case. The granitic gneisses tend to produce excellent aggregate and building stone, whereas the schistose, phyllitic, and slatey units tend to produce poor aggregate that breaks down with time.

Foundation requirements for the various metamorphic rocks are likewise extremely varied. Granitic gneisses form excellent foundation materials, as evidenced by conditions at Ross and Diablo dams in the North Cascades and the Rocky Reach Dam along the Columbia River. Significant dental work may be required to excavate and patch shear zones and fracture zones beneath dam foundations, but generally the rock masses have been of high quality for construction.

Many dams have required the construction of major underground works, including inlet and outlet tunnels. For example, from 1980 through 1983, a 4-mi-long, 14-ft-diameter tunnel was constructed in metavolcanic and metasedimentary rocks as part of the Sultan River Hydroelectric Complex (Wallis, 1983). This tunnel was driven using a TBM and generally supported with only minor spot and pattern bolting augmented locally with shotcrete. Some of the more weathered and sheared lithologies were supported with steel sets and lagging and then lined with concrete. Numerous unlined to totally lined highway and railway tunnels have also been excavated in metamorphic rocks, particularly in the North Cascades.

Rock cuts in excess of 200 ft high have been excavated along highways and railroads in metamorphic lithologies. Due to the pervasive joint sets, remnant bedding planes, and numerous shear and fracture zones, wedge or block failures are reasonably common in metamorphic rocks. Consequently, some cuts have to be excavated at fairly low angles (on the order of 1 H to 1 V), or spot and pattern bolting is required.

Ground water may play a significant role in excavations in the metamorphic rocks, particularly underground and slope excavations. Ground water seeps along the pervasive joint systems and shear zones, causing weathering of the adjacent rock. In tunnels, flows of several thousand gallons per minute have been abruptly encountered when excavating through shear or fracture zones. These zones act as either aquifers or aquicludes depending on their clay content. Ground water may accentuate the tendency for block or wedge failures in rock slopes, particularly during the freeze-thaw cycle.

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REFERENCES

Abbott, R. D. and Strazer, R. J., 1974, Design concepts for tied-back excavation. In *Proceedings, 12th Annual Engineering Geology and Soils Engineering Symposium*, Boise, ID: Idaho Department of Transportation, Boise, ID, pp. 299-321.

Andrews, G. H.; Squier, L. R.; and Klasell, J. A., 1966, Cylinder pile retaining walls; conference preprint 295, *American Society of Civil Engineers Structural Engineering Conference*, Miami, FL: American Society of Civil Engineers, New York, NY, 45 p.

Bartell, J., 1977, Grand Coulee and Bacon Siphon, in *Guidebook, Association of Engineering Geologists, 20th Annual Meeting, Seattle, WA*: Association of Engineering Geologists, Lawrence, KS, pp. 48-54.

Beikman, H. M.; Gowen, H. D.; and Dana, T. A. M., 1984, *Coal Reserves of Washington*: Washington Division of Mines and Geology Bulletin 47, 115 p.

Bestwick, J. K. and Kirkland, T. E., 1967, *Preloading Organic Alluvium*, presented at Annual Meeting of American Society of Civil Engineers, New York, NY: American Society of Civil Engineers, New York, NY, 37 p. [Available at the Shannon & Wilson Technical Library, Seattle, WA.]

Boirum, R. N. and Gifford, A. B., 1986, Settlement of light buildings on loose sand. In *Proceedings, Settlement of Shallow Foundations on Cohesionless Soils–Design and Performance*; Geotechnical Division, American Society of Civil Engineers, Spring Convention, Seattle, WA, April 10: American Society of Civil Engineers, New York, NY, pp. 23-44.

Boirum, R. N.; Wu, M. J.; and Yamane, G., 1980, *Driveability of piles in Pacific Northwest soils*, conference preprint 80-094, American Society of Civil Engineers Convention and Exposition, Portland, OR: American Society of Civil Engineers, New York, NY, 22 p.

Crowser, J. C. and Hansen, O., 1975, Static penetrometer utilization in alluvial soils of western Washington In *Proceedings, 13th Annual Engineering Geology and Soils Engineering Symposium*, Moscow, ID: Idaho Department of Transportation, Boise, ID, pp. 141-155.

Crowser, J. C. and Schuster, R. L., 1973, A case history for a mat-supported silo group. In *Proceedings, 11th Annual Engineering Geology and Soils Engineers Symposium*, Pocatello, ID: Idaho Department of Transportation, Boise, ID, pp. 73-90.

Douglas, P. M.; Bailey, M. J.; and Wagner, J. J., 1985, Chambers Creek interceptor sewer tunnel, in *Proceedings, Rapid Excavation and Tunneling Conference*, New Orleans, LA: Society of Mining Engineers of the American Institute of Mining, Metallurgical and Petroleum Engineers, Inc., New York, NY, Vol. 2, pp. 582-610.

Druebert, H. H. and Yamane, G., 1980, *Small diameter pipe piles*, presented at American Society of Civil Engineers Convention and Exposition, Portland, OR: American Society of Civil Engineers, New York, NY, 9 p. [Available at the Shannon & Wilson Technical Library, Seattle, WA.]

Easterbrook, D. J., 1964, Void ratios and bulk densities as means of identifying Pleistocene tills: *Geologic Society of America Bulletin*, Vol. 75, pp. 745-750.

Galster, R.W. and Olmsted, T. L., 1977, Problems of recent landslides, Cascade Mountain front, Snoqualmie Underground Power Plant. In *Guidebook, Association of Engineering Geologists, 20th Annual Meeting, Seattle, WA*: Association of Engineering Geologists, Lawrence, KS, pp. 79-101.

Gifford, A. B. and Kirkland, T. E., 1978, Uses and abuses of rockeries. In *Proceedings, 16th Annual Engineering Geology and Soils Engineering Symposium*, Boise, ID: Idaho Department of Transportation, Boise, ID, pp. 55-68.

Grant, W. P.; Yamane, G.; and Miller, R. P., 1984, Design and performance of Columbia Center shoring wall, Seattle, Washington. In *Proceedings, International Conference on Tall Buildings*, Singapore: Institution of Engineers, Singapore, pp. 651-661.

Gurtowski, T. M. and Kirkland, T. E., 1979, A simplified preload design In *Proceedings, 17th Annual Engineering Geology and Soils Engineering Symposium*, Moscow, ID: Idaho Department of Transportation, Boise, ID, pp. 249-273.

Gurtowski, T. M. and Wu, M. J., 1984, Compression load tests on concrete piles in alluvium. In Proceedings, *American Society of Civil Engineers Fall Convention and Structures Congress*, San Francisco, CA: American Society of Civil Engineers, New York, NY, pp. 138-153.

Laprade, W. T., 1982, Geologic implications of pre-consolidated pressure values, Lawton clay, Seattle, Washington, in *Proceedings, 19th Annual Engineering Geology and Soils Engineering Symposium*, Pocatello, ID: Idaho Department of Transportation, Boise, ID, pp. 303-321.

Lobdell, G. T., 1981, Hydroconsolidation potential of Palouse loess: *Journal of the Geotechnical Engineering Division*, American Society of Civil Engineers, New York, NY, Vol. 107, No. GT6, pp. 733-742.

Mikkelsen, P. E. and Bestwick, L. K., 1976, Instrumentation and performance: urban arterial embankments on soft foundation soil. In *Proceedings, 14th Annual Engineering Geology and Soils Engineers Symposium*, Boise, ID: Idaho Department of Transportation, Boise, ID, pp. 1-18.

Miller, R. P. and Hilts, D. E., 1970, Experimental open-pit mine slope stability study. In *Rock mechanics, theory and practice, Proceedings, 11th Symposium on Rock Mechanics*, Berkeley, CA: Society of Mining Engineers of the American Institute of Mining, Metallurgical, and Petroleum Engineering, Inc., New York, NY, pp. 147-167.

Mohney, J. W. and Steward, J. E., 1982, Construction and evaluation of roads over low strength soils using nonwoven geotextiles. In *Proceedings, 19th Annual Engineering Geology and Soils Engineering Symposium*, Pocatello, ID: Idaho Department of Transportation, Boise, ID, pp. 161-180.

Mullineaux, D. R.; Nichols, T. C.; and Speirer, R. A., 1964, A zone of montmorillonitic weathered clay in Pleistocene deposits at Seattle, Washington: *U.S. Geological Survey Professional Paper 501-D*, pp. D99-D103.

O'Brien, A. J., 1987, Geotechnical investigation for the Spirit Lake Memorial Highway into the Mount St. Helens National Monument—An overview: In *Proceedings, 23rd Annual Engineering Geology and Soils Engineering Symposium*, Logan, UT: Idaho Department of Transportation, Boise, ID pp. 133-151.

Olmsted, T. L., 1969, Geological aspects and engineering properties of glacial till in the Puget Lowland, Washington. In *Proceedings, 7th Annual Engineering Geology and Soils Engineering Symposium*, Moscow, ID: Idaho Department of Transportation, Boise, ID, pp. 223-233.

Olson, B. O., 1979, Loess Soils in Southeastern Washington: *Journal of the Geotechnical Engineering Division*, American Society of Civil Engineers, New York, NY, Vol. 105, No. GT6, pp. 786-791.

Olson, B. O., 1987, Personal communication, Consulting Engineer, Spokane, WA.

Palladino, D. J., 1971, *Slope failures in an over-consolidated clay, Seattle, Washington* [Ph. D. thesis]: University of Illinois at Urbana-Champaign, Urbana, IL, 188 p.

Palladino, D. J. and Peck, R. B., 1972, Slope failure in an over-consolidated clay, Seattle, Washington: *Geotechnique*, Vol. 22, No. 4, pp. 563-595.

Parker, H. W. and Robinson, R. A., 1983, The world's largest-diameter soil tunnel: *Underground Space*, Vol. 7, No. 3, pp. 175-181.

Rippe, A. H. and Schroeder, W. L., 1976, Consolidation of fine grained Columbia River alluvium In *Proceedings, 14th Annual Engineering Geology and Soils Engineering Symposium*, Boise, ID: Idaho Department of Transportation, Boise, ID, pp. 191-207.

Robinson, R. A.; Kucker, M. S.; Feldman, A. I.; and Parker, H. W., 1987, Ground and liner behavior during construction of the Mt. Baker Ridge Tunnel. In *Proceedings, Rapid Excavation and Tunneling Conference*, New Orleans, LA: Society of Mining Engineering of the American Institute of Mining, Metallurgical and Petroleum Engineers, Inc., New York, NY, pp. 292-308.

Sager, J. W.; Griffiths, J. B.; and Fargo, N. J., 1985, Spirit Lake outlet tunnel: *Newsletter*, United States Committee on Large Dams, No. 77, pp. 4-12.

Sharp, K. D., 1987, Geotechnical design considerations for outfalls in south Puget Sound. In *Proceedings, 23rd Annual Engineering Geology and Soils Engineering Symposium*, Logan, UT: Idaho Department of Transportation, Boise, ID, pp. 409-426.

Sherif, M. A., 1966, Physical properties of Seattle freeway soils: *Soil Mechanics Research Report No. 2*, College of Engineering, University of Washington, Seattle, WA, 27 p.

Sherif, M. A. and Strazer, R. J., 1973, Soil parameters for design of Mt. Baker Ridge Tunnel in Seattle: *Journal of the Soil Mechanics and Foundations Division*, American Society of Civil Engineers, New York, NY, Vol. 99, No. SM1, pp. 111-137.

Smith, M., 1975, *Coal Mine Subsidence in Washington State—Inventory of a Geologic Hazard* [abstract]: Geological Society of America Abstracts with Programs, Vol. 7, No. 3, pp. 377.

Tillson, D. D., 1977, Geology and foundation excavation at the Satsop nuclear power plant, in *Guidebook, Association of Engineering Geologists, 20th Annual Meeting, Seattle, WA*: Association of Engineering Geologists, Lawrence, KS, pp. 102-114.

Tubbs, D. W., 1975, *Causes, Mechanisms, and Prediction of Landsliding in Seattle* [Ph. D. thesis]: University of Washington, Seattle, WA, 88 p.

Wallis, S., 1983, Overcoming those TBM downtime blues: *Tunnels & Tunneling*, Vol. 15, No. 4, pp. 46-48.

Wilson, S. D. and Johnson, K. A., 1964, Slides in over-consolidated clays along the Seattle freeway. In *Proceedings, 2nd Annual Engineering Geology and Soils Engineering Symposium*, Pocatello, ID: Idaho Department of Transportation, Boise, ID, pp. 29-43.

Yamane, G. and Wu, M. J., 1983, 600-ton piles support West Seattle Freeway Bridge. In *Proceedings, 20th Annual Engineering Geology and Soils Engineering Symposium*, Boise, ID: Idaho Department of Transportation, Boise, ID, pp. 223-237.

Completed excavation for the Columbia Center in Seattle, showing lagged tie-back walls typically used in downtown foundation excavations. Photograph courtesy of Shannon & Wilson, Inc.

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Ground Water In Washington

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INTRODUCTION

The subject of ground water concerns not only geology but also hydrology, chemistry, engineering, and water well technology—not to mention land-use planning, politics, and law. Because of the magnitude of its subject, this chapter is limited to an overview of the author's knowledge and opinions. There are numerous excellent texts on the technical aspects of ground water and hydrology, for example, Driscoll (1986). A useful recent annotated bibliography of the subject is found in Hall & Associates (1986).

Ground water, as discussed herein, is the naturally occurring resource that is of interest to the public. Ground water is the water available to wells or issuing from springs that has present or potential benefit to the needs of man. Ground water is the water contained in the interstices of geologic media and below the level of saturation. In most places ground water is in transit, driven by gravity and flowing from recharging precipitation to areas or points of discharge.

Ground water is contained in and travels through aquifers. In simplest terms, an aquifer is a geologic medium with the characteristics that allow water to be drawn from it, through wells or springs, in sufficient quantity to be of benefit.

To some degree, Washington's ground water serves the vast majority of its population. Direct use is through countless wells that serve individual homes and wells that provide water for public and private water districts. Less direct use is through the products of irrigation, industrial works, and food and beverage processors for which ground water is the prime water supply.

The occurrence, means of extraction, and investigation of the beneficial resource within the state are the subject of this chapter. Ground water can also be a critical aspect of civil works construction (such as dams), reservoir containment, slope stability, and foundation dewatering. These construction aspects concern the public in general and the engineering geologist in particular, but they are of separate scope and not further discussed in this chapter.

OCCURRENCE OF GROUND WATER IN WASHINGTON

General

As with climate, culture, and crops, the aquifer systems in Washington differ east and west of the Cascade Range. The Cascade Range (which divides the state) can be considered essentially without aquifers except for some specific Pleistocene or Recent fluvial deposits in valleys.

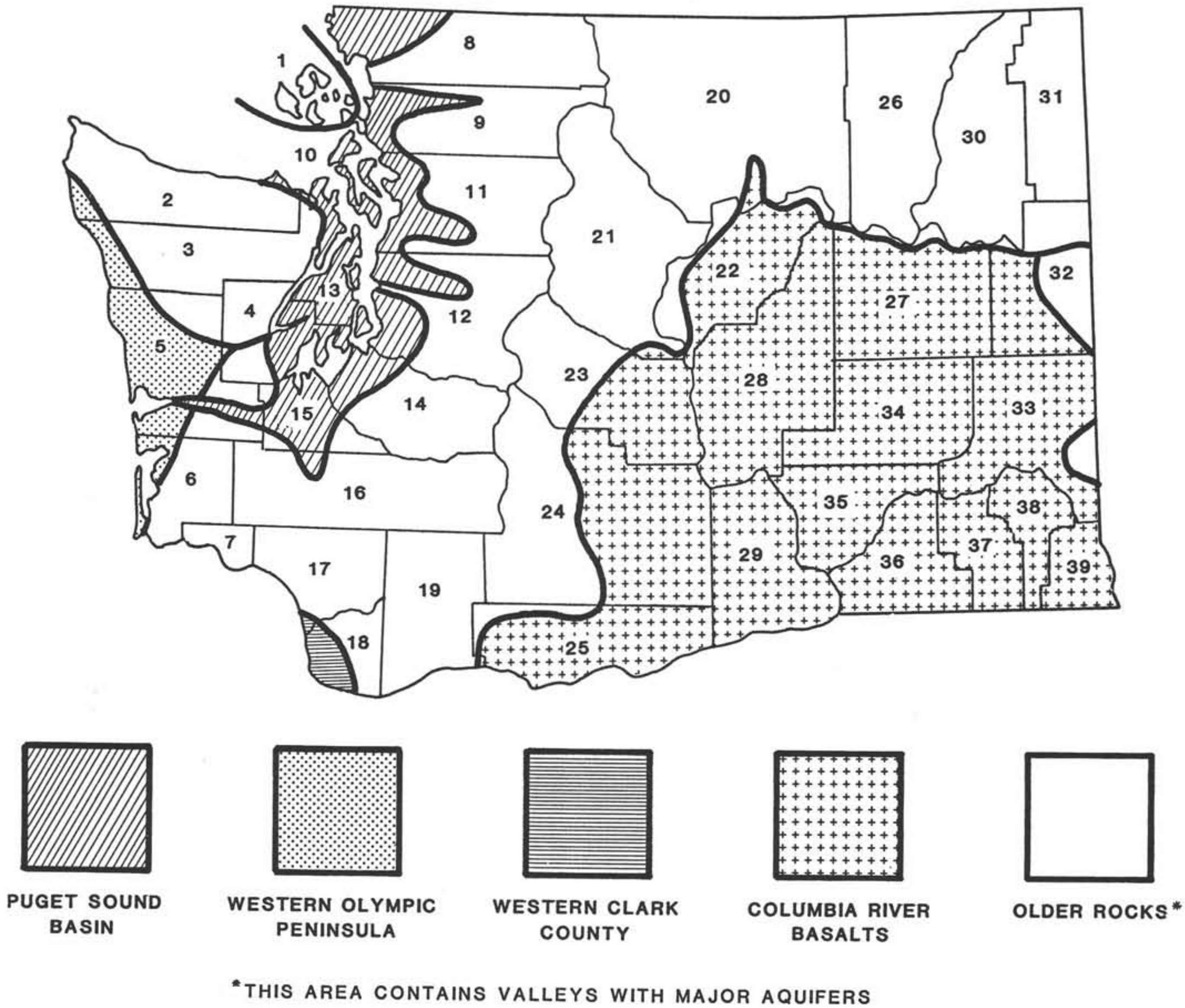
Major aquifers in western Washington are comprised of unconsolidated fluvial or glaciofluvial sands and gravels of Pleistocene and Recent age. Recharge is abundant, annual, and local. In eastern Washington the major aquifers are contained in two major groups. The older group is in permeable zones in basalt and associated fluvial strata of the Columbia River basalts. The younger group consists of Pleistocene and Recent fluvial sand and gravel. Recharge in eastern Washington is sparse and infrequent, except where it is associated with surface-water throughflow (as the Columbia River), in which case it is abundant.

The ground-water resources of western and eastern Washington are discussed separately, below. Figure 1 shows generalized ground-water regimes as related to county boundaries. The Cascade crest divides the eastern and western Washington counties from the Whatcom-Okanogan border in the north through the Skamania-Klickitat border on the south.

Western Washington

The majority of ground-water production in western Washington is from wells in the Puget Sound basin and Georgia Depression that draw from Pleistocene alluvial aquifers. This area is coincident with the main population centers.

The northern part of the basin is in Whatcom County, Island County, the lowlands of western Skagit and Snohomish counties, and the northwestern part of King County. Ground-water use is locally important to these



COUNTY CODE

1. SAN JUAN	11. SNOHOMISH	21. CHELAN	31. PEND OREILLE
2. CLALLAM	12. KING	22. DOUGLAS	32. SPOKANE
3. JEFFERSON	13. KITSAP	23. KITTITAS	33. WHITMAN
4. MASON	14. PIERCE	24. YAKIMA	34. ADAMS
5. GRAYS HARBOR	15. THURSTON	25. KLICKITAT	35. FRANKLIN
6. PACIFIC	16. LEWIS	26. FERRY	36. WALLA WALLA
7. WAHKIAKUM	17. COWLITZ	27. LINCOLN	37. COLUMBIA
8. WHATCOM	18. CLARK	28. GRANT	38. GARFIELD
9. SKAGIT	19. SKAMANIA	29. BENTON	39. ASOTIN
10. ISLAND	20. OKANOGAN	30. STEVENS	

Figure 1. Ground-water regimes in Washington.

areas, but a predominance of fine-grained alluvium in this region tends to limit the existence of major aquifers. Therefore, large ground-water supplies are commonly taken from coarser Recent alluvium near the mouths of the major west-flowing rivers. However, in this northern area the largest public supplies are from direct surface-water sources. Seattle uses the Tolt and Cedar rivers, Everett uses the Sultan basin, Bellingham uses Lake Whatcom, and satellite communities commonly purchase from these larger systems. Attempts to obtain major municipal supplies from ground water have had limited success.

The southern part of the basin is in southwestern King County, northeastern Pierce County, central Thurston County, and north-central Lewis County. Here, major aquifers exist in Pleistocene alluvium that tends to consist of coarser and more permeable gravel than that in the northern basin. With the qualified exception of the City of Tacoma, the vast majority of municipal/industrial and single-domestic water supplies are from wells in that alluvium. Tacoma has a conjunctive-use system wherein a direct surface-water intake from the Green River below Howard Hanson Dam provides the base supply, which is augmented as needed from wells in the Puget Sound basin. Tacoma has yet a further ground-water supply from an intermontane Pleistocene alluvial aquifer above Howard Hanson Dam. That water is primarily a clear-water substitute for the surface supply when the Green River runs turbid.

The west-central part of the basin is in eastern Mason County, Kitsap County, and the easternmost parts of Jefferson and Clallam counties. The population of these areas mainly depends on Pleistocene alluvial aquifers. Exceptions are Port Townsend and Bremerton where surface supplies are the mainstay. In places the west-central aquifers can be excellent producers, particularly where the sediments consist of abundant amounts of gravel from the Olympic Mountains rather than gravels transported from the north by the Puget lobe.

In addition to the Pleistocene alluvium aquifers of the Puget Sound basin, there are only two general areas in western Washington where Pleistocene aquifers are important. These are on the western Olympic Peninsula and in western Clark County.

The western Olympic Peninsula (parts of Clallam, Jefferson, Grays Harbor, and Pacific counties) has Pleistocene glaciofluvial terraces that have not been subjected to much exploration because of the low level of water need in the area. Water wells other than for single-domestic use are not common. To the author's knowledge, the wells with the highest continuous yield which tap the glaciofluvial terrace gravels serve the City of Forks in Clallam County.

Excellent aquifers exist beneath the major longshore spits in Grays Harbor and Pacific counties. These spits are formed by sand and some gravel that has been carried from the Columbia River and to a lesser degree from the Chehalis River from the late Pleistocene through the present time. The spit deposits extend from about 20 ft above to 100 ft below sea level and contain locally recharged fresh water. To date there has been no salt-water intrusion to the main wells, but the system is so delicately balanced that an overdraft could allow intrusion. Population centers served by these aquifers are Ocean Shores, Westport, and the Long Beach Peninsula towns.

Western Clark County has a distinctly different Pleistocene aquifer system. An older sequence of unconsolidated to semiconsolidated alluvium locally contains excellent aquifers; these sediments are generically called the Troutdale Formation. A younger sequence, particularly where hydraulically connected to the Columbia River, contains some exceptional aquifers. This younger sequence, designated by the author as the Orchards gravel, is derived from outwash from the catastrophic floods of ancient Lake Missoula of glacial times. The Orchards gravel, where associated with the Columbia River, yields a practically unlimited water supply for municipal/industrial uses in the Vancouver area.

The lowlands from north-central Lewis County to Clark County (generally the populated corridor along Interstate Highway 5) are beyond the area glaciated by the Puget lobe; they occupy a trough between the Cascades on the east and the Willapa Hills-Black Hills on the west. There are thousands of wells in this area, though yields of more than 50 gpm are generally not expected. The aquifers are mostly in late Tertiary to early Pleistocene sediments.

An extension of the Columbia River basalt is present in Lewis and Cowlitz counties. Moderate yields have been gained from these basalts flows.

The Cowlitz valley of Lewis County has terraces from old alpine glaciations that contain moderately good aquifers above the older sediments.

Eastern Washington

Ground water in eastern Washington is mostly obtained from the Columbia River Basalt Group (CRBG) flows and interbeds, alluvium associated with the Columbia River itself, and valley alluvium of the Cascades and northern highlands.

Figure 1 shows the approximate distribution of the CRBG. Deep wells penetrating the basalt have been drilled throughout this area. Yields are extremely varied, ranging from major irrigation supplies to minor domestic supplies. The western counties, Kittitas, Grant, Benton, Klickitat, and Yakima, have developed the greatest production capability from the CRBG aquifer systems.

Included with the CRBG system are two major areas of Pleistocene alluvium. These are sands of the Quincy basin west of Moses Lake in Grant County and sands and gravels of the Hanford-Pasco area. The Quincy basin has the larger resource of the two by virtue of recharge from irrigation return flow from the Columbia Basin Irrigation Project. The Hanford-Pasco area is deficient in recharge. Major resource use in that area requires that the aquifers have continuity with the Snake or Columbia rivers.

Large production is obtained from interflow alluvium in the Ellensburg region of Kittitas County and the Yakima valley in Yakima County. Recharge to these aquifers is dependent on east-flowing streams from the Cascades and direct precipitation in this area of relatively more humid local climate.

The Columbia River from above Rocky Reach Dam (Douglas County) to below Priest Rapids Dam (Grant County) has deposited a system of Pleistocene and Recent gravel that has exceptionally high permeability in many places. Successful wells in this system depend on the Columbia itself for a recharge balance.

Valley alluvium of Pleistocene and Recent age is the primary aquifer system throughout the remainder of eastern Washington. Valleys where major alluvial aquifers exist are the Wenatchee, Methow, Okanogan, Sanpoil, and Colville. Selected wells in these aquifer systems can produce major amounts of ground water that is recharged by river throughflow.

A special case of valley alluvium in eastern Washington is the Spokane Aquifer, which is derived at least in part from deposits resulting from the repeated evacuations of glacial Lake Missoula in Montana. A concentrated outflow routed through the Spokane River valley left an exceptional aquifer that serves Spokane. Older municipal wells there, which were hand dug and are supported by wood cribbing, yield thousands of gallons per minute.

AQUIFER TYPES

The types of aquifers in the state are as various as the state's complex geology. A simplified grouping of the host geology is:

Unconsolidated Rocks

(a) Recent alluvium

(b) Pleistocene alluvium including glaciofluvial deposits

Consolidated Rocks

(a) Columbia River basalts (CRBG) and associated interflows

(b) Sedimentary rocks

(c) Crystalline rocks (other than CRBG)

Aquifers in Unconsolidated Rocks

This general group provides the preponderance of ground water to wells in both eastern and western Washington. Aquifers in Recent alluvium, by definition, are associated with through-flowing streams and depend upon recharge from the stream. Pleistocene alluvium, as here defined, includes all direct glacial drift and other fluvial deposits resulting from the vagaries of the Pleistocene climate. Accordingly, Pleistocene alluvium is far more widespread and much more complex than Recent alluvium.

Recent Alluvium

Most perennial streams more than a few miles long have developed a post-Pleistocene aggradation of alluvium somewhere along their courses. The alluvium is readily observed at the surface, and shallow exploratory drilling can usually determine the presence or absence of suitable aquifers rather easily. The composition of the alluvium ranges between slack-water silt and high-energy boulder gravel with a consequent variation in permeability.

In many places, particularly in the lower valleys of western Washington rivers, Recent alluvium lies directly on Pleistocene alluvium; in places hydraulic connection exists between the two. These Pleistocene aquifers could be geologically classed with Pleistocene alluvium but depend on recharge more or less directly from the through-flowing stream. Figure 2 schematically shows this relation.

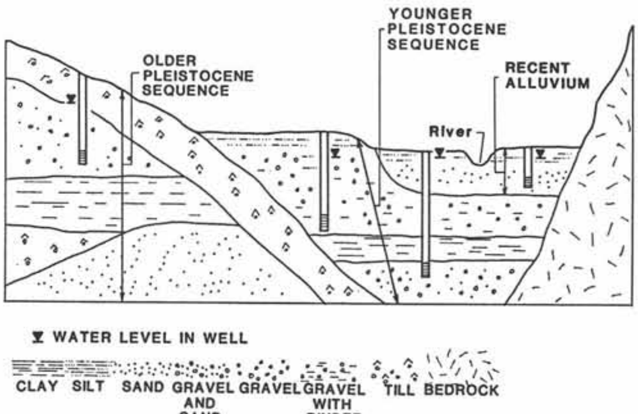


Figure 2. Sketch of possible relation of Pleistocene to Recent alluvium.

Pleistocene Alluvium

This category includes the glacial, interglacial, and periglacial deposits which underlie a major part of the lowlands. In western Washington the thickness of the Pleistocene fill commonly exceeds 1,000 ft and locally exceeds 3,000 ft. In eastern Washington the Pleistocene deposits are thinner and of relatively less importance as aquifers.

In the Puget Sound basin, the most populous part of the state, countless thousands of water wells produce from the Pleistocene alluvium. In spite of the number of these wells, there is no typical well. This is because the controlling geology is glacially derived and exceedingly complex. The aquifer systems have limited areal extent, and, to date, very few systems have been identified to the degree that their hydraulic boundaries are defined. Even where the glacial stratigraphy is known with reasonable confidence, as with the Vashon or Salmon Springs drifts, there is no hydrologic consistency within the stratigraphic unit. As such, there are no widespread "Salmon Springs" or "Vashon" aquifers, although discrete aquifer systems may exist within these stratigraphic units. Furthermore, discrete aquifer systems can readily cross stratigraphic boundaries.

The Pleistocene deposits in the glaciated Puget Sound basin result from a series of continental glacial events (ice masses termed the Puget lobes) alternating with interglacial episodes. The continental glaciers flowed south from British Columbia. Stratigraphers have locally named four glaciations and three intervening interglacial times. The author's experience with deep drilling has suggested that several more similar episodes are recorded in the stratigraphy but are not named. Even the two latest named glaciations may in fact be three. Further compounding the complexity of local glacial stratigraphy are the deposits of alpine glaciers that extended to the lowlands before or after individual advances of the Puget lobe ice. These deposits interfinger with those of the Puget lobes, and their stratigraphic setting is very difficult to define.

The Pleistocene aquifers are commonly, but by no means consistently, contained in glaciofluvial sand and gravel. Glaciofluvial deposits were derived from proglacial streams issuing from either an advancing or a wasting glacier. Where energy was high, the streams were braided, leaving a complex system of clean gravel, clean sand, poorly sorted mixtures of sand and gravel, or gravels nearly choked with silt—all deposited concurrently across an outwash plain. Elsewhere, as in proglacial lakes or broad outwash plains, fine sediments are more prevalent. Some widespread sands were deposited on such broad features, although erosional incision has generally limited their continuity.

To date, the largest defined single aquifer system known to the author is a proglacial, sand-filled channel between Redondo, on Puget Sound, and Milton, in the Puyallup valley. This system is about 1 1/2 mi wide and 7 mi long and is capped by till. There is no topographic expression of the channel. More typically, individual glacial outwash channels can not be traced beyond two or three data points or wells. Working within this framework, the author has been known to advise: "water is where you find it." Figure 3 is a diagrammatic geologic section of conditions that can occur in the Puget Sound basin, and it suggests the difficulty in describing aquifer geometry.

Nonglacial deposits, especially those derived from the main ancestral rivers, do show reasonable continuity. If identified with accuracy, the nonglacial units provide the best marker beds to identify the glacial units. The nonglacial deposits are commonly silts and fine sand, in many places with interbeds of peat. The nonglacial deposits do host useful aquifers but far less commonly than the glacial deposits.

Aquifers in Consolidated Formations

Columbia River Basalts

The Columbia River basalts are generically discussed in the introduction to this volume. These extrusive rocks and associated sedimentary interbeds host widespread aquifers throughout much of eastern Washington. The typical basalt flow consists of a top and bottom colonnade with a central entablature of relatively massive rock. Interflow materials include weathered basalt, scoria, and alluvium. These interflow zones comprise the principal aquifers because they offer the horizontal permeability that is lacking in the more competent sections of the flow rock. Where present, interflow alluvium and lacustrine sediments range in thickness from nearly zero to hundreds of feet.

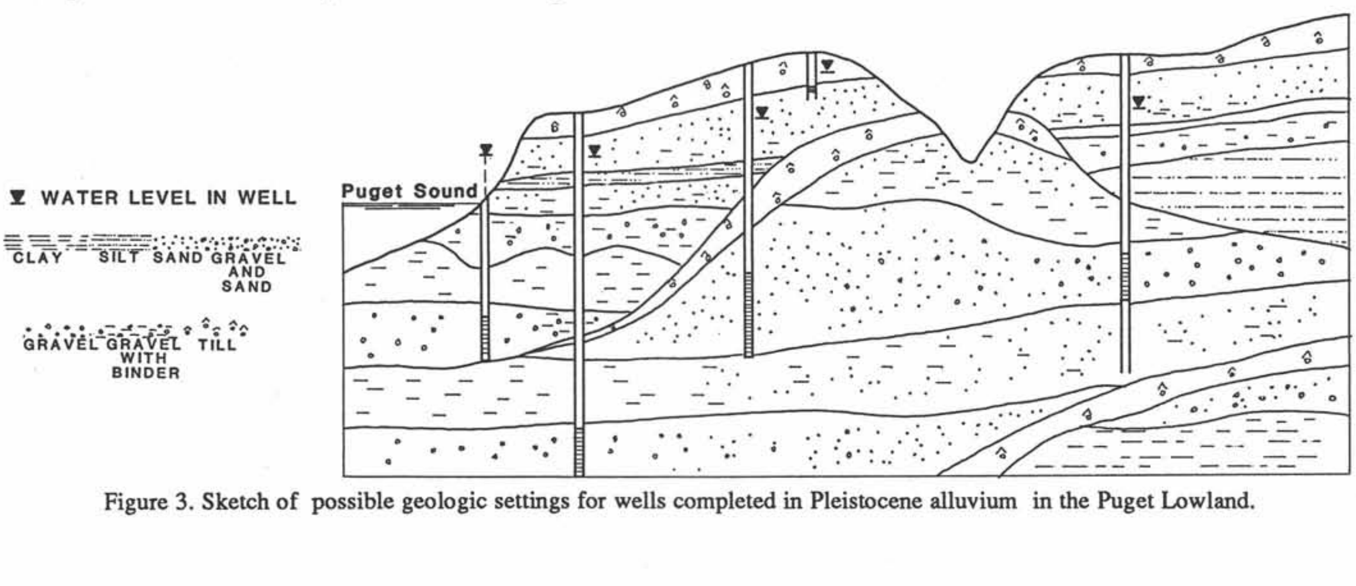


Figure 3. Sketch of possible geologic settings for wells completed in Pleistocene alluvium in the Puget Lowland.

Sedimentary Rocks

Tertiary and older sedimentary rocks, usually fairly well lithified, are a common surficial unit throughout the state where not buried by Pleistocene sediments or the Columbia River basalts. Most of these rocks have very low permeability as a result of low-grade metamorphism, secondary mineralization, or primary grain-size limitations. Therefore, major aquifers are rarely present. Many wells are completed in these older sedimentary rocks, but the vast majority of these are for single-domestic or other low-volume supplies. Many such wells in western Washington yield connate salt water.

Crystalline Rocks

Large areas of the state are underlain by crystalline rocks—granite, granodiorite, basalt, andesite, and middle- to high-grade metamorphic rocks.

Some wells in crystalline rocks allow moderate production; however, in the author's experience most do not. If there is no other option than to drill crystalline rocks, some geologic intuition is in order through the method of fracture trace analysis. The author is not aware of a systematic use of this method, but it could have merit in crystalline terrain.

WATER QUALITY

Ground-water quality in Washington tends to be good in most places for most uses. Potable supplies and most industrial supplies require water with low to moderate total dissolved solids contents, low to moderate hardness, and dissolved iron and manganese in concentrations below 0.3 and 0.05 ppm respectively. Most problems with quality concern iron and manganese contents above these recommended limits.

Waters in eastern Washington tend to be harder than those in western Washington. To a large degree, mineralization results from a combination of available minerals in the host aquifer and residence time. The western Washington soils have undergone more leaching resulting from the humid climate, and the water residence time in the aquifers tends to be less than is typical for eastern Washington. Typical hardness is imparted by the ionic balance of calcium and magnesium with bicarbonate—the most common dissolved solids in Washington's ground water. Some ground water is so hard that treatment is required.

Iron and manganese can occur in troublesome amounts regardless of total mineralization and/or hardness. These ions, to be in a dissolved state, usually require a reducing (anoxic) environment. Problems occur when the water is aerated and the iron or manganese precipitates; such water may stain appliances. Iron and manganese problems are common in western Washington, particularly in aquifers associated with water sources related to modern or ancient organic deposits. Major differences in iron and manganese content are commonly found in wells separated by short vertical or horizontal distances.

Another common quality problem is the presence of dissolved hydrogen sulfide which, upon release to the air, yields its characteristic rotten egg odor. Hydrogen sulfide waters, where present, are usually found below confining zones of clay. The sulfide probably is the result of organic breakdown.

Water with a high chloride content (with associated high total dissolved solids content) is found in two special cases. The first is where sea water has directly invaded the aquifer, usually through over-pumping such that fresh-water levels are drawn below sea level. Proximity to the sea is necessary for this condition. The second case is ancient sea water trapped during deposition (connate water) and is restricted to marine sedimentary rocks of Tertiary age. Also in the second category, and less common, is Pleistocene "hangover" water: fluvial aquifers were inundated by marine water during times of Pleistocene high sea level. The condition occurs where these waters have remained trapped.

To assure that a water supply meets the criteria in the state drinking water regulations requires testing for numerous heavy metals which are known to be toxic. These metals are very rarely found in the state's natural ground waters. Of those metals that are, the most commonly found is arsenic, which can have either natural or manmade origins.

Newly promulgated federal drinking water guidelines require testing for a host of "priority pollutants", most of which are manmade organic chemicals or breakdown products thereof. Where these pollutants are found, further testing nearly always points to an industrial source. Reporting and testing is commonly accompanied by loud announcements from the news media and intensive study by the legal profession and the engineering/hydrogeological community.

DRILLING METHODS

The study and development of ground-water resources ultimately depend on the drill and the pump—and thereby on the drilling industry. The numerous drilling methods are discussed separately and in order of their importance in developing the state's water wells.

Cable-Tool Drilling

Throughout the state the old cable tool or churn drill method has been the main method historically used, although the air rotary drills probably construct more individual wells today. The cable tool, where drilling unconsolidated deposits, typically runs steel casing concurrently with the drilling process. In this way the integrity of the hole is constantly controlled, and all cuttings or bailings are known to be from a defined depth.

The typical domestic well drilled with a cable tool machine has a 6-in. diameter and is completed in the aquifer with open-bottom, perforated casing or a well screen, subject to the driller's judgement. Wells designed for larger yields tend to be of 8-in. through 20-in. diameter and have completion by screens or, in some instances, perforated casing. Single strings of casing drilled in with cable tool have been set as deep as 900 ft. However, for planning purposes, a single string can be expected to "refuse" within 350 ft. Therefore, if a well is expected to be completed at 1,000 ft with 12-in. casing, it should be started with 20-in. to allow for a reduction to 16-in. and a further reduction to 12-in. diameter. These large, deep wells take months to drill and are very expensive.

Air-Rotary Drilling

The air-rotary method has been used for many years where consolidated rocks are present. This drill, with a rotating bit, blows the cuttings rapidly out of the hole. Where saturated rock is struck, the discharge is a combination of water and cuttings. Water is very obvious with air drilling, whereas it is less obvious in the cable-tool hole and is essentially masked with mud rotary drilling. The air-rotary method has a definite depth limitation—the point at which the pressure of water over the bit exceeds the air pressure from the compressor. When this critical depth is reached, the air cannot break through the covering water column, so water and cuttings cannot be blown from the hole. Thus, a well drilled with 200 psi air pressure "drowns out" when the tools are beneath 460 ft of water.

In about 1970 the industry developed a casing hammer, which concurrently drives casing as the air-rotary drill progresses. This method allows the air-rotary method to be easily capable of drilling in unconsolidated formations that require casing. Accordingly, because of the speed of the air rotary, a majority of new domestic wells are now drilled by this method.

A disadvantage to the geologist is that the air-rotary method provides very disturbed samples compared to cable-tool or drive-core samples. A further disadvantage is that a 12-in.-diameter hole is essentially the practical maximum obtainable with the air volume available to most rigs.

Mud or Direct Rotary Drilling

This method, the standard of oil and gas drilling, drills open hole with a rotating bit and circulates a prepared mud (usually bentonite) down the drill column, through the bit and back out the hole annulus outside of the drill column. Cuttings (samples) are very badly disturbed, and water is detected only indirectly through the weakening or loss of drilling mud. The mud-rotary log must be enhanced by borehole geophysical logging, particularly electric logs. The electric log, which shows both the self potential and electrical resistivity in the soil, ideally shows marked anomalies where fresh-water aquifers occur.

Few water wells are drilled with mud rotary. In western Washington the method is almost exclusively used for test drilling where depths exceeding 1,000 ft can be drilled without casing. In eastern Washington some major irrigation and municipal wells have been drilled by mud rotary, with varying degrees of success.

Other Methods

The old hand-dug well is essentially a thing of the past. Notable hand-dug wells are those that supply the City of Spokane from coarse gravel alluvium of the Spokane Aquifer.

Where conditions allow, many domestic supplies are completed as driven or hydraulically jetted "sand points".

Reverse rotary is an excellent method to drill a very large diameter hole if cobbles or boulders are not present. This method requires a large mud pit freely connected to the borehole. There is a drill string and rotating bit as with normal rotary, but the drilling fluids are pumped from the bottom of the hole, through the bit and column, to the pond—whence the term reverse rotary. Few Western Washington wells are drilled with the reverse rotary method, whereas many excellent wells in Pleistocene sand are completed utilizing this method in eastern Washington.

Horizontal collectors are specialty wells that can yield very large supplies from alluvial gravel aquifers in continuity with surface streams. A large caisson with knock-out ports is set to full depth. The ports are then removed as steel pipes are jacked laterally into the water-bearing formation. Where numerous laterals are placed, the structure can be called a radial well. Horizontal collectors are generally constructed after extensive test drilling by more conventional means. Most of the largest of these wells are termed Ranney wells. Ranney wells provide the water supplies for Anacortes and Kennewick from Skagit and Columbia river alluvium, respectively.

PRACTITIONERS AND PRACTICE

General

Present-day professionals who deal with the ground-water sciences and the study of aquifers usually have their academic roots in geology. Several decades ago the practice tended to be the realm of a high ratio (if not an outright majority) of engineers. Ground-water science requires the application of both engineering and mathematical principles that have been largely developed by engineers. However, these principles must be tempered by geologic considerations, and there the contributions by geologists have been significant.

Today, many of the practitioners have graduate training in hydrogeology, a field which few universities offered 20 years ago. The professional training available earlier was largely promoted by the U.S. Geological Survey (USGS), whose work remains the standard for the science. The older personnel classification of "ground-water geologist" appears to have been nearly replaced by the synonymous "hydrogeologist". The Hellenic root of the latter is apparently more prestigious than the Anglo-Saxon of the former. The end result is the same.

The ground-water geologist in Washington is herein considered to be the professional who deals with ground water in aquifers, that is, the resource itself. (Engineering geology investigations commonly focus on the presence, movement, pressures, and effects of ground water as it affects civil works, but these concerns are not addressed in this chapter). As here considered, ground-water geologists work in the following categories: (1) production, (2) protection, (3) regulation, and (4) research.

Production

The production-oriented hydrogeologist's goals are to assist with the development of ground-water supplies, usually through wells, and to rate the source for safe, sustained yield. To accomplish these goals, the hydrogeologist not only requires a thorough understanding of geologic and engineering principles but must also possess extensive knowledge of the water well drilling industry. The hydrogeologist's product is directly dependent on the quality of the well's construction, its design, and its development. The hydrogeologist must also relate the well's use and behavior to the aquifer system at large.

The hydrogeologist begins a water-supply project by addressing the geologic potential of the site for probable ground water. If the project is feasible, drilling follows, with either small-diameter test wells or with what will become the capital well itself. If drilling is successful, the capital well is completed through the hydrogeologist's direction. Completion consists of design and placement of appropriate screens followed by "development" to render efficient water entry. (In the drilling industry the term development is restricted to the specific task of improving well efficiency during the final stages of well construction.) Typically, the final effort is a controlled pumping test to rate the capital well and to determine its relation to the aquifer. Water-quality tests are made during the pumping phase.

Ground-water production is not totally dependent on the service of a hydrogeologist, as many a well driller, farmer, water witcher, engineer, or town water purveyor will attest. However, cost-efficient, optimum safe sustained yields are usually gained through the contributions of a hydrogeologist. The production-oriented hydrogeologist has a very direct economic relationship with the project. Ideally, his or her services have high cost effectiveness for the benefit of the water obtained.

Protection

Ground-water protection is highly dependent on the services of hydrogeologists. The need for these services is second only to the political drive to protect the resource. Washington's Department of Ecology has stated that one-sixth of the state's population (nearly 700,000 people) is presently at risk of being harmed by contaminated ground water. That figure was developed by assigning an arbitrary radius around each hazardous waste site in the state and placing at risk the contained population. No qualifications were made as to the existence or use of aquifers within these radii. In fact, however, most highly publicized and geologically tested hazardous waste sites are not in association with regional aquifers that supply water to the public. Instead, though hazardous materials may be present, they pose no problem to that area's drinking-water supplies

The ground-water protection community consists of lawyers, planners, chemists, engineers, drillers, and hydrogeologists, not to mention the generator of the questioned substance that has entered the geologic regime. In such a potentially litigious setting, the work by the hydrogeologist must be done with great care. This includes extensive record keeping and working in a very carefully controlled sampling environment. Since the testing can involve components in concentrations of only a few parts per trillion, the hydrogeologist must take special care in the collection and custody of the samples tested for these extremely minute amounts of contaminants.

The protection-oriented hydrogeologist fills a sensitive economic role in that she or he is often a necessary evil, particularly when working for an industrial client. Frequently, the client's goal is to be rid of a perceived or real moral or legal obligation. As such, the hydrogeologist is key to a solution that is often reluctantly funded.

The public awareness of hazardous substances in ground water has caused a burgeoning need for hydrogeologists in recent years. The actual degree of hazard to the public is not well known. Without question, however, water-quality concerns related to man-made organic pollutants have generated a public awareness of a geologically dependent subject greater than for any other aspect of engineering geology. Love Canal, Times Beach, and, locally, American Lake Gardens get more press than the failure of the Teton Dam. The "hazard sites" get far more press than the fact that Grand Coulee Dam did not fail.

Regulation

Ground-water regulation requires the services of many hydrogeologists. The regulations administered deal with both allocation (production) and protection.

Most state ground-water regulation is by the Washington Department of Ecology, whose responsibility it is to administer water rights, to advise and rule on certain water-quality aspects, and to administer the well driller's licensing requirements. Therefore, the regulators must have a thorough knowledge of not only the regulations but also the principles of hydrogeology and well-drilling technology.

Research

Ground-water research, in the broad sense, remains mostly in the hands of the USGS, as it has historically. Good ground-water research consists of descriptions of the surface and subsurface geology, basic-data compilation for wells and well tests. It also includes water quality measurements and plotting of water levels, and interpretive calculations of aquifer parameters. Ideally, such a study shows the controlling geometry (geologic framework) and the aquifer's transmissivity/storativity. Further, optimum methods of well construction can be shown.

In the author's opinion, the general applicability of ground-water research has suffered in the last 20 years because of lack of basic-data reporting and the decision to study specific-need projects rather than general hydrologic areas. With all the current interest in both regulation and protection of ground water, a general imbalance has developed between the basic research required and the regulations applied to ill-defined aquifer systems. One of the larger hydrogeologic research studies ever done is for the proposed Basalt Waste Isolation Project at Hanford. The cost and study effort for this special project probably outweigh all other regional hydrogeological research studies done anywhere. (By early 1988 the study goal became moot because politics sent the basic problems of radioactive storage to Nevada.)

Both regulators and researchers tend to be in direct or indirect government employ and thereby subject to bureaucratic funding. Political philosophy is such that regulation of the resource has priority over research—the typical bane of the scientist who requires funding for pure research. Today's state of knowledge of regional hydrogeology suffers because of the imbalance between regulation and research.

FUTURE NEEDS AND SIMPLE THOUGHTS

Washington's ground-water resources are sporadically distributed, but essential and generous in many places. However, with rare exceptions, the resource is not sufficiently understood. The preliminary understanding of an aquifer system requires a knowledge of two hydrologic parameters, gradient and permeability, and the aquifer geometry. These data are obtained in small part by conventional geologic methods but must mainly depend on reliable subsurface information—essentially from existing water wells and test wells drilled for information purposes. The principal key to the understanding of the aquifer systems is basic well data.

During the 1940s through 1960s the USGS, in cooperation with the state's water resources offices (now Department of Ecology), sent people into the field to collect basic well data and to process and present this information, with interpretations, in a series of ground-water reports. These reports still provide the best data because collection was performed and compiled in a professional manner. Since the late 1960s there has been a vast mount of information generated that does not appear in published reports by the USGS or state agencies.

Today most basic data are derived from the obligatory "Water Well Report" prepared by drillers and sent to the state Department of Ecology. The information quality in these reports is directly related to the precision, ability, memory, interest, and integrity of the particular driller at the time of preparation. In many reports, locations are best-guess and surface elevations are lacking. The inherent inaccuracy of these reports allows the possibility for an unacceptable degree of error from their use; field verification is required. Yet, both consulting and agency personnel use the records freely and with few reservations.

We need new and updated data files and associated interpretations. Interpretations alone are insufficient and require the validated backup data. In the author's opinion, these research projects are the reasonable domain of the public agencies that are mandated to make objective information available for public use. The fine quality of work historically attributable to the USGS is needed again.

At the present time, massive effort is spent chasing site-specific alarms of "hazardous" materials in ground water without sufficient knowledge of the basic resource constraints, let alone the true severity of the hazard. A more regional approach to research is needed to better qualify the specific problem area.

A few simple concepts are presented which are intended to be helpful to the growing knowledge of ground water in the state. The author believes the concepts to be valid but not necessarily popular.

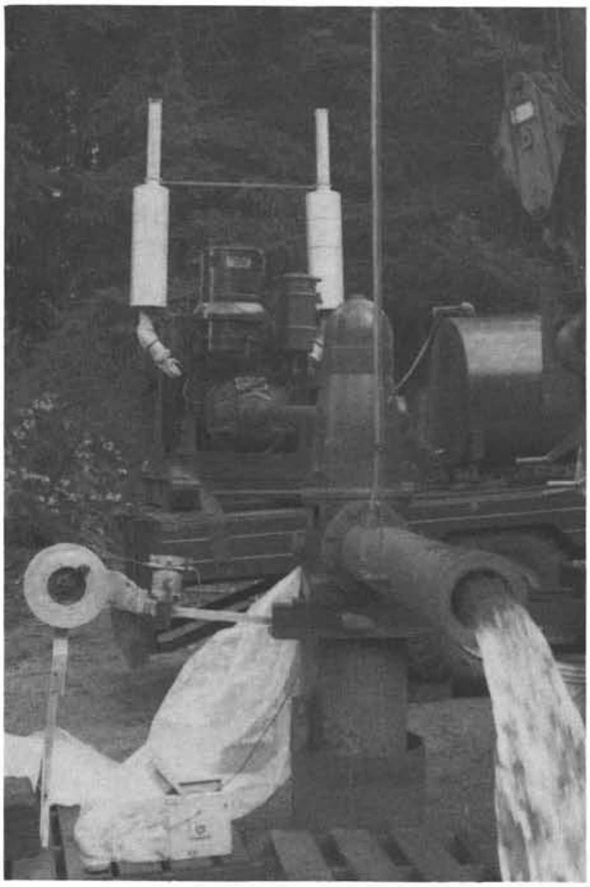
- Water always runs downhill—even ground water.
- There is no known affinity, however remote, of ground water to willow branches, other branches, or welding rods.
- There is no direct underground conduit between Mount Rainier and any water wells. This is also true of Mount Adams and Mount Baker.

- Bacteria do not swim nor otherwise travel extended distances through the state's aquifers.
- As a corollary to the above, there are no aquifers contaminated by bacteria. (There are, however, contaminated wells.)
- Where aquifers are present, there are exceedingly few overlying natural materials that are truly impermeable.
- Few wells go dry.
- There are no bottomless lakes.
- There are no underground lakes or underground rivers.
- There is no firm evidence of a user of public water supplies from wells ever becoming ill as a result of consuming man-made organic chemicals from the water.
- Ground water is derived from precipitation, often within sight distance of the well.
- From the standpoint of sanitary protection, ground water is superior to surface water.
- No one is known to have died as a result of drinking ground water in the state.
- The state's population is the beneficiary of a complex, not well understood, but valuable ground-water resource.

REFERENCES

Driscoll, F. D., 1986, *Groundwater and Wells* (2d Ed.): Johnson Division, St. Paul, MN, 1,089 p.

Hall & Associates, 1986, *Ground Water Resource Protection; A Handbook for Local Planners and Decision Makers in Washington State*: Prepared by King County Resource Planning in cooperation with Washington State Department of Ecology. (This publication contains a 31-page annotated bibliography principally devoted to ground water in Washington).



Pumping test of a new well for the Manchester Water District, Kitsap County. The well's discharge is measured by means of a "circular orifice" and manometer. Changes in the water level are measured with a sounding device, at the left. The portable power supply is a direct-drive diesel engine. Photograph by Joel W. Purdy.

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Erosion

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Consulting Engineering Geologist

INTRODUCTION

Erosion and the complementary action of deposition or accretion are probably the most common and most important geologic processes with which modern man has had to contend in his effort to live on the Earth's surface and maintain a reasonable amount of harmony with nature. Other sections of this volume focus on these complementary processes in terms of landslides and volcanic hazards. This section will focus on the more common, though no less dynamic and perhaps even more influential, aspects of erosion and deposition as they tend to influence the works of man. It is important to comprehend that erosion and deposition are natural and continuing processes that operate within definable limits. An understanding of the processes involved and establishment of these limits by the engineering geologist is of critical importance to the siting, design, construction, and operational safety of engineered structures.

ASSESSMENT FACTORS

General

The assessment of erosion and deposition potentials requires an understanding of three elements: the geologic conditions of the ground involved, the agent and process or processes, and the stage in the erosional or depositional cycle. Although it is common in normal geologic endeavor to consider erosion and deposition in terms of thousands or tens of thousands of years, engineering geology requires consideration in terms of a project's useful life, which may range from several tens of years to a few centuries. Only recently, with the advent of nuclear waste repository evaluations, are longer periods being seriously considered. Thus it is important to consider the above three elements in terms of recent geologic history, project life, and the likelihood of erosional/depositional events occurring during the project life.

Geologic Conditions

The rates of erosion are directly related to the geologic competence and structure of the underlying and adjacent ground involved. Most subaerial erosion in Washington takes place through the action of water, wind, or ice. The general paucity of limestone and gypsum over most of the state precludes major development of subterranean erosion through solution producing surface sinkholes and other karst features. The only exception is in the eastern half of the Okanogan-Selkirk Highlands where extensive limestones are exposed or occur in the subsurface. Areas underlain by sound bedrock are not highly susceptible to erosion in the engineering sense, though they are constantly eroding in a strict geologic sense. However, defects in the rock mass, such as zones of weaker rock, fault gouge, and adversely oriented geologic structures, can easily provide avenues for erosion even in more competent bedrock. Thus, a thorough assessment of the character, structure, and configuration of the bedrock surface is required when siting or designing structures, especially in high-energy areas, such as along the extensive Washington coastline and along high-volume or steep-gradient streams. Some so-called bedrock can be highly erodible—in places more so than the overlying supposedly less consolidated materials.

Assessing the erodibility of material overlying the bedrock surface can be equally difficult. Erodibility is largely a function of sediment composition and compaction—the grains and glue of an unconsolidated deposit. For example, massive, compact glacial till, common over large portions of the Puget Sound Basin, tends to be somewhat more resistant to erosion than the sand beds that commonly underlie it. The sand and gravel of river bars and beaches are in annual or constant motion, and their frequent erosion and redeposition is a natural and anticipated event. The consequent (directly downslope) erosion, which characterizes the great silt "dunes" of the Palouse Hills, attests to their easy erodibility even under low and infrequent rainfall conditions. Similarly, the poorly consolidated overbank sediments of a flood plain are highly erodible. The proper recognition of the character of underlying geologic materials is therefore a critical factor in assessing the erosion potential for a site.

Agents and Processes

The major agents of erosion, as well as of transport and deposition of eroded materials, are water, wind, and ice. Before these major agents can do their work, however, the parent material must be broken down into particles capable of being handled by the eroding/transporting agents. Where surficial fine-grained sediments are truly unconsolidated, the primary agent can work easily. However, where consolidated overburden material or bedrock are involved, the process of erosion first begins with weathering—chemical breakdown (decomposition) and/or disintegration (mechanical breakdown of blocks), either by alternately freezing and thawing of water in cracks and joints in the parent material, or by vegetative root action. Material then moves downslope initially by gravity, as talus, slopewash, or a variety of landslide types (all forms of colluvium), before the major eroding-transport agent can move it away.

Although ice (glaciers) creates some spectacular erosion features in mountainous areas of the Cascades and Olympics and wind is responsible for much of the localized sand dune movement along portions of the ocean coast as well as local erosion of unconsolidated materials on the Columbia Plateau, water is the prime eroder and transporter of detritus in Washington. Water operates in two major ways: (1) as streams flowing seaward with varying discharges and gradients; and (2) as waves and currents along the ocean coast and in Puget Sound and other inland waters. There are similarities in the work of streams and of coastal waters in that these agents have achieved, or are attempting to achieve, a balance between erosion and deposition depending on the kind and size of detritus and energy available. In the case of a stream, it is the balance between discharge and detrital load over a period of years (Mackin, 1948) that governs the gradient and the width and other characteristics of its channel and flood plain. Coastal waters depend on wave action and longshore currents to develop and transport littoral material by erosion in one area and deposition in another. A constant, natural effort is under way along the coast to achieve a hydraulically efficient, smooth coast line in conformance with available energy. Both dynamic processes tend to create a great deal of havoc with works of man when they are ignored, improperly assessed, or misunderstood.

Stage in the Erosional Cycle

In a geologic sense, classic erosional cycles cover a very long period of time—much longer than we are accustomed to thinking of in terms of engineering project life. Yet it is important to understand the stage in the erosional cycle, especially for events, which, although they may not be frequent in human years, may well be important in site assessment. For example, the 100-yr frequency storm or 1,000-yr frequency storm, each based on statistical methods using best available climatological data, and the potential influence of such storms on streams and coastal landforms should be a consideration in siting and design of structures. Frequently these events are ignored, either because of the perceived unlikelihood of their occurrence or because of failure to recognize the signs of previous, albeit rare, occurrences. Thus, it is important to understand what a stream is doing in a given reach over the long term—downcutting, abrading laterally, aggrading, or simply transporting detritus through a graded reach. Once this is determined by fluvial geomorphic analysis, the problems of erosion can be mitigated by proper land-use zoning and/or design. Similarly, through coastal geomorphic analysis, the dynamics of coastal erosion and deposition can be determined and zoned or designed for. Unfortunately, it is the lack of appreciation of the stage in the erosional cycle, together with man's ontogenetic desire to be close to the water, yet be safe from it, which causes most engineering-related erosion problems. What is even more unfortunate is the "point band aid" or "brute force and awkwardness" approaches to mitigating stream bank and coastal erosion problems that commonly tend to create more problems than they solve. The overall effect of erosion protection on nearby areas is infrequently assessed in terms of both process and stage in the erosional cycle. The effects of bank or shoreline protection should be analyzed, not only for the site, but also for adjacent areas upstream and downstream, updrift and downdrift, prior to construction of facilities or protective works.

ASSESSMENT OF STREAM EROSION

Major Streams

A discussion of stream erosion in Washington must include problems of the full range of streams from major rivers to minor intermittent streams, for all have important effects on the works of man. Major streams in the state generally approach what is defined as a graded profile, and hence, they tend to respond rapidly to various changes in discharge, detrital load, or base level with significant changes in gradient and/or channel characteristics (Mackin, 1948; Mathewson, 1981). Such streams are characterized by high gradients and coarser detritus in their mountainous, upper reaches, by more moderate gradients and smaller detritus in their middle reaches, and by low gradients with fine-grained detritus in their lower, near-sea-level and deltaic reaches. The relative lengths of each of these reaches are variable, depending on discharge, detrital load, position of tributaries, gradient, and other controls to the stream's course, such as inherited valleys, underlying geology, and geologic structure. What must be kept in mind, however, is that channel characteristics are a function of flood discharges and detrital loads over a period of many years. Consequently, an analysis of what constitutes the geologically "normal" channel beyond human memory is required. Of special concern are "braided" channels, which characterize segments of glacier-fed streams such as the White, Nisqually, Carbon, Cowlitz, and Puyallup rivers, all emanating from the ice fields of Mount

Rainier. Such channels, over a period of years, anastomose over a large width of valley floor, and changes in river course occur quickly and often without warning. These characteristics are not always considered in present zoning practice nor in the issuing of construction permits.

Erosion by "normal" (unbraided) streams is usually, but not always, more predictable, especially for major rivers that have few or no flood control facilities in their upper reaches and/or are not artificially leveed in the lower reaches. Erosion by these streams takes place primarily during the flood season, wintertime on the west slope and springtime on the east slope. Their upper reaches are in a stage of downcutting and subject to rapid erosional changes owing to the availability of discharge and to the coarse, detrital gushes from tributaries and adjacent mountainous slopes. Thus, when a heavy winter storm produces a high volume of detritus and water from a tributary basin, considerable erosion and excessive deposition can be anticipated both within the tributary basin and downstream for some distance. Because the history of such occurrences commonly can be recognized in downstream river banks, investigations of such occurrences should be preliminary to any cultural developments, especially in valleys in mountainous areas.

The mid-sections of normal streams tend to develop meandering courses through mature or, in places, inherited valleys and lowlands. Typical are the middle sections of the Nooksack, Okanogan, Chehalis, Wenatchee, and lower Snoqualmie rivers. Meander development is accomplished by erosion at the outside of bends accompanied by deposition on the inside of bends, principally during flood periods (Figure 1). This process continues until the stream is nearly graded—it has reached a state of essential equilibrium where the channel slope is sufficient to produce the velocity that can move the detrital load with the available discharge (Mackin, 1948). However, because relatively few rivers completely reach such a state, the potential for channel migration must be analyzed. One thing is certain—the restraint of such migration of erosion and deposition by riprap or other erosion protectors will have repercussions both upstream and downstream, a fact often overlooked in the "band aid" approach to erosion mitigation.

The distal (deltaic) reaches of streams have a number of manifestations, varying from the broad distributary delta of the Skagit River to the direct and more confined mouth of the Quillayute River along the ocean coast. The confluences of major Columbia River tributaries with the mainstem river in eastern Washington have little in the way of deltaic characteristics. Erosion in deltaic reaches is again primarily a function of flood discharges and the tendency to vary the dominance of certain distributaries. Deposition during flood stages results in flood waters spilling into "abandoned" distributaries or creating new ones. Thus, the recognition of low areas on deltas susceptible to such breakthroughs is important in cultural development.

Many of the lower reaches of major western Washington rivers have been subjected to some form of alteration by man. Most evident are major modifications of the Snohomish, Duwamish and lower Puyallup rivers where rechanneling and erosion protection have been extensive. Engineered erosion mitigation along most streams is usually in the form of rock riprap blankets or

Figure 1. Aerial view west of the Nooksack River west of Deming. The braided character of the channel is a result of excess detritus being deposited where the stream passes from the mountain front onto the glaciated plain. Deposition on the right bank results in channel shifting by erosion on the left bank. The stream resumes a more normal channel configuration downstream (center). Photo by the author.

designed mats. The unengineered efforts of erosion mitigation, such as automobile bodies and felled trees, commonly have little real effect in preventing erosion; in many places they increase turbulent flow and result in greater erosion. All efforts to control stream flow will have some effects on erosion and deposition, either upstream or downstream, or both.

Construction of flood control dams tends to augment deposition upstream from the reservoirs, owing to the rise of base level. Downstream erosion changes may be more evident than those upstream, owing to frequent high discharges and significant changes in detrital load. Natural levees in the lower reaches of streams commonly are augmented by artificial levees, in places with additional dikes constructed normal to the stream-flow direction to protect special areas. Although such levees may temporarily assist in controlling floods, they tend to have major impacts with respect to long-term erosion and deposition. The tendency to constrict and concentrate river flows by such structures may increase point erosion locally, but it will eventually result in aggrading the channel by deposition during low-flow periods. Thus, the flood stage of the river becomes higher, and consequent breaching of levees, because of such higher river levels, can have significant impacts on lowland areas that the levees were built to protect.

Reservoired Streams

The impoundment of reservoirs on some of the state's major rivers imposes erosional conditions similar to what one would expect on coastal shorelines. Most reservoirs are fluctuating lakes; their shorelines are subject to erosion by wave action, which, in many places, creates landslides. The degree and frequency of fluctuation, the period of time and the time of year a reservoir level is held at a particular elevation, together with slope declivity and underlying geologic conditions, are all factors in the assessment of erosion. The rise in base level caused by the impoundment produces considerable sediment deposition in the upper reaches of all reservoirs.

The series of reservoirs along the Columbia and Snake rivers offer some excellent examples of erosion and slope retreat. These effects are especially prevalent on the upper Columbia where the presence of extensive areas of highly erodible and landslide-prone glacial and glaciolacustrine deposits has created a continuing management problem along both Franklin D. Roosevelt Lake (behind Grand Coulee Dam) and Rufus Woods Lake (behind Chief Joseph Dam). The problem is lessened in downstream reservoirs where overburden deposits tend to be more gravelly and the reservoir slopes self-armoring. In western Washington, however, most reservoirs are in mountainous terrain where thick colluvium developed on the valley sides commonly tends to become unstable during fluctuating reservoir conditions and high rainfall. Wave erosion and landslide failures are major factors in slope retreat on reservoir peripheries.

Small and Intermittent Streams

Small streams in the more mountainous areas of the state and intermittent streams that characterize much of the eastern, drier part of the state are highly reactive to intense storm activity. They tend to erode rapidly, albeit infrequently, as a function of spring or winter snowmelt or rainfall concentrated over a small area. At other times

Figure 2. Aerial view showing development of tributary alluvial fans by intermittent stream erosion of a glaciofluvial terrace along the Columbia River near Chelan Falls. Note the homestead located on the the fan. Waterville plateau is in background. Photo by the author.

they are dry or have small discharge. Where such a stream enters a larger valley, an alluvial fan, usually of coarse detritus, is deposited in the main valley (Figure 2). The diminutive stream flows in a random consequent manner down the fan, and the channel migrates back and forth across the fan over a period of years. Such fans are frequently selected for construction because of topographic advantage. Several cities and towns are sited on or near enough to such features to make them susceptible to damage by infrequent but disastrous flooding, erosion, and deposition. Examples are Wenatchee and Ephrata.

Consequent erosion (sheet and rivulet erosion) of the great silt dunes of the Palouse Hills section of the Columbia Plateau is a result of infrequent, but torrential and concentrated rainfall. Erosion is not so acute where the hills are covered by well established grasslands. However, farming methods prior to the advent of contour plowing allowed considerable erosion to take place locally and in an intermittent manner.

ASSESSMENT OF COASTAL EROSION

Perhaps nowhere is the importance of the balance between erosion and deposition (accretion) more evident in the state than along its approximately 2,250 mi of coastline. The rate of postglacial eustatic rise in sea level appears to have decreased greatly beginning about 5,000 yr ago (Downing, 1983); only minimal rise in the stand of the sea has occurred since (Terich, 1987). Thus, coastal erosion and development of depositional landforms is geologically very recent. The influence of wave action and longshore currents, which have continually modified the shoreline, is surely the major factor affecting cultural development along the inland waters, the ocean coast (Figure 3), and straits of Juan de Fuca and Georgia. It is most dynamically apparent in the relationship between geologically ephemeral landforms (beaches, spits, bars, hooks) and their detrital source areas. The balance between source and deposit usually varies over an annual cycle owing to climatic, wave, and current changes between summer and winter. Such changes occur within definable littoral cells, each of which includes an internal source of littoral detritus (usually a stream or an area of active erosion), a zone of transport (a "neutral", dynamically stable shoreline), and a zone of deposition (a sediment sink). Any attempt to modify any of the three components within the cell has serious consequences for downdrift components (Downing, 1983; Galster, 1987). For this reason it is necessary to assess the entire littoral cell together with both the dominant littoral drift direction and seasonal changes in drift direction before considering coastal erosion mitigation. In addition, assessment of the rate of these processes is essential owing to the great variability in the dynamics of the processes. For example, because the ocean coast is a much higher energy area than some of the more protected inland waters, reactions to man-induced changes along the ocean coast are more rapid and far-reaching, both temporally and spatially.

Washington's ocean coast consists basically of two segments: a southern (Columbia) segment south of Point Grenville, and a northern (Olympic) segment (Galster, 1987). Both segments exhibit landforms that confirm a dominant northward littoral drift direction in the winter months and a recessive drift reversal to the south in the summer (Schwartz et al., 1985; Galster, 1987). The Columbia segment is basically a single accretionary cell

Figure 3. Erosion of the coastal roadway behind the timber seawall at Point Brown, mouth of Grays Harbor. The decimated North Jetty lies seaward of the timber wall. Photo by the author, February 1974, prior to rehabilitation of the North Jetty.

with detritus supplied by the Columbia River. It displays the greatest coastal dynamics found in the state, dominated by the barrier beaches and major embayments (Grays Harbor and Willapa Bay) that serve as sediment sinks. In spite of its accretionary character, the segment exhibits major erosion problems at Cape Shoalwater and, locally, near the segment's northern end. For example, between 1911 and 1967 Cape Shoalwater retreated about 2 mi northward (Galster, 1987), and 400 to 600 ft of shoreline recession (erosion) occurred at Toke Point on the north side of Willipa Bay between 1911 and 1966 (U.S. Army Corps of Engineers, 1966). The Olympic segment is dominantly an erosional segment characterized by numerous quasi-independent littoral cells (Mahala, 1985). Similarly, the south coast of the Strait of Juan de Fuca is characterized by a series of quasi-independent cells responding to dominant eastward littoral drift. The dynamics of erosion and deposition may be lower than those along the ocean coast, yet they are most impressive, as can be seen in the erosion of sea cliffs, both in the bedrock and glacial deposits and in the formation of shore forms such as Ediz Hook and Dungeness Spit (Galster and Eckman, 1977; Galster, 1987).

The inland waters exhibit a great variety of net drift directions and an equal variety of sea-cliff retreat rates and shore forms, including cuspate forelands, spits, bars, and delta fronts (Terich, 1987). Most of the erosion occurs by slow sloughing, block calving, and landsliding through intermittent undermining of sea cliffs by wave action. Approximately 36 percent of inland shorelines (including the Strait of Juan de Fuca) is considered depositional in character, 32 percent is erosional, 24 percent consists of modified shoreline, and only 8 percent is considered neutral (Downing, 1983). Thus, construction of erosion mitigation structures such as sea walls, bulkheads, groins, and riprapped mats, is likely to fall into the 56 percent of the shoreline that is erosional or modified in character. Moreover, such erosion mitigation structures affect the neutral and depositional areas as well. Thus, while the local (point) approach to arresting shoreline erosion has effects on adjacent areas, broad protection can have drastic repercussions over a considerable area.

SUMMARY

The ease of living with erosion and/or deposition as a natural process is directly related to the appreciation of both the extent and limits of the natural agents involved and in the appropriate zoning and design. Areas highly susceptible to rapid and frequent erosion or deposition are perhaps best left as parks or other common areas, generally devoid of engineered structures. Where transportation routes or other infrastructure elements are required across such areas, appropriate assessment and design for the continuance of the geologic process must be accomplished.

The importance of working with nature cannot be overemphasized, for the results of opposing or interrupting natural processes can be far-reaching. Failure to make such assessments may provide much employment for future generations of engineers, geologists, and lawyers.

REFERENCES

Downing, J., 1983, *The Coast of Puget Sound, Its Processes and Development*: Puget Sound Books, University of Washington Press, Seattle, WA, 126 p.

Galster, R. W., 1987, A survey of coastal engineering geology in the Pacific Northwest: *Bulletin of the Association of Engineering Geologists*, Vol. 24, No. 2, pp. 161-197.

Galster, R. W. and Eckman, M., 1977, Coastal engineering geology, northern Olympic Peninsula, in *Guidebook to Field Trips*: Association of Engineering Geologists, 1977 Annual Meeting, Seattle, WA, pp. 116-133.

Mackin, J. H., 1948, Concept of the graded river: *Geological Society of America Bulletin*, Vol. 59, pp. 463-512.

Mahala, J., 1985, *Net Shore Drift Along the Pacific Coast of Clallam and Jefferson Counties, Washington* [M.S. thesis]: Western Washington University, Bellingham, WA, 73 p.

Mathewson, C. C., 1981, *Engineering Geology*: Charles E. Merrill Publishing Co., Columbus, OH, 409 p.

Schwartz, M. L.; Mahala, J.; and Bronson, H. S., III, 1985, Net shore-drift along the Pacific coast of Washington State: *Shore and Beach*, Vol. 52, pp. 21-25.

Terich, T. A., 1987, *Living with the shore of Puget Sound and the Georgia Strait*: Duke University Press, Durham, NC, 165 p.

U. S. Army Corps of Engineers, 1966, *Toke Point, Washington, Cooperative Beach Erosion Study*: U.S. Army Corps of Engineers, Seattle District, Seattle, WA, 64 p., 12 plates.

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Flood Hazards in Washington

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INTRODUCTION

Flooding by water is a problem with which man has had to contend throughout history. Early human settlements were commonly developed along rivers, lakes, and seacoasts because these water bodies provided sources of food and systems of transportation, trade, and communication. To a considerable extent this utilization of water bodies is continued in modern times. Many cities and towns, however, were founded and grew with little regard for the historic variations in water-level norm; and long-term water-level fluctuations, often of greater magnitude, were rarely considered. Flooding is common in low areas along the seacoast, especially during periods when high tides and low barometric pressure, which accompanies storms, combine to cause tidal flooding. Flooding in river valleys occurs more frequently (often annually) and is a normal geologic process, affirming that the river channel and flood plain comprise a single system.

The rivers of western Washington and their tributaries (Figure 1) are subject to rapid rises during late fall and winter from high-intensity rainfall. Heavy rain, accompanied by warm, moist wind, commonly occurs from October through February (U.S. Army Corps of Engineers, 1967). These intense regional storms generate runoff adequate to cause tributaries to reach flood stage, resulting in floods on the main river and major damage to downstream areas. East of the Cascade Range, flooding on the Columbia River system generally occurs during April, May, and June (Washington Department of Ecology, 1983), and peak flows are generated by snowmelt on the eastern slopes of the Cascade Range and in the northern Rocky Mountains.

Many of the large rivers in western Washington have extensive flood plains subject to periodic inundation. The flood plain is a broad, fairly flat strip of land bordering a stream, and it is generally inundated during periods of high discharge. Flood damage is a result of human habitation on flood plains, although development of flood-prone land for urban, agricultural, and industrial purposes continues. In 1955, Hoyt and Langbein estimated that the population density on flood plains in the United States is more than twice that for other areas, as a national average. Flood plains are attractive areas for settlement for several reasons. Farmers use flood plains because of the fertile soils developed in the valley floor. The rivers themselves provide water supply, waste disposal and transportation routes (Dunne and Leopold, 1979), and the broad, flat land is convenient for developing urban and residential areas close to transportation routes. A consequence of human occupation of flood plains is extensive and expensive flood losses (Hoyt and Langbein, 1955).

Often people choose to live on land subject to flooding because of a sense of security generated by upstream flood-control works (Dunne and Leopold, 1979). These structures, however, do not provide absolute protection. Commonly, flood-protection works such as levees, channel improvement projects, and flood control reservoirs, are constructed in stream valleys to minimize impacts from flooding. However, the most effective means for minimizing flood hazard and damage is by enforcing zoning and subdivision regulations for flood-prone areas. Proper design and construction of facilities located in flood-prone areas requires an assessment of the magnitude and probable frequency of recurrence of potentially damaging floods in the basins. Although the hydrologist is charged with the responsibility of making such an assessment, the engineering geologist is often called upon to provide input. Some of the qualitative and quantitative methods used for evaluation of flood-prone areas are discussed later in this paper.

FLOOD-PLAIN MORPHOLOGY

The flood plain bordering a river is constructed by the river during lateral migration and by deposition of sediment (Dunne and Leopold, 1979). Through time, the river moves laterally by eroding one bank while it simultaneously deposits material on the other. Throughout this process the channel maintains its capacity. Hence, the flood plain is an active part of the river, and it is frequently flooded when discharge exceeds the channel capacity.

When the natural banks of a river are overflowed by excess discharge, it is said to have exceeded bankfull stage or reached flood stage. The recurrence interval of the natural bankfull stage for most rivers is in the range of 1 to 2 yr (Leopold et al., 1964). Increasingly higher stages occur with decreasing frequency.

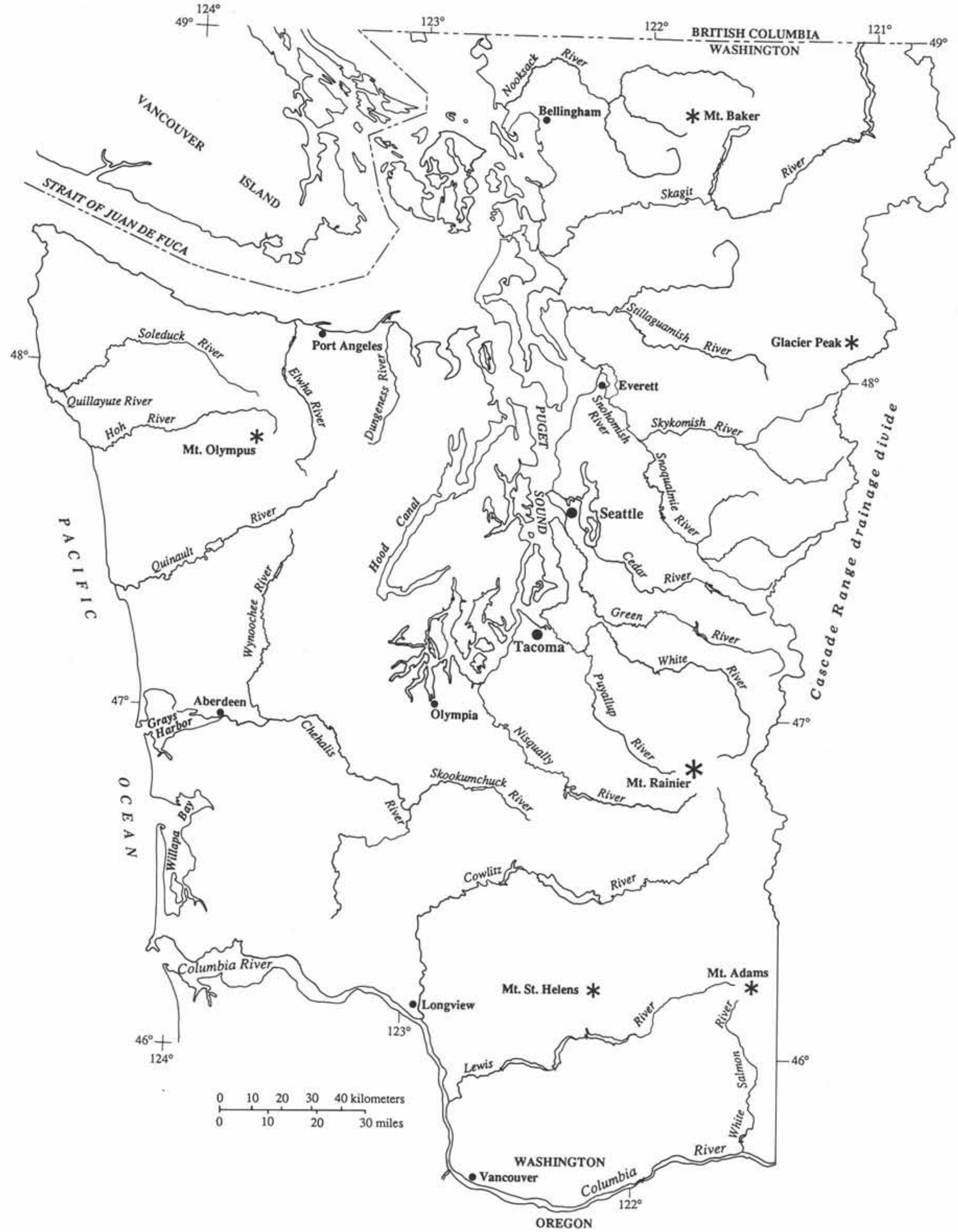

Figure 1. Major drainages in Washington.

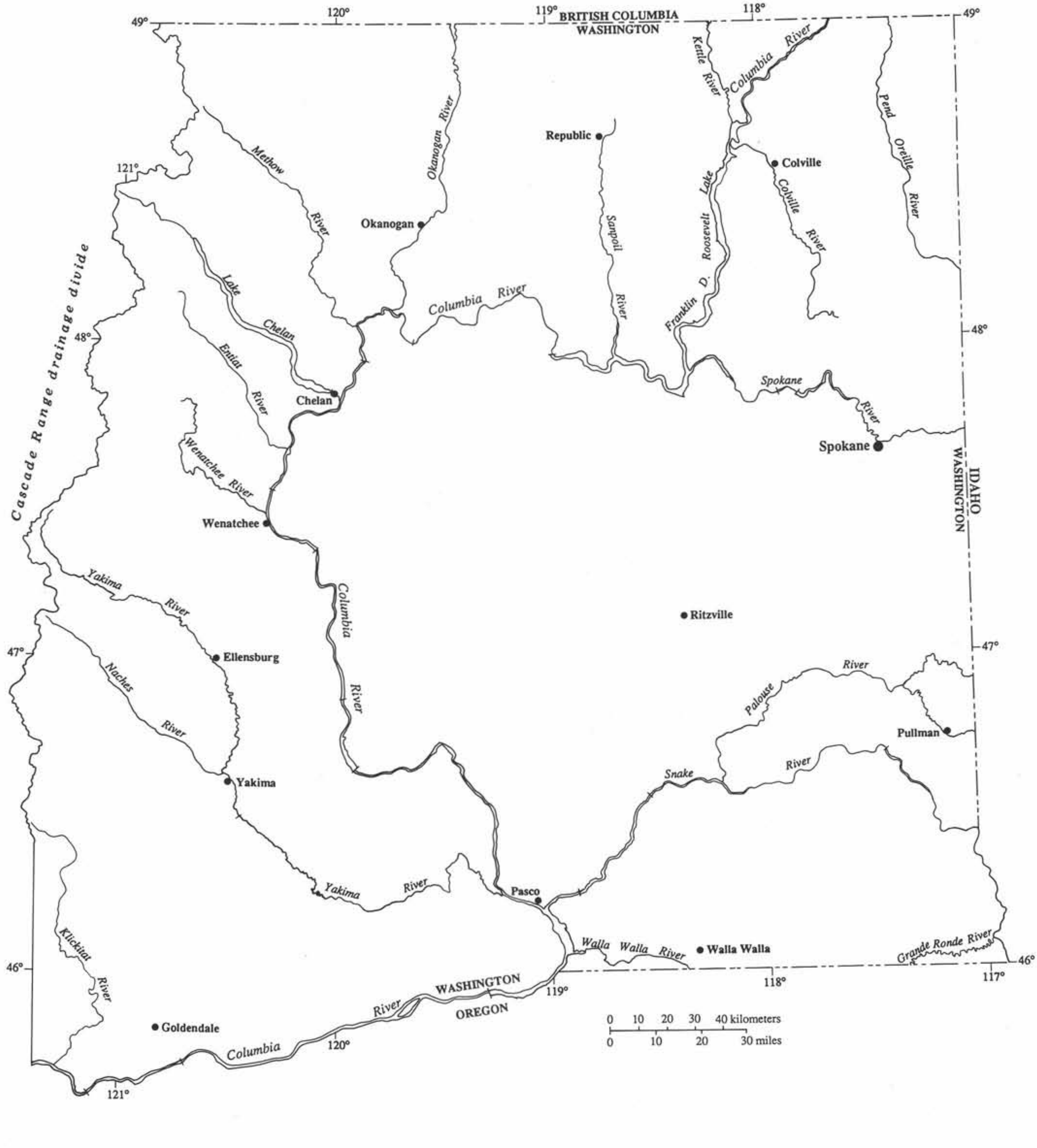

Figure 1. Major drainages in Washington–continued.

FLOOD FREQUENCY ESTIMATION

Prior to flood-plain development, the magnitude and frequency of flooding must be evaluated. In prediction of potential flood occurrence and assessment of flood hazards, the hydrologist and the engineering geologist must assess several features of a flood. These features include the peak flood discharges, flood elevations, and the area inundated by various floods (Dunne and Leopold, 1979).

The average interval of time within which a flood of given magnitude will be equalled or exceeded once is the recurrence interval. Floods are considered random events because the meteorologic and hydrologic factors affecting flood generation vary sufficiently with time that the combination has the characteristics of chance events (Leopold et al., 1964). Floods having a specific magnitude and their corresponding frequencies are referred to as the X-year flood, such as the 10-year flood, the 50-year flood, or the 100-year flood. As specified by the probability analysis of stream data, a 10-year flood has a 10 percent chance of being equalled or exceeded in any given year. Similarly, a 50-year flood has a 2 percent chance of being equalled or exceeded in any given year, and a 100-year flood has a 1 percent chance of being equalled or exceeded in any given year. Estimates of probable future floods are most reliable when based on analysis of historical stream flow data. One primary source of river discharge data in the United States is publications of the U.S. Geological Survey. These data have been published annually since 1961 on a state-boundary basis. Data for Washington are published under the title "Water Resources Data for Washington—Water Year X". In recent years, Part I of these releases contains surface-water data. Prior to 1961, stream-flow data were published by the U.S. Geological Survey under the title "Surface Water Supply of the United States, Part 12, Pacific Slope Basin in Washington and Upper Columbia River Basin." Other sources of data for many streams are the U.S. Army Corps of Engineers and the National Weather Service.

For Washington, the U.S. Geological Survey maintains discharge records for more than 200 gaging stations and stage records for 22 gaging stations. Data for each station include mean daily stream discharge, the maximum instantaneous flow for the year, and the gage height. Preceding the record for each station is a description of the station location, drainage area, period of record, type and history of the gage, average discharge, and extremes of flow recorded at the station. Data for peak flows are used to graphically view the relation between gage height and discharge and to develop a rating curve and a flood-frequency curve.

Estimates of flood frequency are derived by fitting a probability distribution to a sample of maximum discharges observed at a gaging station. The estimated parameters of the distribution are then used to predict the average recurrence intervals of floods of chosen magnitudes or the magnitudes of events of specific frequencies at the gaging station which the plotted data represent.

Flood-frequency analysis by generation of a flood frequency curve applies to evaluation of discharge records from a specific gaging station. The curve describes the flood history of that locality for a finite time. Application of past records to predict future flooding assumes that factors causing floods remain unchanged in time. Flood records represent relatively small samples; therefore, the data base for an individual station may depart from a representation of the stream flood-frequency characterization (Dalrymple, 1960). Linsley (1986) suggested that the standard error for flood frequency estimates is usually 20 percent or more. Further, Benson (1960) demonstrated that for a short record for a single station, the range in variation of flood frequency curves can be very large.

Combining records for a region can reduce the sampling error. This analytical process bases the results on a uniform time period and produces regional flood-frequency estimates. Flood-frequency characteristics of various catchments can be correlated with meteorologic and physiographic features (Dunne and Leopold, 1979). For ungaged basins, then, flood estimates can be attained using the regional curve, providing the drainage basin characteristics are similar. The regional flood-frequency curve is developed by computing the median ratio values of each recurrence interval and drawing an average curve (Dunne and Leopold, 1979). Linsley (1986) noted that use of regional flood-frequency curves reduces bias because these curves are based on observed data. Hence, the regional curve commonly is the basis for design and planning for development in flood-prone areas.

In general, on inhabited land prone to flooding, safety cannot be guaranteed because the cost of protection from the maximum probable flood is very high (Linsley, 1986). Usually structures are designed within "reasonable" tolerances of flood damage. However, it is sometimes desireable to design a structure to withstand the maximum probable flood. Examples include the design of spillways for large flood-control dams, or nuclear power plants (Linsley, 1986). The probable maximum flood (commonly referred to as PMF) is assessed by consideration of the probable maximum precipitation (or PMP), measurements of the largest recorded floods, and maximum snowmelt runoff (Dunne and Leopold, 1979).

FLOOD-PLAIN MAPPING

Qualitative assessments of potential flood hazards are performed by identifying and mapping the morphologic features of stream valleys, such as sediment accumulation characteristic of fluvial deposition and landform development in the valley. Flood-plain mapping is accomplished by combining field investigations and aerial photograph interpretation to delineate topographic, pedologic, and botanical features that can be correlated with floods of various recurrence intervals (Dunne and Leopold, 1979). If a flood plain that is inundated on an average of every 1 or 2 yr can be recognized and mapped, an approximate map of the 1.5-yr flood plain can be compiled. In some river valleys it is possible to correlate river terraces or deposits with particular flood events. The extent of flood hazard along valley floors can also be mapped by plotting gage records on a topographic map.

Linsley (1986) stated that flood-plain mapping is associated with nonstructural flood-damage mitigation. Federal regulations impose restrictions on land use, require citizens to purchase flood insurance in order to be considered for federal emergency assistance, and affect new construction costs within the flood-plain boundaries adopted by the Federal Emergency Management Agency (FEMA). FEMA maps are useful for quick identification of flood hazards in stream valleys and lowlands or on stream deltas. Such maps are available on a county and community basis for the State of Washington at the FEMA Region X office in Bothell and at other locations throughout the state.

FLOOD HAZARD MITIGATION

The costs and associated side effects of flood control have changed attitudes about flood-plain development. Generally, flood damage is reduced by levee construction, channel improvement projects, and small flood-control dams. Levees are large dikes constructed along river banks; they restrict flood-stage discharge to the channel, preventing overflow into developed areas adjacent to the river. Before undertaking building of levees to control potentially damaging flood waters, effects on downstream reaches of the channel need to be considered. In the absence of levees, flood waters are distributed over the flood plain and the river stage remains relatively low. When flood waters are confined to a channel by levees, the water level in the channel is increased, although the discharge may equal that prior to levee construction. The effect of levees during flood discharge is increased flood levels downstream.

Flood hazard mitigation by channel improvement projects involves deepening, widening, lining, and straightening the channel with the goal of increasing its conveyance capacity. This type of project allows high discharges to pass without raising the water surface to potentially damaging levels. An adverse effect of channel improvement projects is an increased velocity of flood peaks in the improved channel, which results in increased flood peaks downstream (Dunne and Leopold, 1979).

Flood-control reservoirs are generally of two types: flood-detention reservoirs, or multipurpose storage reservoirs. The pool level of a flood-detention reservoir is usually low except at the time of flooding, when a portion of the water is impounded behind the dam and the remainder flows downstream through a tunnel or over a spillway in the dam. Multipurpose storage reservoirs impound water for municipal water supplies, irrigation, recreation, and power generation. For flood control, the level of the reservoir is lowered to provide storage volumes for flood runoff.

FLOOD OCCURRENCE IN WESTERN WASHINGTON

The U.S. Army Corps of Engineers has evaluated flood plains and major flood hazards of most of the major rivers in Washington. Their results are published; one example is "Flood Plain Information Study: Snohomish River Basin, Washington" (U.S. Army Corps of Engineers, 1967).

In western Washington, drainage basins along the west side of the Cascade Range and around the periphery of the Olympic Mountains have similar characteristics and flood histories. Of the 11 major drainage basins of the western Cascade slope, 8 drain into the Puget Lowland, 2 into the Columbia River, and one into Grays Harbor. Although none of the major cities in the lowland are situated in flood-prone areas, some of their industrial areas and suburban communities are located on flood plains. Only the White River (a major tributary of the Puyallup River) and the Green River have major storage reservoirs specifically constructed for flood control. Many of these rivers have a variety of artificial dike and channel systems in the lowland areas to assist in passing peak flows, but none of these systems totally prevents flooding in the lowlands. Thus substantial portions of these major river flood plains are subject to flooding. Chronic flooding is experienced on the Snohomish River and its major tributary, the Snoqualmie River, and on the Skagit, Nooksack, Chehalis, and Cowlitz rivers. Despite flood storage on the Green and White rivers, occasional flooding is still experienced in the lower Green River valley and on the Puyallup River upstream of the town of Puyallup. Sometimes the duration of flooding is lengthened by a high water table within the flood plain and the inability of the flood plain to drain naturally. In some areas pumping stations have been installed on the flood-plain side of levees to provide a measure of relief. Flooding on the distal portions of many western Washington flood plains may also be influenced by tidal action, acutely so when the flood crest coincides with high tide stages. This is especially true of the flood plains of the Skagit, Snohomish, Nisqually, Skokomish, and Chehalis rivers. Most of the streams radiating out from the Olympic Mountains are well-incised and have narrow flood plains and limited habitation. Therefore, the flooding hazard is not as great.

The Cowlitz basin is the largest drainage basin in western Washington, draining a large area of the Cascade Range extending from the southeastern slopes of Mount Rainier to the northern slopes of Mount St. Helens. Two hydropower dams on the middle reach of the Cowlitz River are operated to maintain river flows of 70,000 cfs or less at Castle Rock. Artificial levee systems designed for the 100-yr flood guide the flows through the Kelso-Longview urban area to the Columbia River. Debris from the catastrophic flooding associated with the 1980 eruption of Mount St. Helens filled the leveed channel and required removal in order to maintain pre-eruption flood protection levels.

FLOOD HAZARDS IN EASTERN WASHINGTON

In eastern Washington, flooding occurs most often during the months of high runoff, normally in late winter or early spring (Brown, 1979). Generally two scenarios are relevant in terms of flooding within eastern Washington, canyon flooding and basin flooding (Gephart et al., 1979). Canyon flooding generally refers to flooding on small unregulated, intermittent, or ephemeral streams adjacent to upland areas. Basin flooding refers to flood occurrence on major streams of the Columbia River system.

Construction of major storage reservoirs on the Columbia River and its major tributaries has essentially eliminated flooding on the main stem. The last major flood was in 1948. However, major levee systems continue to protect the low areas of Richland-Pasco-Kennewick and Portland-Vancouver. Flooding occurs with considerable frequency along the entire length of the Okanogan and Methow rivers. It is less frequent on the Yakima River at Yakima owing to the presence of U.S. Bureau of Reclamation storage facilities in the headwaters. Local flooding continues to occur along the Wenatchee River both above and below Tumwater Canyon. On the surface of the Columbia Plateau, uncontrolled flooding periodically occurs along the upper Palouse River in the vicinity of Colfax and in the upper Crab Creek basin. Flooding from spring drainage off the Blue Mountains is a hazard in the Walla Walla basin. The Walla Walla urban area is protected from flood damage by the Mill Creek reservoir, one of the largest off-stream flood storage projects in the state.

CONCLUSIONS

Flood plains and streams are developed by a natural geologic process of overflow of stream banks during periods of excessive discharge. The flood plain, then, is clearly an active portion of a stream channel, although it is only periodically occupied by water, and flooding of these areas can be expected during periods of high discharge resulting from heavy rainfall or snowmelt.

Using a variety of assessment techniques, hydrologists and engineering geologists have helped to minimize damage due to flooding in developed areas. Facilities such as roadways, bridges, dams, and flood protection works are usually planned, designed, and constructed taking into account specific flood-frequency and magnitude criteria such as the 25-yr or 50-yr flood. Construction of structures that would provide 100 percent protection against a large-magnitude, low-frequency flood is very costly; therefore, completed facilities are generally engineered within "reasonable" tolerances. Alternatives to the above methods of flood hazard mitigation include relocation of present structures, zoning the floodway for non-construction, and raising structures above the frequent flood elevation. The latter has been successfully accomplished for residential structures in the town of Snoqualmie (Washington Department of Ecology, 1987). The best proven method for the prevention of flood damage, however, is to minimize development of flood-prone areas.

REFERENCES

Benson, M. A., 1960, Characteristics of Flood Frequency Curves Based on a Theoretical 1000-Year Record. *In* Dalrymple, T., *Flood Frequency Analysis*: U.S. Geoloical Survey Water Supply Paper 1543A, pp. 51-74.

Brown, J. C., 1979, *Geology and Water Resources of Klickitat County*: Washington Department of Ecology Water Supply Bulletin 50, Olympia, WA, pp. 67-111 [surface water.]

Dalrymple, T., 1960, *Flood Frequency Analysis*: U.S. Geological Survey Water Supply Paper 1543-A, 80 p.

Dunne, T. and Leopold, L. B., 1979, *Water in Environmental Planning*: W. H. Freeman and Company, San Francisco, CA, 817 p.

Gephart, R. E.; Arnett, R. C.; Baca, R. G.; Leonhart, L. S.; and Spane, F. A., Jr., 1979, *Hydrologic Studies Within the Columbia Plateau, Washington—An Integration of Current Knowledge*: Rockwell International, Rockwell Hanford Operations Energy Systems Group RHO-BWI-ST-5, Richland, WA, 647 p.

Hoyt, W. G. and Langbein, W. B., 1955, *Floods*: Princeton University Press, Princeton, NJ, 468 p.

Leopold, L. B.; Wolman, M. G.: and Miller, J. P., 1964, *Fluvial Processes in Geomorphology*: W. H. Freeman and Company, San Francisco, CA, 522 p.

Linsley, R. K., 1986, *Flood Estimates—How Good Are They?*: Water Resources Research, Vol. 22, No. 9, pp. 159S-164S.

U.S. Army Corps of Engineers, 1967, *Flood Plain Information Study—Snohomish River Basin, Washington*: U.S. Army Corps of Engineers, Seattle District, Seattle, WA, 7 p., 25 plates, appendices.

Washington Department of Ecology, 1983, *Flood Freshets*: Washington Department of Ecology, Shorelands Division, Vol. 1, No. 1, Olympia, WA, 4 p.

Washington Department of Ecology, 1987, Snoqualmie Builds out of Flood's Reach: *Washington Coastal Currents*, Vol. XII, No. 1, Washington Department of Ecology, Shoreland and CZM Program, Olympia, WA, 8 p.

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Landslide Provinces in Washington

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INTRODUCTION

Probably few areas on Earth of comparable size approach the geologic and physical diversities of Washington State. The recent eruption of Mount St. Helens and regional seismicity attest to active tectonism in the state's western part, while the northeast is characterized by rocks as old as 2.6 billion yr and relative stability. The basalts of the Columbia Plateau, one of the largest such accumulations on Earth, have been deeply eroded by floods comparable only to those recently discovered on Mars. Modern streams and shorelines are still adjusting to the effects of isostatic rebound and sea-level changes after the last continental glaciation. Some soils of that recent glaciation are more competent than certain "rocks" of southwestern Washington—for example, those converted to laterites by periods of subtropical weathering tens of millions of years ago. (In this paper the term soil, where unmodified, refers to unconsolidated material overlying bedrock and is not confined to the definition used by soil scientists.) Superimposed on such geological factors are modern environments that include hot and arid, temperate rain forest, alpine, and arctic.

Many of these contrasting characteristics are reflected in the traditional physiographic provinces of the state (McKee, 1972); others are not. However, all are among the many factors that determine the nature and distribution of landslides. Thus, boundaries delineating the types and distribution of landslides do not necessarily coincide with physiographic boundaries. For example, the boundary between the Okanogan Highlands and the Cascade Range provinces is rather arbitrary in regard to either landslides or physiography. Figure 1 compares Washington's main "landslide provinces" with the traditional physiographic provinces. The principal reason for the differences between the two probably relates to the fact that glaciation occurred relatively recently, and, in places, has removed most earlier slide masses, created new ones, and set the stage for others. This "resetting of the clock" results in some significant differences in the nature and extent of landslides.

A general discussion of Washington's major geologic provinces is presented in the Introduction of this volume. Further, it is beyond the scope of this overview to discuss all landslide types in each province. In any case, certain types of landslides (for example, rockfall or soil fall) occur throughout the state. Instead, this paper examines some of the factors that appear to characterize a landslide province or subprovince. The most common kinds of landslides and their physical settings, or a single particularly good example, can illustrate such distinctions. Landslide types, in general, follow Varnes (1978). This discussion emphasizes the Puget Lowland, in part because of its unique physical setting and geology, and in part because population pressures make even small landslides in such a setting potentially hazardous.

PUGET LOWLAND-NORTH CASCADE FOOTHILLS

General

This landslide province is here defined as that portion of the Puget Lowland physiographic province (including valleys and intervening foothills) that was overridden by ice of the last continental glaciation. Thus, vegetation-sustaining soils are young and commonly only a few feet thick. They are underlain by relatively impermeable glacial sediments or bedrock in many places. The province is also characterized by abundant rain or, in the foothills, rain and snow. The foothills are generally less than 3,000 ft in elevation and were rounded by the overriding ice sheet. Their flanks are commonly oversteepened by meltwater erosion or landslides and have been deeply incised by Holocene streams. The province also contains the largest and fastest growing population in the state. The increasing colonization of foothill and valley areas for recreational, retirement, and bedroom communities is another reason for including the glaciated northern foothills of the Cascades in the Puget Lowland rather than the Cascade landslide province.

Landslides in Unconsolidated Materials

Repeated continental glaciations alternating with long periods of interglacial flood plain, delta, and lacustrine deposition has left unconsolidated material overlying the bedrock of much of the Puget Lowland.

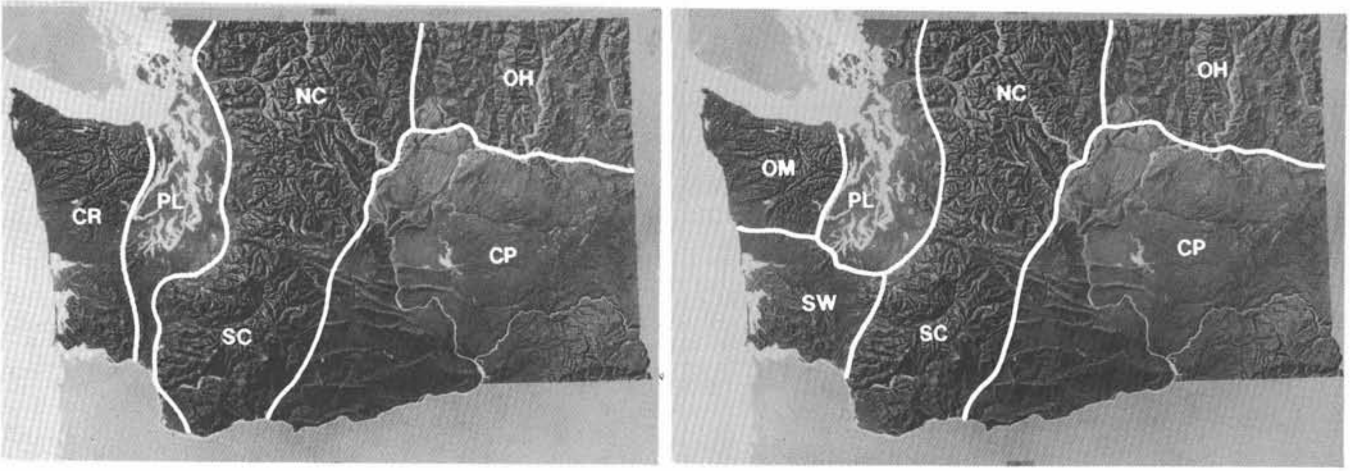


Figure 1. Main physiographic (1A) and landslide (1B) provinces of Washington. Physiographic provinces after McKee (1972). OM, Olympic Mountains; CR, Coast Range; SW, Southwest Washington; PL, Puget Lowland; NC, North Cascades; SC, South Cascades; OH, Okanogan Highlands; CP, Columbia Plateau.

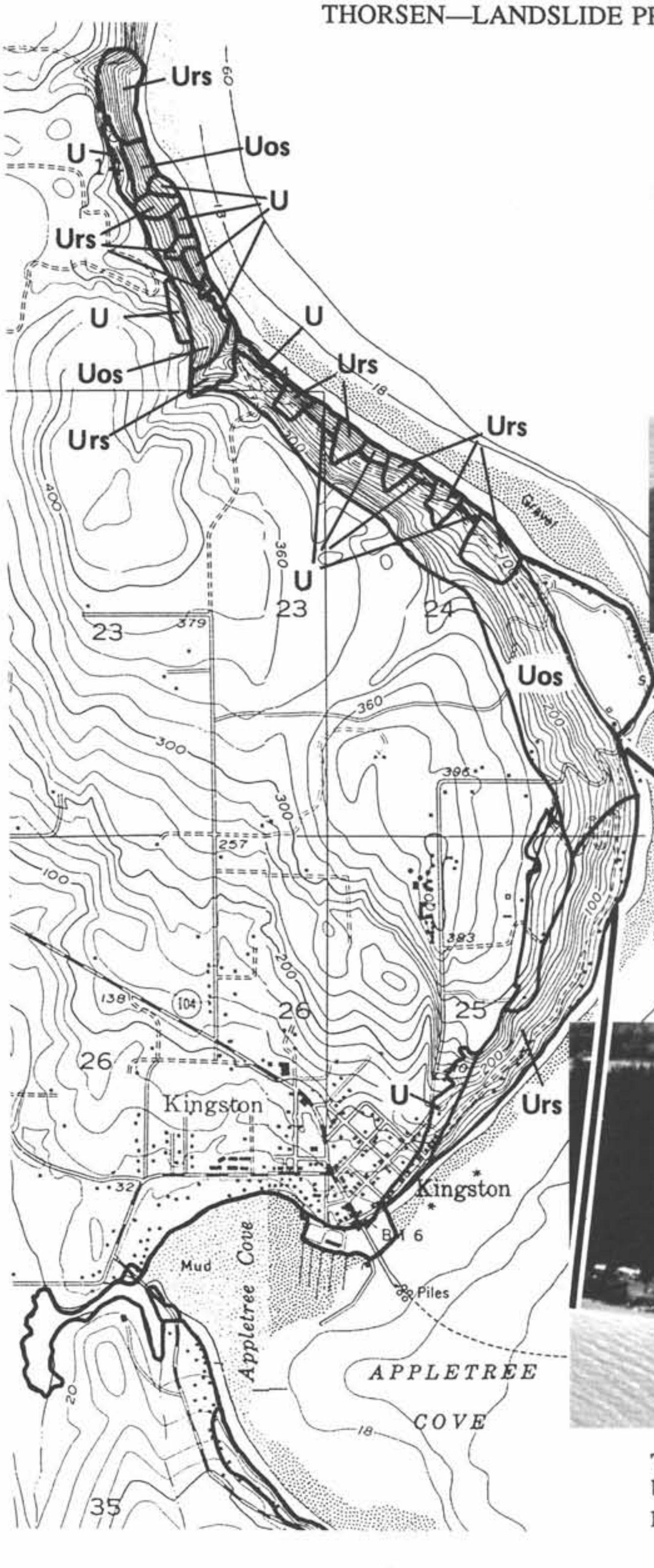
These deposits are hundreds or even thousands of feet thick in places. Following the sculpting and compacting by the last continental ice sheet to occupy the lowland, glacial meltwater, postglacial streams, and wave action have cut hundreds of miles of steep bluffs into these sediments. Many of these bluffs are in or near population centers. Thus, the pressure for residential development on them is great and increasing (Figure 2).

Figure 2. Demand for view property, such as this area overlooking the Strait of Juan de Fuca, continues to increase along with the Puget Sound area's population. Winter storms remove the dry-flow deposits, re-exposing the toe of the bluff to wave erosion.

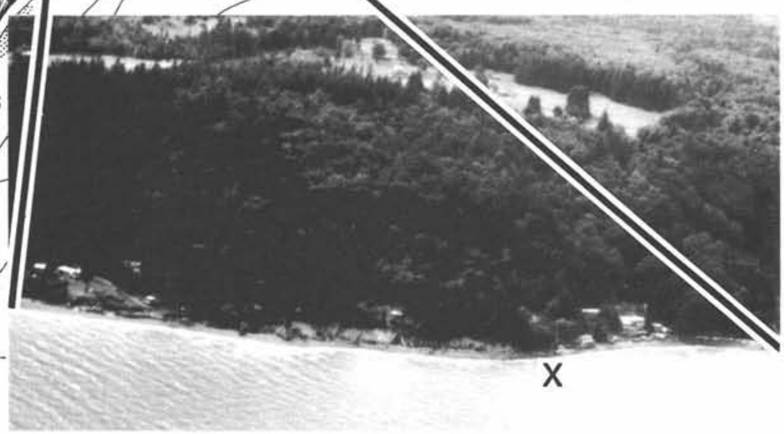
Of these bluffs, those along the marine waters of the Puget Lowland have probably been the most systematically studied. The slope stability maps of the Coastal Zone Atlas (Washington Department of Ecology, 1978-80) show more than 660 mi of these bluffs as "unstable" (Figure 3). Included in this category are approximately 71 mi of recently active landslides and 65 mi of old, apparently dormant slides, but both figures are, no doubt, understated. This is because recent slides narrower than about 200 ft were difficult to show at the map scale used and some old slides were probably not recognized. Marine bluffs may not be fully representative of the bluffs fringing modern flood plains or glacial meltwater channels, but they vividly display the geologic factors and the range of stability problems that exist wherever erosion has incised the thick sediments.

During "landslide season" (generally November-April) familiar names commonly reappear in the Puget Lowland news media. The Alki, Queen Anne, and Magnolia districts of Seattle are mentioned nearly every winter. This repetition is because natural landslides usually occur where they have occurred before and development is apt to trigger slides in areas already unstable. In spite of such warnings, a variety of reasons encourages people in this area of rapid population growth to crowd development against or even to occupy slide hazard areas. If these reasons are important enough, the risks and/or extra costs may be acceptable. Possibly of equal importance is that, especially in recent years, some of the responsibility for and costs of landslide damage have been passed on to others in the form of lawsuits.

Common reasons for individuals choosing to live with the slide hazards of Puget Lowland bluffs are the views from the top (Figure 2) or access to beaches and water from the bottom. Where industry is concerned, more compelling reasons may exist to accept such



In early spring 1974 an ancient slump just south of Apple Cove Point re-activated. Uplift of the slide toe raised a segment of the beach (right side of the photograph) almost 8 ft.



This photo illustrates the section of Kitsap County shoreline bracketed by the leaders. (Toe uplift at X is shown in the photograph above.)

Figure 3. Slope stability map for part of the shoreline near Kingston. U, unstable slopes; Uos, post-glacial but prehistoric slide; Urs, recent or historically active slide. Modified from Washington Dept. of Ecology, Coastal Zone Atlas, Kitsap County (v. 10, 1979).

hazards than for residential development. For example, a railroad requires a relatively level, albeit narrow route. A beach can meet both criteria (Figure 4). However, in the Puget Lowland, beaches are commonly backed by unstable bluffs.

Such compromises of location and risk must also be made with other transportation systems. The Seattle section of the Interstate Highway 5 was built, at a staggering cost, through a zone of unstable bluffs and dormant landslides. Because of slope stability problems, the zone had been relatively unoccupied. Thus political and economic decisions for selecting such a route were considered justifiable. Similarly, some of the most popular shoreland parks (such as Kopachuck, Camano, South Whidbey, Sequim Bay, and Golden Gardens) probably exist largely because the areas were too unstable for other development.

Gulleying, dry ravelling, and other forms of essentially particle-by-particle erosion are important bluff-modifying processes in the sediments of the Puget Lowland. Landslides, however, may remove as much material in minutes or hours as other forms of erosion do in hundreds of years. The bluffs of the Puget Lowland are particularly susceptible to landslides for a variety of reasons. Among these are their steepness, the abundant rainfall and resulting ground water, and the commonly striking contrasts in permeability of their materials. These permeability contrasts create local ground-water concentrations that commonly dictate where, when, and how a landslide will occur.

It is the "how"—the type of slide failure and movement—that commonly determines the nature and extent of the slide hazard in populated areas. Safe construction setback distances from both top and bottom of a bluff must consider such factors and can reduce the hazard of slides. At the same time, names of slide types derived from how the slides initially fail can be misleading, especially in the Lowland. Many landslides fail in one manner but travel in another—for example, a slump or rotational failure in the soggy soils of the Puget Lowland may ultimately move as a flow (Figures 4 and 5). Slide types are discussed here mainly because the type of initial failure may provide clues to the nature of the hazard and how to avoid it.

Slumps

A common Puget Lowland slide form is the upper-bluff slump. In most places where these occur, the upper bluff is a pervious sand, whereas the lower bluff is very compact silt or blue clay. As a consequence, ground water tends to move down through the sand, concentrate at the sand/silt contact, and move laterally to the nearest bluff. The existence of such a saturated zone on a steep bluff is apt to cause everything above to slump. The

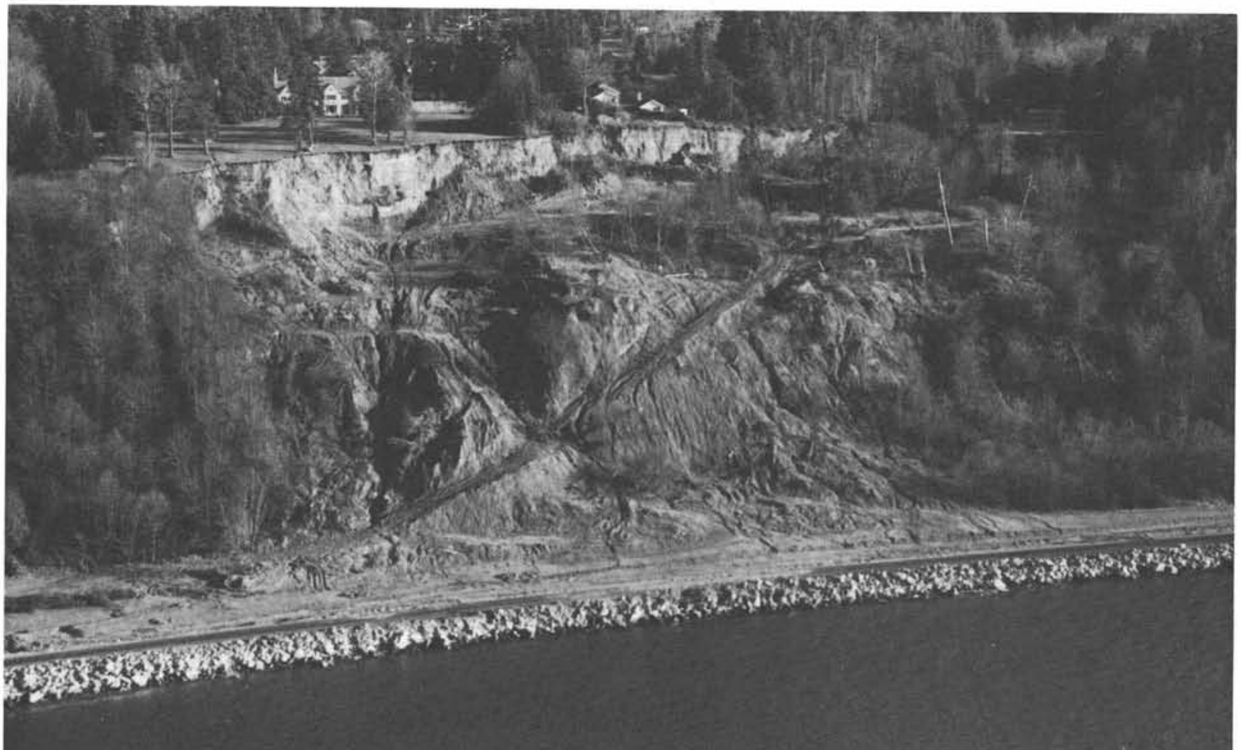


Figure 4. A large landslide complex south of Edmonds. The activities of railroad track maintenance crews have replaced wave erosion as the means of removing mudflow deposits at the toe.

Figure 5. Falling trees caused much of the damage to this beach cabin near Kingston. The steep clay bank behind the cabin did not fail, but mud and trees from slumps higher on the slope flowed over it. Photo by Kurt Othberg.

slumped and locally saturated upper bank material, once it is disturbed, turns into mud and flows down and over the steep but generally still intact lower bluff (Figure 5). This mode of failure leaves a distinctive landform, the mid-bluff bench, along the top of the lower unfailed silt or clay. Where erosion is removing the landslide deposits, the bluff below the bench is very steep, commonly exceeding 60°. The bench itself tends to have a hummocky surface, and the steepness of the slope above it increases upward, approaching vertical at the scarp of the slump. This bench is not apt to be easily recognized in aerial photos if the last movement was prehistoric and the vegetative cover is dense.

Some of the best examples of upper-bluff slumping in the Seattle area are in the Alki area, Fort Lawton, and Golden Gardens. In the last instance, the park area itself has apparently not had a serious slope failure in many decades, but the telltale bench and abundant ground water are obvious. A slump just north of the park damaged or destroyed almost a dozen homes in 1974, and the city street in the park requires frequent repairs. Other classic upper-bluff slump areas are Scatchet Head on Whidbey Island and the Thorndyke Bay area of Jefferson County.

Debris Avalanches

Shallow debris avalanches are another common form of landslides along the bluffs of the Puget Lowland, especially where bluffs are made up of compact silt, clay, or silty sand. Characteristically, the landslides are only a few tens of feet wide, and the "mat" of material that moves is seldom deeper than the depth of penetration of tree roots—3 to 4 ft. These uppermost sediments are made less compact or loosened by roots and by freeze-thaw cycles, but the underlying undisturbed material remains relatively impervious to infiltrating rainfall. The result is that a zone of saturation may develop at the base of the loosened soil/root mat during periods of heavy rain. Where the slope is steep enough, the smooth surface of the underlying silt or clay may then become a slide plane. An individual storm may trigger many such shallow slides. Their lineal scars are rapidly colonized by red alder, leaving telltale stripes of trees of nearly the same age and size.

Storm drainage, even from a single lot, may also trigger such debris avalanches. The common practice of disposing of trash, construction rubble, and land-clearing debris on these steep bluffs also may set the stage for a debris avalanche. Because they involve only a thin layer of materials, debris avalanches are seldom a threat to homes or other structures at the top of a bluff. However, these avalanches are a serious hazard to those living below, in spite of their relatively small volume. They attain a high rate of speed as they flow downslope, and even a small debris avalanche can easily smash through the wall of a frame house and/or drop uprooted trees through the roof.

Mudflow

Few Puget Lowland landslides begin as flows, but most end up traveling as such, at least in part. This should be no surprise, as almost all Puget Lowland landslides are triggered by excessive ground water. Such ground water, especially in combination with focused surface runoff, will commonly turn a slump, slide, or soil fall into a mudflow. The mudflow is capable of great destruction because its weight and viscosity enable it to move bedload, logs, and even houses. The hazards posed by the mudflow's cargo may be as great as those of the mud itself. Material from the collapsing walls of headward-sapping "box canyons" in Pleistocene terraces is largely removed as repeated mudflows. One such combination has introduced on the order of 1,000,000 cy of silt and sand into the Deer Creek/Stillaguamish River system in recent years.

Ancient Landslides in Unconsolidated Materials

While not technically a special type of slide, ancient dormant landslides in the thick sediments of the Puget Lowland warrant separate attention because of their large size, the difficulties of recognizing them, and development pressures. The combination of their sheer size, the erosion or grading of diagnostic features, and commonly dense forest cover can disguise their true character if a person examines only a particular small building site in an ancient dormant slide complex. Such slide areas may be under intense development pressure, especially in shoreline areas, as they commonly are the only "low bank" areas for miles and may have easy beach access.

The toe-area uplift characteristic of a slump can be one of the first signs of renewed movement of an ancient landslide, especially where the headscarp zone is uninhabited and/or densely wooded (Figure 3). Wholesale reactivation of such slides generally occurs slowly and may consist of only a few feet of movement in a particular episode, usually in spring after an unusually wet winter. However, even this small amount of movement can be enough to cause severe damage to structures and utilities, especially if they are founded on both stable and unstable ground (Figure 6). Piecemeal reactivation of large slides is more common than reactivation of the entire mass. One 7,000-ft stretch of coastal bluff along Admiralty Bay on Whidbey Island is an ancient slide complex that undergoes piecemeal "adjustments" every few years.

Ancient landslides and landslide complexes in thick sections of unconsolidated or poorly consolidated material are areas not only of broken, disturbed, and weakened materials, but also of disrupted ground-water flow. The resulting erratic distribution of conditions in these old landslides make drainage or other stabilization techniques all the more difficult and expensive. Such difficulties are further compounded by the generally large areas involved. Ownership of land parcels on such large slides is commonly divided, especially in high-value shoreline residential areas. In such instances, some kind of group effort, such as formation of a "Natural Hazard Abatement District" (Kockelman, 1986), may be the best approach to a solution of slide control. Piecemeal or lot-by-lot stabilization efforts are usually doomed from the start.

Submarine Landslides

The seafloor beneath the straits of Juan de Fuca and Georgia, as well as Puget Sound, has relief in many places comparable to that of the adjacent uplands. With many square miles of slopes veneered by loose, fine-grained, saturated sediments, one would expect landslides and/or turbidity currents to be common. However, unless such slides involve adjacent uplands, trigger noticeable water waves, or damage submarine utilities, they are apt to go unnoticed. There is evidence "that submarine slides and slumps along the margins of the Sound may be the dominant process by which material is moved from shallow to the deep basins" (Holmes, 1988). Holmes and his co-workers have identified sediments, hundreds of yards thick in places, that are believed to have been deposited soon after the ice sheet left the Puget Lowland. In addition to these largely late-glacial deposits, hundreds of miles of submarine slopes fronting Holocene wavecut terraces and bluffs may still retain much of that eroded material. The latter setting probably accounts for the recent problems with sewer outfalls off Duwamish Head in Seattle. Here, two 64-in.-diameter sewer outfall pipes were left unsupported for more than 650 ft when bottom sediments slid or flowed from under them (Holmes et al., 1988).

Delta fronts, with their relatively rapid sedimentaion rates and steep slopes, are also settings for landslides. Because deltas are common sites for port facilities and industrial development, such slides can be very damaging.

Much of the devastation of the 1964 Alaska earthquake was caused by landslides involving subaqueous slopes and adjacent developed uplands. In places these slides also triggered water waves that compounded the damage. Washington's historic earthquakes, with their brief durations of moderate ground shaking, have apparently not triggered massive submarine landslides. [The collapse of the Nisqually delta, apparent from sub-

Figure 6. Part of a building in Poulsbo on an ancient, deep-seated slide. Reactivation of the slide in 1974 severely damaged the building and adjacent streets and utilities. As the building was financed by a federally insured loan, the public, as is commonly the case, paid much of the price of this landslide.

bottom seismic profiling, may have been triggered by a prehistoric earthquake (University of Washington, Department of Geologic Science, 1970)]. A massive failure of part of the Puyallup delta in 1943 (University of Washington, Department of Oceanography, 1953) apparently was not seismically triggered.

Landslides in Bedrock Terrain

Landslides both in and on bedrock are common in the northern Cascade foothills segment of this landslide province. Although the foothills are relatively low and subdued compared to the adjacent Cascades, their flanks are commonly steep. In addition, the foothills are subject to moist Pacific storms, and the orographic effects of the foothills enhance both the amount and intensity of precipitation. Such storm cells can be localized, dumping several inches of rain in a few hours on a small area, while a nearby lowland site away from the mountain front may be experiencing a light drizzle. One such storm in western Whatcom and Skagit counties on January 10, 1983, triggered hundreds of debris avalanches. The impact was millions of dollars in private as well as public property damage, resulting in numerous tort claims. Such avalanches also occur in the foothills of the South Cascades and in southwestern Washington, but litigation is limited because the sparse population is generally not affected..

Debris Avalanches/Torrents

The combination of thin permeable soils on a relatively smooth and impermeable substrate, steep slopes, and intense precipitation provides a setting conducive to debris avalanches. Stability problems in such a setting are commonly compounded by the many miles of old logging roads, "orphaned" long before current techniques and standards of abandonment, such as water bars and fill removal, were adopted. The end results of such debris avalanches in the foothills generally differ from those in lowland sediment bluffs. Because they may occur in drainage basins of several square miles or more, there can be numerous avalanches in a single basin, and the debris as well as the runoff can be cumulative. Because the avalanches are triggered by intense rainstorms or rain on snow, they commonly enter flood-swollen streams. Thus, their diluted debris becomes much more mobile than that of an isolated sediment bluff avalanche and can travel miles from the point of origin (Figure 7). The ultimate destination of such debris torrents or debris laden floods is commonly an alluvial fan on which there are residential developments and transportation/utility routes.

Bedrock Landslides

Most of the bedrock landslides are in the folded and faulted sandstone, with weak shale or coal interbeds, that fringe much of the northern lowland. Many are bedding-plane failures. Almost all are ancient (late Pleistocene or Holocene) events probably triggered by removal of support either by melting ice or oversteepening by meltwater erosion. In general, the slide masses appear now to be quite stable and have withstood the hydrologic impacts of past wildfires and clearcutting with no remobilization. These large ancient bedrock landslides also appear to be rather insensitive to impacts by logging road systems. A few such landslides have oversteepened and still active headscarp areas, which are sites of rolling rocks and/or earthflows, or toe areas undergoing erosion by modern streams. The toe of one ancient deep-seated bedrock landslide, oversteepened by stream erosion, had a minor failure during the 1983 storm previously mentioned, which triggered a damaging debris torrent.

OLYMPIC PENINSULA

Although commonly included in the Coast Range physiographic province (McKee, 1972), numerous reasons exist to consider the Olympic Peninsula separately. A characteristic that the peninsula shares with the Coast Range to the south is that both are underlain entirely by Tertiary sedimentary and volcanic rocks. However, the area is not a good example of a landslide province throughout which slope stability factors are relatively uniform. The peninsula has marked contrasts with adjacent provinces but little that unifies it internally. Instead, it contains good examples of both slope stability conditions and landslides that occur throughout the state. This is largely a result of its geologic and physical diversities.

Most of the Olympic Peninsula was too high to have been overridden by the last continental ice sheet. Thus, it split the oncoming ice, diverting lobes into Puget Sound and the Strait of Juan de Fuca. Also, the penin-

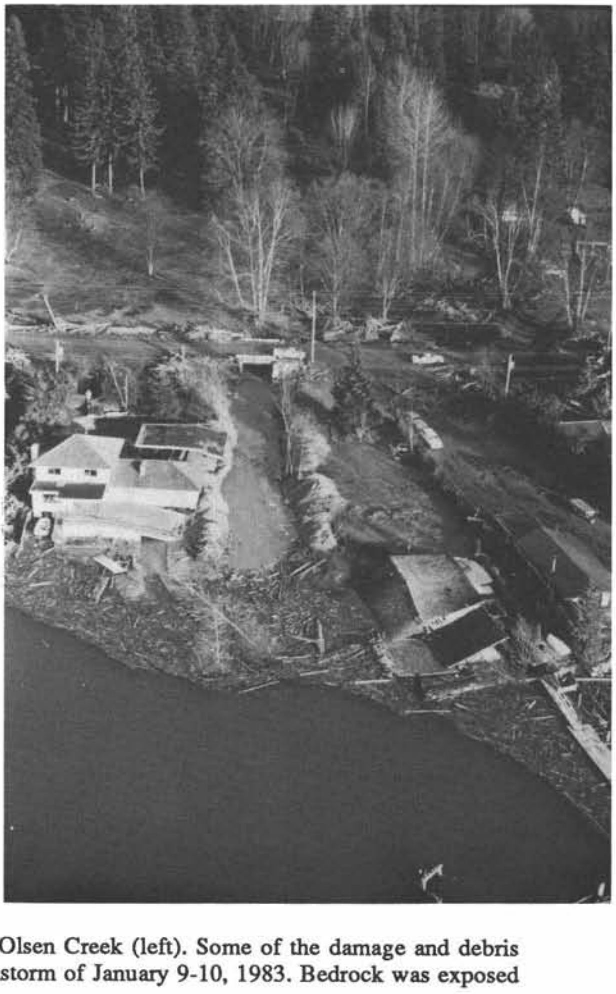


Figure 7. Debris avalanche of less than 150 cy at the head of Olsen Creek (left). Some of the damage and debris where the creek enters Lake Whatcom, 4 mi away (right). Rainstorm of January 9-10, 1983. Bedrock was exposed later by water piping from the scarp.

sula was large and high enough to develop some extensive valley glaciers. Apparently, the heads of some shorter drainages were not high enough to accumulate sufficient snow; only the larger drainages supported valley glaciers. Thus, some lower unglaciated valleys contain thick sections of weathered soil and bedrock comparable to those in the Southwest Washington landslide province. In such areas earthflows are locally extensive. Adjacent glaciated valleys, however, contain fresh gray till and varved silt and/or unweathered outwash comparable in age, texture, physical properties and behavior to late Pleistocene sediments in the Puget Lowland. The road up the Hoh River valley, for instance, is periodically cut by large slumps in glacial silt.

Recently glaciated valleys that penetrate competent core rocks have landslide problems akin to those in the North Cascades. Slopes in tilted sedimentary rocks that have been intensively altered and/or contain weak interbeds have been undercut by wave action in places along the Strait of Juan de Fuca. Here, extensive slump-flows or bedding-plane block glides along the interbeds have resulted, similar to failures in the southern Cascades.

When one superimposes upon such a range of geologic conditions an annual lowland precipitation ranging from 17 in. in the "rain shadow" at Sequim to 134 in. at Quinault, it is obvious that land owners and government agencies are presented with a broad spectrum of landslide problems. The brunt of such problems is borne by transportation corridors, shoreline residents, and the primary industry, logging. The indirect impacts of landslides and sedimentation on salmon fisheries from logging activities have become an important concern. Careful logging road placement, improved drainage systems, and even paving some primary haul routes have helped reduce these impacts.

SOUTHWEST WASHINGTON

The boundaries of this landslide province are also at variance with physiographic boundaries (Figure 1). The boundaries are, in places, indistinct, but the landslide province itself seems to have features relevant to slope stability that, as a whole, are distinct. Probably the most fundamental characteristic is the lack of glaciation and only localized exposure to glacial meltwaters. Much of the latter is confined to the northeast part of the province and is largely the result of pre-Wisconsin glaciation. Thus, in places, surfaces in the province have been exposed to weathering processes for millions of years. This is in stark contrast to the adjacent Puget Lowland, where weathering "began" less than 15,000 years ago.

In addition to a longer duration of weathering, the old surfaces in southwestern Washington were undoubtedly exposed to different kinds of weathering processes than have operated in the Quaternary. The thick lateritic soils remaining on some undissected uplands suggest extended periods of subtropical climate. Overlying this deeply weathered bedrock, in places such as uplands along the Columbia River, is a loess blanket as much as 40 ft thick, also largely altered to clay (Livingston, 1966). Remnants of this loess are probably widespread but unrecognized in other places. Independent of the locally thick clay soils, extensive areas are underlain by Tertiary sedimentary and volcanic rocks that are inherently weak. Tuffaceous siltstone and tilted sedimentary rocks having weak interbeds are common. The volcanic units are generally altered and/or mechanically weak as a result of brecciation or other primary factors.

The terrain made up by these materials is, in most places, deeply dissected. Much of the province has mature topography; gentle slopes are uncommon. In some areas, however, deep steep-sided canyons separate areas of relatively moderate slopes on adjacent uplands, suggesting recent and/or still active incision. Areas with elevations exceeding 2,000 ft are small and scattered. Average annual precipitation, generally rain, is 40 to 50 in. in the lower terrain between the Puget Sound and the Columbia River. However, extensive areas, mainly the low mountains in the western part of the province, receive more than 100 in. of rain.

The dominant form of landslide in this province is the earthflow or slump-flow (Figure 8). Many of these are made up of both soil and bedrock, in places too oxidized to be differentiated. Both ancient and active earthflows are common, not only in the high and steep terrain but also in the relatively low and rolling hills of the Chehalis-Centralia area. The larger dormant flows appear to be rather insensitive to the direct effects of human activities such as clearcut timber harvesting and construction of logging roads. Reactivation of landslides in such areas can usually be traced to stream cutting along the toe of the flow. Larger excavations can, of course, reactivate dormant earthflows or start new ones in the materials common to this province. Both have been triggered by freeway excavations.

Debris avalanches and torrents are locally a problem in this province. They tend to occur where the rocks are strong and relatively unweathered. Such rocks, predominantly massive sandstones, tend to have steep slopes and smooth surfaces overlain by thin colluvial soils. Such settings, common also to forested areas of the western Cascades and Olympics, are particularly susceptible to shallow avalanches involving only soil and vegetation. They are triggered by intense rainstorms or rain on the wet snow common to these elevations.

CASCADE RANGE

General

This major physiographic province has much geologic and topographic diversity as well as contrasts in glacial history and climate. The result is significant differences in landslide types. The nature of the slide

Figure 8. A large prehistoric slump/earthflow complex in deeply weathered material, southwest Washington, beyond the reach of the last continental glaciation in Thurston County, southwestern Washington

hazard relates to these differences, but it is also a result of the type of human occupancy. There are few permanent settlements within the Cascades themselves, and these tend to be small and/or seasonal. Land use is largely confined to recreation, water supplies, and transportation corridors; logging is important on both flanks. This relatively low and transient occupancy may be why, in an area of great relief and steep, commonly unstable slopes, there have been few deaths from landslides (excluding those related to the eruption of Mount St. Helens). Historically, snow avalanches have been a greater hazard, at least in the northern Cascades and on the flanks of the stratovolcanoes.

The diversity of this area is significant enough to warrant dividing the Cascades into several subprovinces for this discussion. A break, defined largely by geologic contrasts, at Snoqualmie Pass is appropriate. The pass marks the boundary between the dominantly metamorphic and intrusive igneous rocks to the north and the largely volcanic rocks to the south. Another subprovince includes the five stratovolcanoes, Baker, St. Helens, Glacier Peak, Rainier, and Adams. Although widely scattered, these peaks have distinctive slope stability characteristics.

North Cascades

The central core of the North Cascades is largely made up of gneiss, schist, migmatite, and granitic rocks. The flanks are dominantly sedimentary and volcanic rocks. Flank rocks have been folded to various degrees, and essentially all North Cascade rocks have been pervasively faulted and/or occur as fault-bounded blocks. Thus, in spite of their general competence, even the rocks of the crystalline core have numerous planes of weakness. Where relatively continuous, such planes have been excavated by streams and/or ice erosion. One striking example of this is Twin Sisters Mountain, where the Nooksack River drainage system effectively follows the sheared boundary of this oval mass of dunite.

As one might expect in such a diverse setting, there are significant differences in the nature and extent of slope failures. The essentially massive core rocks, intensely scoured by alpine glaciers (and in the north also by continental glaciers), have been thoroughly tested. Weaknesses found were removed, leaving miles of steep to near-vertical valley walls in extremely competent crystalline rocks. Such slopes commonly have active rock chutes and areas of small-scale rockfalls that have extensive talus aprons but relatively few active or Holocene slide masses of significance. Beyond the limits of the last ice sheet, however, R. B. Waitt has recognized extensive "incipient blockslides" along ridgetops in crystalline rock (*in* Tabor et al., 1987). He suggests that at least some of the movement of these deeply crevassed and fractured bedrock areas may have taken place in the Holocene.

In contrast, the layered sedimentary and volcanic rocks making up the flanks or the sedimentary rocks filling major grabens are not only less competent but have through-going planes of weakness in the form of shale, siltstone, or coal or tuffaceous interbeds. Thus, their mode of failure may be more like those of the bedrock of the northern Cascade foothills described under the Puget Lowland heading. Large Holocene landslide masses are locally common. Farther south, beyond the reach of the last continental glaciation, large dormant Pleistocene landslides are also abundant, particularly in sandstone that has weak interbeds, such as the Chumstick and Roslyn Formations (Tabor et al., 1987).

South Cascades/Columbia Gorge

The peaks of the southern Cascades of Washington are lower than those of the North Cascades, and the mountains are made up predominantly of volcanic rocks. These volcanic flows and pyroclastic rocks were erupted throughout most of the Tertiary and Quaternary (including Holocene). These rocks have varied compositions and modes of deposition. Individual units range from welded tuffs and lava flows well in excess of 100 ft thick to lahars and mudflow deposits too discontinuous to map except on very large scales. Lava flows commonly filled paleodrainages. Highly competent units are commonly separated by weak sedimentary interbeds or, in places, by saprolites. Ground water is locally discontinuous. In places, contacts have considerable slope, both primary and tectonic.

Much of the area has experienced multiple alpine glaciations, with at least one extending into some lowland areas (Crandell and Miller, 1974). Thus, the province experienced not only glacial erosion and oversteepening but also localized interplay between volcanic eruptions and ice. Hammond (1987) describes the events and resulting deposits of such interplay in the upper Wind River area. This complex history suggests that the southern Cascades cannot be passed off as "just" volcanics and that slope stability problems can be complex and wide-ranging. One of the many deep-seated bedrock landslides in this subprovince is shown in Figure 9. In addition to such slumps, earthflows and block glides are also common. Geologists of the U.S. Forest Service have recently completed the monumental task of mapping the landslides in the Gifford Pinchot National Forest, which makes up much of this province (Wooten, 1988). They identified many previously unsuspected landslides.

As a natural geologic cross section of Washington's South Cascades, the Columbia River gorge may logically be included in this Cascade landslide subprovince. The "story of the ancestral Columbia River in the gorge region began about 15.6 Ma" (Beeson and Tolan, 1987, p. 322). The early course of the Columbia followed a syncline in the developing Yakima Fold Belt that trended southwest from the present The Dalles. Similar troughs apparently were common in the ancestral Miocene Cascades, at least locally, permitting not only the river but also some flows of the Columbia River basalt to reach the Pacific Ocean. Over the millennia some of these flows, in places augmented by deposits from Oregon Cascade volcanism, blocked the river channel, forcing it into progressively more northerly synclinal troughs until it incised at its present location. The modern Columbia River, with the help of numerous glacial meltwater floods, has cut as deep as 4,000 ft into the slowly rising Cascade Range.

With such relief, rainfall approaching 100 in. annually, and hydrothermally altered rocks and/or rocks with weathered interbeds locally dipping as much as 30° into the gorge, the abundance of large bedrock landslides should be no surprise. More than 50 sq mi of landslides are found in the gorge; less than 10 percent of this area is currently active. However, because of the importance of the gorge as a transportation and utilities route, these slides are significant and "have caused millions of dollars worth of damage or costs to prevent damage" (Palmer, 1977, p. 69).

With extensive landslide deposits and major active landslides to be traversed by this important power and transportation corridor, engineering geology has had many applications. Most of these are the usual methods of coping with slides (prevention, avoidance, or stabilization). Living with a landslide is not so common. Thus, some of the accommodations necessary for "co-existing" with the active Wind Mountain (Collins Point) landslide might be of interest.

- A hotel and spa developed near the Collins Hotspring within the toe area of the slide was abandoned in the early 1900s, probably at least in part due to slide problems.
- The navigation beacon, installed along the reservoir bank in 1938, has been moved, repaired, and reset several times (U.S. Army Corps of Engineers, 1971). The rail line, also near the river level, was constructed in 1907-1908. It experienced only about 1 ft of movement from 1907 to 1947, but a resurvey

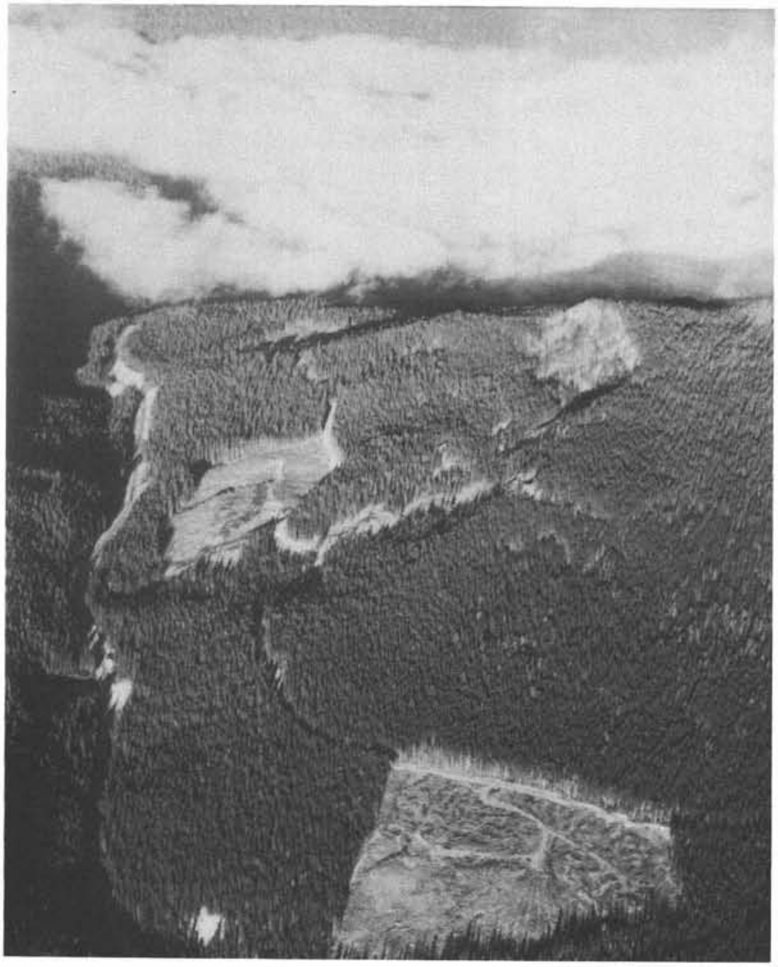


Figure 9. The toe of the ancient landslide is crossed by the White Pass Highway (Southern Cascade mountains; view to the west). Such large deep-seated bedrock landslides are often quite forgiving. Apparently the only problem has been ravelling of the shattered rock along the landslide toe.

in 1970 recorded as much as 15.7 ft of movement in places. During the 1960s, track maintenance including adding sections of track as the curve along the toe grew.

- Maintenance records for State Highway 14 are not available, but the uneven road surface and extensive patching observed in 1969 attested to continuing stability and foundation problems.
- The Girl Scout camp, near the middle of the slide, earlier adapted to slide movement by using an above-ground water system. The pipe was zigzagged, with flexing elbows supported on blocks.
- Movement of the Bonneville power line, built in 1941 across the upper part of the slide, was first noticed in 1946 and had increased to as much as 35 ft/yr in 1952. By then, 16 towers had been mounted on skids in an effort to maintain alignment. In the mid 1950s the power line was rerouted to above the headscarp of the landslide.

There reportedly is current concern among some landowners on the slide regarding the ownership of timber as it migrates downslope.

Stratovolcanoes

Although scattered geographically, Washington's five major stratovolcanoes share a scale of landslide potential distinct from that of the rest of the Cascade Range. Mount Baker, Glacier Peak, Mount Rainier, Mount St. Helens, and Mount Adams are not simply large mountains that stand out because of shape and elevation. Their common geologic histories have also left a legacy of factors that combine to make them inherently more unstable than most other mountains. Possibly most basic of the stability factors is that the bulk of these peaks is, as the term stratovolcano implies, made up of layered rock lying parallel to the slopes. These deposits contain many weak contacts and interbeds, all potential failure planes. Large volumes of the rock, especially on the upper slopes, have been further weakened by hydrothermal alteration. In many places these mid- and upper slopes have been undermined and oversteepened by glaciation and mass wasting; slopes commonly average 30° but locally approach vertical. Potentially compounding these elements of instability is water in the form of crater lakes, at least on Mounts Rainier and Baker. Still more water is available in the form of abundant ice and snow, both adding to the mobility of any landslide that might occur.

Relatively small rockfalls and avalanches are common localized hazards on these volcanoes. The potential for much larger ones, possibly triggered by strong earthquakes, obviously exists. Crandell (1973) suggests that such an avalanche from Mount Rainier could bury valley floors within a few miles of its base. Townley and Allen (1939) report large rock avalanches from Mount Rainier were triggered by earthquakes in 1894 and 1903. There undoubtedly have been more, and from other volcanoes, that went unreported. In addition to such direct hazards, Evans (1986) considers Quaternary volcanic centers to have a high potential for creating landslide dams, with the consequent potential for downstream flooding when breached. Eruption-related volcanic hazards are discussed elsewhere in this volume, but it is important to remind planners and emergency managers that Cascade volcanoes do not have to erupt to be dangerous.

OKANOGAN HIGHLANDS

This province grades west into the North Cascades and east into the Selkirk Mountains with no abrupt physiographic boundaries. However, the Columbia/Kettle Rivers and the Okanogan River mark the east and west boundaries of a distinctive central orogenic province that extends north far into British Columbia and is covered by Columbia River basalt flows to the south (Fox et al., 1977). East of this orogenic province are folded and faulted, very competent metasedimentary rocks, some metavolcanic rocks, and extensive areas of granite. Similar, but somewhat younger rocks lie to the west. Cutting north-south through the center of the province is the Republic graben, filled with generally less competent Tertiary sedimentary and volcanic rocks that are hydrothermally altered in places.

Except locally along the southern boundary, much of the highlands was scoured by the last continental ice sheet, so bedrock exposures are, in general, fresh and unweathered. However, certain granitic rocks, especially those rich in biotite, tend to disintegrate rapidly in place into grus, which may accumulate to as much as several yards thick in places. Grus is easily eroded during periods of heavy storm runoff and may locally fail as surficial debris avalanches.

Another form of slope failure closely associated with local bedrock conditions occurs particularly in the highland's central orogenic belt. Gneiss domes, on which dip of foliation increases out from the center, are an important part of this terrain (Fox et al., 1977). Since the retreat of the continental ice sheet from the area, block glides have taken place along weak planes of foliation, but some stopped in midslope. A readily visible example of such is along the east side of the Okanogan Valley between Omak and Riverside. These arrested block glides and accompanying boulder fields appear to be stable under present conditions. However, they stand as a reminder to the construction engineer that these massive-appearing rocks have subtle but potentially serious planes of weakness.

The primary slope stability problems in this province are in Pleistocene sediments within and along the boundary of the Okanogan Highlands. Thick sections of these sediments remain as terraces along the valleys of the Columbia, Spokane, and Sanpoil rivers. The sediments are the result of repeated damming of the Columbia River by lobes of the continental ice sheet and repeated catastrophic floods from breached ice dams to the east. Thus, sediments range from thick sections of varved clay and silt, through sand and gravel, to cobble/boulder lenses that have virtually no matrix. Some landslides in these relatively weak sediments with striking permeability contrasts are as old as late Pleistocene. The occurrence of new slides and reactivation of old ones increased dramatically with the filling of the reservoirs behind Grand Coulee and Chief Joseph dams. Drawdowns for flood control and power generation also trigger new slides and/or reactivate and extend old ones (Figure 10). Some of these landslide complexes extend for thousands of feet along the shores, head in terraces 300 ft or more above reservoir level, and extend well below its surface.

With such landslide activity common along hundreds of miles of shoreline it is apparent that conventional engineering remedies are generally out of the question. Instead, both the U.S. Bureau of Reclamation (USBR) and the U.S. Army Corps of Engineers have attempted to maintain unoccupied buffer zones along the slide areas fronting private property. Means of accomplishing such buffer zones have been through outright purchase of land, obtaining legal releases from owners of land or facilities in a landslide area whereby the owner assumes responsibility for further problems (USBR, 1986), or obtaining "slough and slide" easements on certain lands. Landslides in or near public parks are fenced off. To ensure that such efforts remain effective, both the USBR and the Corps of Engineers have established continuing monitoring programs along reservoirs behind Grand Coulee and Chief Joseph dams.

One hazard that might be expected in such settings is water waves generated by fast-moving landslide masses. These events are difficult to predict or cope with. Jones (1961), in his study of reservoir landslides, reported a 65-ft wave from one slide near Kettle Falls. Hazards of such waves would, of course, depend in part on the reservoir level at the time of the landslide.

COLUMBIA BASIN

The basalt flows that dominate the Columbia Basin were erupted into a structural and topographic low between the northern Rocky Mountains and the rising an-

Figure 10. One of many small landslides entirely within the reservoir area behind Grand Coulee Dam, May 1971. Such slides can set the stage for much larger ones that encroach on adjacent uplands.

cestral Cascade Range. Because the Cascades were not then high enough to create the present-day rain shadow, the climate during extrusion of the basalts was considerably wetter than at present (McKee, 1972). The resulting drainage systems and impoundments were responsible for the extensive layers of sediments between, interfingering with, and overlying the basalt flows. These sediments are generally thicker in areas peripheral to the flows, especially in and along the western part of the basin. In places they suggest a hiatus between flows on the order of a million years or more—time enough to develop deep saprolites on some flow surfaces. Present topographic relief on the basin has been provided largely by a series of east-west-trending anticlinal folds, by the cutting by the catastrophic glacial meltwater floods, and by the modern Columbia River system.

The most obvious evidence of bedrock slope failures in the basin province is the nearly ubiquitous presence of basalt talus slopes fringing the river canyons and abandoned glacial-meltwater channels. Such slopes, made up of clasts of nearly the same size, demand respect but are not apt to hold any surprises for the engineer. The high, vertical bluffs above these slopes are also quite predictable and attest to the general resistance of the basalts themselves to deep-seated slope failure.

Bedrock failures are most commonly in the form of very large ancient slumps or slump-flows (Figure 11). Block glides may be locally important and probably result from failures along interbeds or palagonite zones at flow contacts, although failure planes are commonly obscured. Most of these ancient failures occur in areas of regional tilting or are associated with folds, commonly on an overturned north limb. The final triggering mechanism, in many cases, appears to have been oversteepening or removal of toe support by stream incision or glacial floods.

Elsewhere, sediments contemporary with the Columbia River basalt flows or overlying them may be thick enough to make up all or a major part of the large landslide complexes. In the Spokane area landslide deposits fringe many of the buttes. Here, disoriented blocks of basalt lie like plums in a pudding of disturbed interflow silts. Similar deposits are present in landslide-formed benches in the Grande Ronde area, where some of the landslides are still active (Stoffel, 1984). Along the west edge of the province and in a structural basin near Pasco, other sections of sediments interfinger with and/or overlie basalt flows. Some of these sediments are compact enough to be considered siltstone or sandstone and are rich in montmorillonite. Such materials caused major landslide problems during the relocation of transportation routes required by filling of the reservoir behind John Day Dam (Anderson and Schuster, 1970). Slumps and translational failures were common, in some places along planes sloping as little as 8°. Most landslides here were considered to be associated with pre-existing failure surfaces developed by folding and/or ancient landslides.

Landslide problems in parts of the Columbia Basin have been compounded by irrigation (Figure 12). Irrigation, within and to the east of the Pasco Basin, has simulated a tenfold (or more) increase in precipitation and has produced ever-increasing drainage and landslide problems beginning in 1957 (Brown, 1972). A spectacular increase in slope failure since 1970 was reported by Hays and Schuster (1987). They found not only new landslides but re-activation of ancient landslide complexes, with active volumes as great as 14 million cy. These landslides, discussed elsewhere in this volume, are in bluffs along the Columbia River upstream of Richland. The inundation of the bases of these bluffs by the waters behind proposed Ben Franklin dam would compound the problem caused by any continuing seepage of irrigation water (Hays and Schuster, 1987).

SUMMARY AND CONCLUSIONS

Washington's diverse topography, geology, glacial history, and climate combine to create a broad spectrum of landslide types. The nature and abundance of these slides vary markedly among geologic or physiographic provinces. Whether these landslides present hazards depends, of course, to a great extent on population distribution. On the average, there are probably no more than one or two landslide-related deaths in Washington State per year. Thus, addressing landslide hazards is generally low on the priority list of most elected officials. Nevertheless, State and local governments are becoming more interested in landslides and landslide-hazard mapping. Much of this interest may well stem from concerns about potential liability as a result of land use and building regulations.

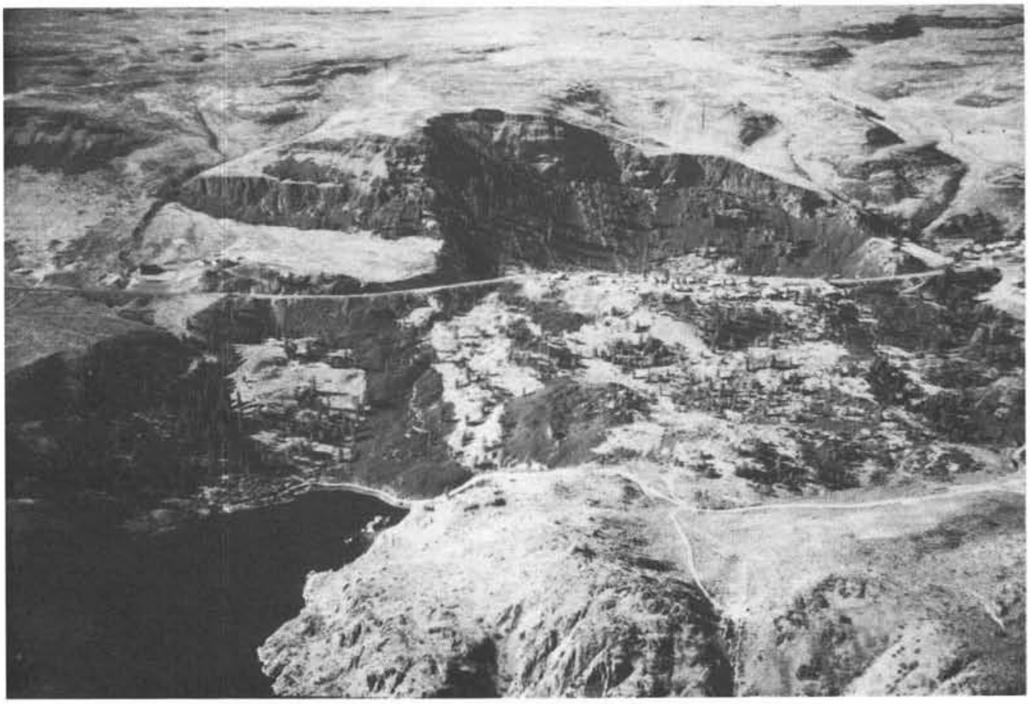


Figure 11. This prehistoric landslide in Columbia River basalt is buttressed against the granite knob in the foreground. Grand Coulee-to-Wilbur highway (State Route 174) crosses the head of the landslide. Reservoir behind Grand Coulee dam is at the lower left. Photo by Dale Stradling.

Figure 12. This landslide of compact silty sediments (Ringold Fm.) collapsed onto a settling pond, broke up, and traveled as a thin, fast-moving sheet. Dark band (upper right) is brush thriving on irrigation seepage. Colluvium there began slumping later. Photo by Ralph Smith, Tri-City Herald.

REFERENCES

Anderson, R. A. and Schuster, R. L., 1970, Stability of slopes in clay shales interbedded with Columbia River Basalt. In *Proceedings of the eighth annual engineering geology and soils engineering symposium*: Idaho Department of Highways, Boise, ID, pp. 273-284.

Beeson, M. H. and Tolan, T. L., 1987, Columbia River Gorge—The Geologic Evolution of the Columbia River in Northwestern Oregon and Southwestern Washington. In *Centennial Field Guide–Cordilleran Section, 1987*: Geological Society of America, pp. 321-326.

Brown, R. E., 1972, *Environmental Changes Caused by Irrigation in the Pasco Basin, Washington*: Society of Mining Engineers, Fall Meeting, Seattle, WA, 1971, 8 p.

Crandell, D. R., 1973, *Map Showing Potential Hazards from Future Eruption of Mount Rainier, Washington*: U.S. Geological Survey Miscellaneous Investigations Series Map I-836, 1 sheet, scale 1:250,000.

Crandell, D. R. and Miller, R. D., 1974, *Quaternary Stratigraphy and Extent of Glaciation in the Mount Rainier region, Washington*: U.S. Geologic Survey Professional Paper 847, 59 p.

Evans, S. G., 1986, Landsliding in the Cordillera of Western Canada. In Schuster, R. L., (editor), 1986, *Landslide Dams–Processes, Risk and Mitigation*: American Society of Civil Engineers Geotechnical Special Publication 3, pp. 111-130.

Fox, K. F. Jr.; Rinehart, C. D.; and Engels, J. C., 1977, *Plutonism and Orogeny in North-Central Washington–Timing and Regional Context*: U.S. Geological Survey Professional Paper 989, 27 p.

Hammond, P. E., 1987, Lone Butte and Crazy Hills–Subglacial Volcanic complexes, Cascade Range, Washington. In *Centennial Field Guide–Cordilleran Section, 1987*: Geological Society of America, pp. 339-344.

Hays, W. H. and Schuster, R. L., 1987, *Maps showing ground-failure hazards in the Columbia River Valley between Richland and Priest Rapids Dam, south-central Washington*: U.S. Geological Survey Miscellaneous Investigations Series Map I-1699, 2 sheets, scale 1:100,000.

Holmes, M. L. and Sylwester, R. E., 1988, Personal communication, U.S. Geological Survey, Seattle, WA.

Holmes, M. L.; Sylwester, R. E.; and Burns, R. E., 1988, Post-Glacial Sedimentation in Puget Sound (The Container — History and Hazards) [abstract and poster session]: *Program with Abstracts*, Research in Puget Sound, Puget Sound Water Authority, Seattle, WA, 3 p., 5 figures.

Jones, F. O.; Embody, D. R.; and Peterson, W. L. 1961 [1962], *Landslides along the Columbia River Valley, Northeastern Washington*: U.S. Geological Survey Professional Paper 367, 98 p.

Kockelman, W. J., 1986, *Some Techniques for Reducing Landslide Hazards*: Bulletin of the Association of Engineering Geologists, Vol. 23, No. 1, pp. 24-52.

Livingston, V. E., Jr., 1966, *Geology and Mineral Resources of the Kelso-Cathlamet Area, Cowlitz and Wahkiakum Counties, Washington*: Washington Division of Mines and Geology Bulletin 54, 110 p., 2 plates.

McKee, Bates, 1972, *Cascadia–The Geologic Evolution of the Pacific Northwest*: McGraw-Hill, Inc., New York, NY, 394 p.

Palmer, Leonard, 1977, Large Landslides of the Columbia Gorge, Oregon and Washington. In *Reviews in Engineering Geology, Volume 3*: Geological Society of America, pp. 69-83.

Stoffel, K. L., 1984, *Geology of the Grande Ronde Lignite Field, Asotin County, Washington*: Washington Division of Geology and Earth Resources Report of Investigations 27, 79 p., 1 plate.

Tabor, R. W.; Frizzell, V. A., Jr.; Whetten, J. T.; Waitt, R. B.; Swanson, D. A.; Byerly, G. R.; Booth, D. B.; Hetherington, M. J.; and Zartman, R. E., 1987, *Geologic map of the Chelan 30-minute by 60-minute quadrangle, Washington*: U.S. Geological Survey Miscellaneous Investigations Series Map I-1661, 29 p., 1 plate, scale 1:100,000.

Townley, S. D. and Allen, M. W., 1939, Earthquakes in Washington–1833 to 1928. In *Descriptive Catalog of Earthquakes of the Pacific Coast of the United States, 1769 to 1928*: Bulletin of the Seismological Society of America, Vol. 29, No. 1, pp. 259-268.

U.S. Army Corps of Engineers, 1971, *Collins Point, Washington, Slide Study*: U.S. Army Corps of Engineers, Portland District, Design Memo. No. 1 Supplement No. 7, Portland, OR, 28 p.

University of Washington, Department of Geological Sciences, [1970], *The Nisqually Delta*: University of Washington, Seattle, WA, 88 p.

University of Washington, Department of Oceanography, 1953, *Puget Sound and Approaches; A Literature Survey, Vol. II*: University of Washington, Seattle, WA, 118 p.

U.S. Bureau of Reclamation, 1986, *Annual Inspection Report–Franklin D. Roosevelt Lake*: Grand Coulee Project Office, Grand Coulee, WA, 43 p., 4 photos, 2 plates.

Varnes, D. J., 1978, *Slope Movement and Types and Processes in Landslides–Analysis and Control*: Transportation Research Board, National Academy of Sciences, Washington, DC, Special Report 176, Chapter 2.

Washington Department of Ecology, 1978-1980, *Coastal Zone Atlas of Washington*: Washington Department of Ecology, 12 volumes.

Wooten, R., 1988, Personal communication, U.S. Forest Service, Wind River District.

The Bridgeport landslide viewed from the west above Chief Joseph Dam on the Columbia River . Photograph by the U.S. Army Corps of Engineers, October 20, 1978.

Computer analysis of slope stability makes it possible to factor in the risk of landslides when planning timber harvest from slopes such as this. Photograph courtesy of the U.S. Forest Service.

Geotextile materials are used for several purposes on logging roads, including improving slope stability. Here a geotextile forms a stack of aggregate-filled envelopes that are tiered to form a wall. A road can then be built across the top. Photograph courtesy of the U.S. Forest Service.

A slide scar on a slope above and debris that flowed across Aurora Avenue (U.S. Highway 99) in Seattle, January 1984. The site is now occupied by an apartment complex. Photograph courtesy of Shannon & Wilson, Inc.

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Volcanic Hazards in Washington

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INTRODUCTION

The apparent tranquility of the major volcanoes in the Cascade Range of Washington and northern Oregon (Figure 1) is deceptive. Most have been at least mildly active in historic time (past 150 yr), and all have erupted lava and volcanic ash several times in the last 10,000 to 12,000 yr. However, prior to the violent eruption of Mount St. Helens on May 18, 1980, most practicing geologists and engineers gave little thought to the potential hazards from volcanic eruptions in Washington. According to Schuster (1981), much of the destruction and disruption of civil works and operations from that eruption likely could have been avoided if land-use planning, based on potential eruptive hazards, had been applied to development in the vicinity of the volcano and downvalley along the major streams draining it.

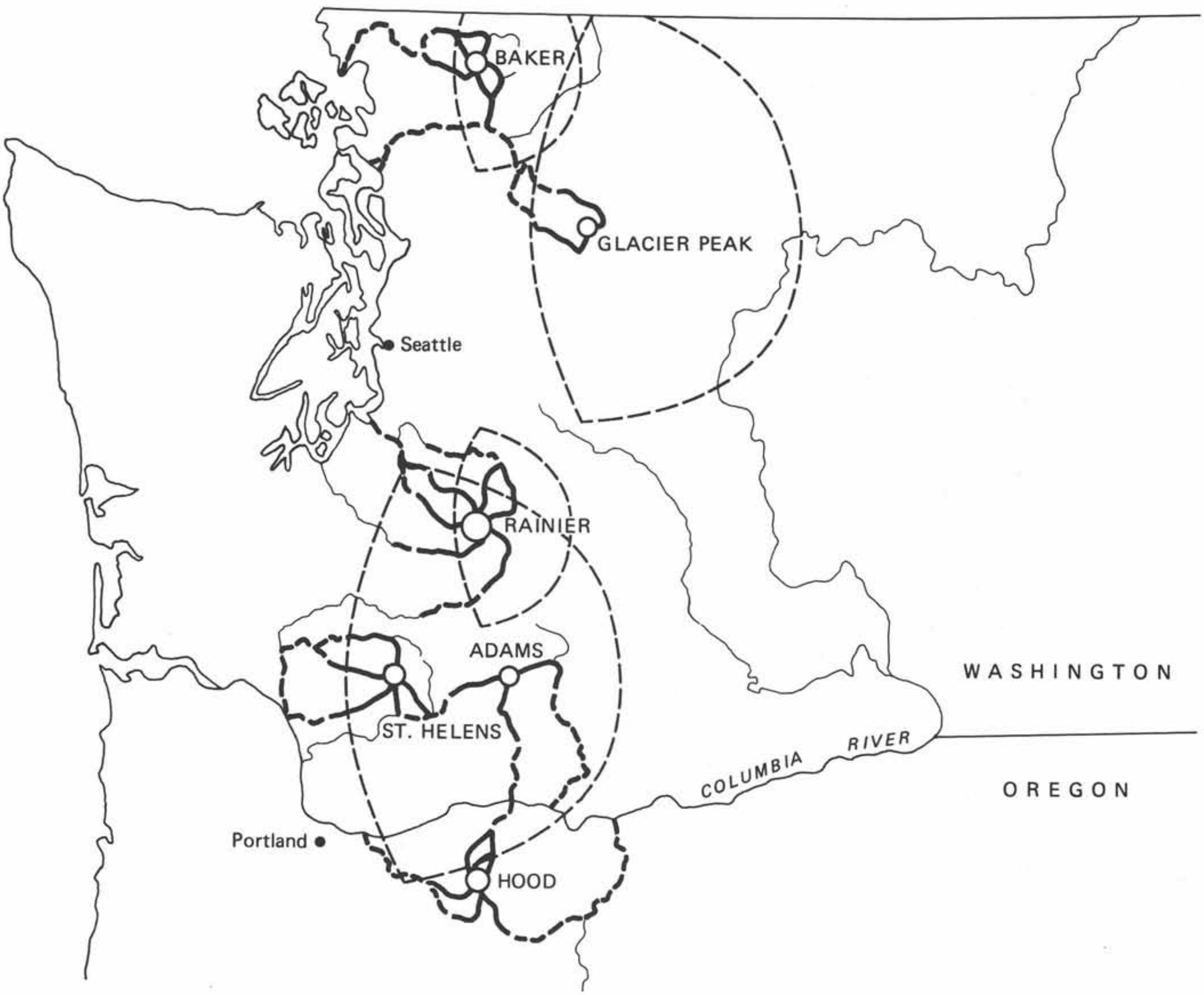
The kinds of volcanic events and eruptive products or effects that can result in damage and/or disruption to civil works and operations in Washington include: violent lateral blasts of hot gases and rock fragments, ash and rock debris avalanches, air-borne ash falls, lava flows, mudflows, and floods and sedimentation. Many of these hazards are the types that can occur suddenly, but usually some warning precedes the event. Each kind will be discussed in this paper relative to its potential hazards to civil works and operations. The potential hazards from such rare events as the birth of a new volcano, which happened at Paricutin, Mexico, in 1943, or of a cataclysmic eruption of one of the volcanoes, such as occurred at Mount Mazama volcano (Crater Lake) in Oregon between 6,000 and 7,000 yr ago, are not considered. Although these kinds of eruptions conceivably are possible in Washington, the likelihood of such an event occurring is believed to be very remote.

Investigations and assessments of the potential hazards from volcanic eruptions of all of the major volcanoes in the Pacific Northwest have been made during the past 15 yrs by geologists with the U.S. Geological Survey. References to some of these studies are in the bibliography at the end of this paper. Additional references can be found in a Washington Division of Geology and Earth Resources compilation of bibliographies on the geology and volcanic hazards of volcanoes in the Pacific Northwest (Rigby, 1981). Of particular interest to engineers and engineering geologists is a report by Schuster (1981) on the damaging effects to civil works and operations in the Pacific Northwest from the 1980 eruptions of Mount St. Helens.

VOLCANOES: THEIR ERUPTIVE PRODUCTS AND EFFECTS

Volcanoes

Volcanoes originate from eruptive mechanisms that result in a variety of forms. Their eruptive differences are largely based on the fluidity and gas content of the subsurface molten rock, or magma, as it reaches the surface. Commonly, the higher the gas content and the more viscous the magma, the more explosive and violent the eruption. All of the Cascade volcanoes are classified as "composite" or "strato-" volcanoes, i.e., the type that has been built up of interbedded lava flows and layers of ash and coarser rock debris, indicating that both explosive eruptions of fragmental rock materials and more quiet, effusive eruptions of molten rock, or lava, have occurred during their development. It is evident from the history of each of the major Cascade volcanoes that they have developed over periods of several thousands of years, each recording in their development long dormant intervals interspaced between fairly active episodes. Thus, a relatively quiet interlude now does not necessarily mean that a volcano should be considered extinct. Crandell and Mullineaux (1975) pointed out that although the potential volcanic hazard to life and property may be small by comparison with that from earthquakes, storms, or floods, nevertheless the hazard is real and warrants concern. Their concerns were well borne out during the 1980 violent earthquake eruption of Mount St. Helens. The potential hazards to civil works and operations from volcanic eruptions in Washington can range from very minimal to very destructive, depending on the kind and extent of the eruption, the location of the volcano with respect to population concentrations, the prevailing winds and their strengths aloft during the eruption, the topographic setting surrounding the volcano, and the duration of the eruption. The kinds of eruptions can range from quiet and nonviolent to explosive and extremely violent. Smaller events, which tend to occur more frequently than larger events, usually are confined to the immediate flanks of the volcano.The



MAP EXPLANATION

- LARGE VOLCANO - FLANKS SUBJECT TO LAVA FLOWS AND OTHER KINDS OF VOLCANIC HAZARDS.
- VALLEY FLOORS SUBJECT TO BURIAL BY HOT AVALANCHES OR SMALL- TO MODERATE-SIZED MUDFLOWS.
- VALLEY FLOORS SUBJECT TO FLOODS AND RELATIVELY LARGE BUT INFREQUENT MUDFLOWS.
- ASHFALL-HAZARD ZONE SUBJECT TO DEPOSITION OF 5 cm OR MORE DURING A MODERATE ERUPTION. MOST ASHFALL (75-80%) EXPECTED TO FALL IN AREA RANGING FROM NNE TO SSE OF VOLCANO.

(MODIFIED FROM CRANDELL, 1976; MULLINEAUX, 1976)

Figure 1. Locations of major Cascade volcanoes and principal eruptive hazard zones for each.

larger events tend to occur less frequently, but they may endanger sizeable areas,particularly those downvalley or downwind from the vent. Risks from all eruptions decrease with distance from the eruptive vent; risks from downvalley hazards also decrease with altitudes above the valley floors.

Eruptive Products and Effects

The eruptive products and other effects related to volcanism that can be hazardous to civil works and operations include: (1) the direct effects from the eruptive products, such as lava flows, violent lateral blasts, hot avalanches of volcanic gas and rock debris, and volcanic ash falls; and (2) the indirect effects from mudflows, flooding, and sedimentation that can accompany or occur as a result of the eruption. The volcanoes in the Cascade Range are especially dangerous with respect to mudflows and floods because most have a perennial ice and snow cover that can be melted readily by lava flows or by hot avalanche flows, or by some other volcanic process.

Lava flows, or streams of molten rock, are confined chiefly to the flanks and to the upper parts of valleys downslope from the erupting vent. Although they may move at different speeds, most move slowly enough to be easily be avoided. However, because the lava flows engulf and bury everything in their path, they can be disastrous to any civil works that may lie in their path. The indirect effects of lava flows also can be hazardous. For example, if they move into vegetated areas, they can start forest fires, or if they move out onto snow and ice fields, they can cause rapid melting, and large floods or mudflows could be expected downvalley.

Because of their confinement to the flanks of the volcano and to the upper reaches of valleys draining the volcano, the potential hazards of lava flows to civil works and operations are principally to buildings and roads and bridges built on the lower slopes of the volcano or on the floors of valleys cut in these slopes. In some localities, they also might be hazardous to reservoirs and dams that occupy the upper reaches of valleys draining the volcano.

Lateral blasts consist of massive amounts of hot, dry, rock debris blown out laterally and downslope by a violent and explosive eruption from a vent on the volcano. The blast may come from a summit vent or from a vent lower down on the flank of the volcano. Damage usually is confined to those areas of total devastation that occur immediately downslope from the vent, but some damage may occur in zones peripheral to the devastated area where shock-wave and thermal effects occur. In 1980 at Mount St. Helens, total destruction from such a lateral blast extended for a radial distance of about 8 mi downslope within an arc of approximately 120°, with blast and thermal effects apparent for another 4 to 5 mi downslope.

Because of the confinement of lateral blast effects to the flanks of the volcanoes, the hazard potential to civil works principally affects roads, bridges, and buildings in those areas.

Hot avalanches are flows of hot, dry, gas-laden rock debris that can be caused directly by an eruption of masses of hot rock fragments or as a result of the collapse and disruption of a mass of hot, solid rock. These flows, which are capable of moving downslope at high speeds (as much as 75 mph), generally move along and bury valley floors for distances downvalley that may exceed 10 mi; clouds of ash generated by these flows can form extensive deposits downwind from the flows. Such avalanches are extremely dangerous, owing to their speed and their potential for total destruction of life and property in areas they cover.

Avalanche flows also may constitute a potential hazard farther downvalley for some time after the eruption because they are a source of easily eroded sediment capable of producing potentially destructive mudflows during periods of heavy rainfall. In addition, because these avalanche flows fill major valleys, they can temporarily block or dam tributary valleys and result in the formation of potentially hazardous lakes in the tributary valleys.

Mudflows are masses of water-saturated rock debris of all sizes that can move down steep valley floors at speeds of 20 to 55 mph and extend for considerable distances from the volcano. On gentle slopes they tend to move more slowly and spread out widely. Principal hazards to civil works from mudflows are the burial and destruction of homes, buildings, roads, railroads, and bridges, and the potential disruption or destruction of towns and of water-supply and sewage-disposal systems that may lie in their paths. Power and communication lines also are vulnerable to disruption by these mudflows.

Most periods of volcanic activity by the major volcanoes in the Cascade Range have been accompanied by mudflows of varying sizes. For example, Crandell (1971) identified more than 55 postglacial mudflows or debris flows in valleys that head on Mount Rainier. One of the largest in the world, the Osceola Mudflow (Crandell and Waldron, 1956), occurred during a period of volcanic activity at Mount Rainier several thousand years ago. This mudflow extended down the White River valley to the Puget Sound lowland, where it spread out over an area of more than 125 sq mi, with an estimated total volume of about 2.6 billion cy (Crandell, 1971). Although it ranges in thickness from a trace to as much as 350 ft, in general, the flow deposit is only about 20 to 75 ft thick. In the lowland, the mudflow flowed into and partly filled much of what at the time was an arm of the Puget Sound but which is now the Duwamish valley (Mullineaux, 1970). The possibility of another mudflow as large as the Osceola occurring in the Cascade Range, however, is very unlikely.

A younger, smaller mudflow from Mount Rainier, the Electron Mudflow (Crandell, 1971), flowed down the Puyallup River valley about 600 yr ago for 35 mi to the vicinity of Puyallup and Sumner. It had an estimated volume of about 200 million cy and is as much as 16 ft thick in the vicinity of Orting.

Because of the speed with which they can move and their possible large size, volcanic mudflows constitute a significant potential hazard to life and to civil works. Any recurrence of one of these large mudflows in Washington could devastate homes and communities that are situated on valley floors or that may lie in their paths. The presence of dams and reservoirs on rivers and streams draining these volcanoes can be either beneficial or endangering. If the reservoirs are low or drained in time, then they can be used to trap all or much of a mudflow, but the loss of storage may be permanent. If, on the other hand, the reservoirs are full, the possibility of overtopping and destruction of the dams exists, with concomitant damaging floods downstream.

Flooding and sedimentation caused by volcanism can extend for many miles downvalley from a volcano. Because floods of volcanic origin commonly carry much greater suspended loads than ordinary floodwaters, submersion and burial from these debris-laden waters is considerably more hazardous to civil works located along the valley floors and adjacent floodplains than might be expected from ordinary flooding. Particularly vulnerable are the communities, homes, roads, railroads, bridges, and water-supply and sewage-disposal systems within these valleys. Recession of these debris-laden waters generally will leave thick accumulations of mud and rock debris, and previous stream courses may be altered.

During the 1980 eruption of Mount St. Helens, an estimated 50,000,000 cy of rock debris was deposited in the 21 mi of the Cowlitz River downstream from the mouth of the Toutle River, and an additional 45,000,000 cy was deposited in the Columbia River, upstream and downstream from the mouth of the Cowlitz (Bechly, 1980), all within a 24-hr period after the initial lateral blast. These deposits essentially eliminated the natural channel capacity of the Cowlitz River and severely blocked the Columbia River channel for navigation by deep-draft vessels for 3 to 4 weeks.

Volcanic ash consists of fine-grained rock debris that is blown into the air above a volcano; it commonly accompanies eruptive episodes. Only the finer materials erupted, which predominantly move downwind rather than downslope from an erupting volcano, present a hazard to civil works and operations. This ash-laden air can seriously endanger lives and property at considerable distances downwind from the volcano. The downwind distribution and thickness of air-fall ash is determined by the grain size and density of the rock fragments, the height to which the material is erupted, the strengths and directions of the high-altitude winds, the volume of material erupted, and the duration of the eruption. Surface winds may subsequently redistribute the finer fraction of the ashfall, in a manner similar to the winnowing and drifting of new-fallen snow.

Modern meteorological records show that both high-altitude wind directions and speeds in Washington and northern Oregon have been more prevalent and stronger toward the east than toward the west. Nearly 80 percent of the winds at altitudes of 10,000 ft to more than 50,000 ft blow toward a sector that extends from the north-northeast to the south-southeast. Studies of past air-borne ashfall distributions and thicknesses from Cascade volcanoes indicate that this easterly prevalence of wind direction has apparently existed for many thousands of years (Crandell, 1976; Mullineaux, 1976).

The principal hazards to civil works and operations from air-borne volcanic ash include the possibility of injury to personnel from breathing the ash-contaminated air, of damage to property that can result from the weight of the ash (particularly when wet), of smothering effects, of abrasion, and of corrosion. Machinery is especially vulnerable to the abrasive and corrosive effects of ashfalls, from both the fine rock debris in the ash and from the acidic gases and acids in the ash. Other potential hazards from air-fall ash include: the impedance and disruption of transportation facilities, especially roads, highways, and airfields; the clogging and corrosive effects on drainage facilities; the clogging and disruption of water-supply and sewage-disposal systems; and the possible interruption of telephone and electrical services, principally owing to overloading of the facilities.

A secondary hazard from air-fall ash deposits is the effect it may have on vegetation and on runoff characteristics. For example, during the prolonged eruption of Irazu Volcano in Costa Rica, which erupted air-borne ash almost continuously for more than 20 months in the mid-1960s, widespread damage to life and property occurred from accelerated erosion and repeated floods of water, mud, and rock debris from the slopes of the volcano. All of these problems were the result of profound changes in the hydrologic regimen of the streams, brought about by the accumulation of a thick mantle of ash on the upper slopes of the volcano and its effects on the runoff accompanying precipitation (Waldron, 1967).

CASCADE RANGE VOLCANOES

Six major volcanoes in the Cascade Range of Washington and northern Oregon could be considered to be potentially hazardous to civil works and operations in Washington, especially in the vicinity of and downvalley and downwind from them. From north to south (Figure 1) the volcanoes are: Mount Baker in Whatcom County, Glacier Peak in Snohomish County, Mount Rainier in Pierce County, and Mount Adams and Mount St. Helens in Skamania County, all in Washington, and Mount Hood in Clackamas County, Oregon. Mount St. Helens was frequently active during the first half of the 19th century (until 1856), and then it erupted violently in May 1980. Mount Baker and Mount Rainier each erupted at least once during the first half of the 19th century. Mount Adams has erupted several times in the last 10,000 to 12,000 yr, but it apparently has been relatively quiescent for the past 2,000 to 3,000 yr. Glacier Peak has been intermittently active during the last 14,000 yr, but it has been relatively quiescent for the past few hundred years (Beget, 1981). Although Mount Hood also has been active several times during the past 15,000 yr, and most recently between 200 and 300 yr ago and in the mid-19th century, none of the eruptive products have affected Washington.

Numerous scattered volcanic vents of Quaternary age are present in the Southern Cascades, principally occurring south of Mount Rainier and south and east of Mounts St. Helens and Adams. Eruptive products of future eruptions from such vents are believed to be probably very limited in area distribution and likely to consist largely of lava flows and very small amounts of air-fall ash (Crandell, 1976).

Based on the past eruptive histories and an assessment of the expectable kinds of future eruption of the six Cascade volcanoes in Washington and Oregon, the two greatest potential hazards to civil works and operations from future eruptions are considered to be the direct and indirect effects of the downwind fallout of air-borne ash and those of mudflows and floods moving downvalley from the erupting volcano. Hazards from air-fall ash predominantly would affect those areas east of the erupting volcano, especially in the sector ranging from north-northeast through south-southeast. Only two of the six volcanoes, Glacier Peak and Mount St. Helens, however, have produced large quantities of ash during the past 10,000 to 12,000 yr. Hazards from mudflows and floods, on the other hand, could occur in any of the stream valleys that head on the flanks of the volcano.

Although all six of these volcanoes can be considered to be potentially dangerous to lives and property, the most hazardous are believed to be Mounts Baker, Rainier, and St. Helens. These three volcanoes are considered to be the most hazardous during and after a violent eruption, not only because of their past histories of eruptive activity, but also because of their potential to affect significantly more lives and property than any of

Table 1. Summary of recent eruptive activity and probable greatest potential hazards from major Cascade volcanoes in Washington and Oregon (Data principally from Crandell, 1976, 1980; Beget, 1983)

Volcano	Relative explosiveness of eruptions	Average frequency of past eruptions based on period of years in parentheses	Probable greatest potential hazards
Mt. Baker	Low	1 per 100-200 yr (4,000 yr)	Direct and indirect effects of mudflows or hot avalanches moving into reservoirs in Baker Ridge valley
Glacier Peak	High to low	1 per 900-1,100 yr (5,500 yr)	Airborne ashfalls in central or north-central Washington; mudflows and floods may extend several miles down valleys
Mt. Rainier	Low	1 per 500-1,000 yr (10,000 yr)	Mudflows and floods that could extend down valleys for several miles
Mt. St. Helens	High to low	1 per 100-200 yr (4,000 yr)	Airborne ashfalls in central and south-central Washington; hot avalanches, mudflows, and floods extending down valleys for several miles
Mt. Adams	Low	1 per 5,000 yr(?) (10,000 yr)	Mudflows and floods that could extend down valleys for miles
Mt. Hood	Low	1 per 4,000 yr (12,000 yr)	Mudflows and floods that could extend down valleys to the Columbia River

the other volcanoes, which have lower frequencies of volcanic activity, and except for Mount Hood, are located more distant from population concentrations.

Both Figure 1 and Table 1 provide summary data on the greatest potential hazards in Washington from future volcanic eruptions of the six major Cascade volcanoes. Figure 1 shows the probable aerial extent of greatest hazards from airborne ashfalls and the probable down valley extent of hot rock and ash avalanches and of mudflow and floods.Table 1 shows the relative explosiveness of each volcano, the average frequency of their past eruptions, and the probable greatest potential hazards from future eruptions.

REFERENCES

Bechly, J. F., 1980, Mt. Saint Helens eruption—Restoration of Columbia and Cowlitz River channels, in *Texas A&M University Dredging Seminar*: College Station, TX, 52 p.

Beget, J. E., 1981, *Postglacial Eruption History and Volcanic Hazards at Glacier Peak, Washington*, [Ph.D thesis]: University of Washington, Seattle, WA, 192 p.

Beget, J. E., 1983, Glacier Peak, Washington—A potentially hazardous Cascade volcano: *Environmental Geology*, Vol. 5, No. 2, pp. 83-92.

Crandell, D. R., 1971, *Postglacial Lahars From Mount Rainier Volcano, Washington*: U.S. Geological Survey Professional Paper 677, 74 p.

Crandell, D. R., 1976, *Preliminary Assessment of Potential Hazards From Future Volcanic Eruptions in Washington*: U.S. Geological Survey Miscellaneous Field Studies Map MF-774, 1 sheet, scale 1:1,000,000.

Crandell, D. R., 1980, *Recent Eruptive History of Mount Hood, Oregon, and Potential Hazards From Future Eruptions*: U.S. Geological Survey Bulletin 1492, 81 p.

Crandell, D. R., and Mullineaux, D. R., 1975, Technique and rationale of volcanic-hazards appraisals in the Cascade Range, northwestern United States: *Environmental Geology*, Vol. 1, No. 1, pp. 23-32.

Crandell, D. R., and Waldron, H. H., 1956, A recent volcanic mudflow of exceptional dimensions from Mt. Rainier, Washington: *American Journal of Science*, Vol. 254, pp. 349-362.

Mullineaux, D. R., 1970, *Geology of the Renton, Auburn, and Black Diamond Quadrangles*: U.S. Geological Survey Professional Paper 672, 92 p.

Mullineaux, D. R., 1976, *Preliminary Overview Map of Volcanic Hazards in the 48 Conterminous United States*: U.S. Geological Survey Miscellaneous Field Studies Map MF-786, 1 sheet, scale 1:7,500,000.

Rigby, J. C., 1981, *Bibliographies of the Geology and Volcanic Hazards of the Cascade Range Volcanoes of Washington and Mount Hood, Oregon*: Washington Division of Geology and Earth Resources Open File Report 81-5, 42 p.

Schuster, R. L., 1981, Effects of eruptions on civil works and operations in the Pacific Northwest, in Lipman, P. M., and Mullineaux, D. R., *The 1980 Eruptions of Mount St. Helens, Washington*: U.S. Geological Survey Professional Paper 1250, pp. 701-718.

Waldron, H. H., 1967, *Debris Flow and Erosion Control Problems Caused by the Ash Eruptions of Irazu Volcano, Costa Rica*: U.S. Geological Survey Bulletin 1241-I, 87 p.

Eruption of Mount St. Helens, Washington, July 22, 1980. Washington Department of Natural Resources photograph.

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Tectonics, Seismicity, and Engineering Seismology in Washington

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INTRODUCTION

An improved understanding of the relation among tectonics, seismicity, and geology has resulted in significant changes in the siting and design of major engineered structures during the past 30 years. Just as the importance of appropriate geologic assessments for engineered projects was not recognized until the early days of large dam construction, the importance of seismology to similar projects was not recognized until the advent of the commercial nuclear power industry in the 1950s (Tocher, 1975). As the development of that industry continued during the 1960s and 1970s, the practice of engineering geology changed dramatically. The influence of seismology and, later, the study of tectonics resulted in the development of new areas of specialization in the disciplines of engineering, seismology, and geology. As a consequence, earthquake engineering and other multidisciplinary activities that integrate specialized disciplines with the more traditional practice of engineering seismology and seismotectonics came into use. Today, investigations for most large engineering projects include seismology and geology. This discussion focuses on the tectonics and seismicity of Washington and surrounding regions, two topics that have a significant impact on the practice of engineering geology.

Although scientists today still do not have a full understanding of the complex interactions that affect the Earth's outer shell, in the past 25 to 30 yr dramatic progress has been made that has changed much of our perception of processes and structures within the Earth. The theory of plate tectonics serves as a unifying concept for many diverse observations and fields of earth science. Scientists recognize distinct regions of the Earth's rigid outer shell (lithosphere) that interact to store and release strain energy in the form of earthquakes and tectonic deformation. Such interactions are of particular concern to engineering applications; understanding and predicting their consequences are central to estimating geologic hazards.

Tectonic stress results from the interaction of the nearly rigid lithospheric plates, which are driven by processes such as convective flow originating deeper within the Earth's mantle. Ultimately, heat within the Earth's interior drives such processes. Earthquakes are one manifestation of the interaction between lithospheric plates. Strain energy accumulates in the elastic part of the lithosphere, particularly near plate boundaries, as plates move relative to one another. When the elastic limit is exceeded, much of this strain energy may be released in earthquakes. In many areas, the process of strain energy buildup and subsequent release occurs in cycles that are of short duration on a geologic time scale, allowing scientists to make generalized predictions of the temporal behavior of earthquakes.

Over longer geologic periods, the forces that drive the various plates that make up the Earth's crust have changed, altering tectonic stress within the crust, including plate boundaries and faults. As a result, the rate of release of accumulated strain energy may change slowly with time, evidenced by either a decrease or an increase of earthquake activity, including the generation of new faults. However, because such long-term changes in stress are measured in terms of geologic time scales, they are not considered in the design of engineered structures. The single exception may be for a deep geologic repository for high-level radioactive waste, where performance may be measured in terms of thousands of years.

This paper is divided into four sections. The first section discusses the tectonic setting of the Pacific Northwest region on the basis of geologic evidence. The second section discusses seismicity, the study of the earthquakes within the region as recorded by documented history or instrumentation. The third section discusses the tectonic implications of historic and instrumental seismicity. Finally, the last section discusses engineering seismology, the application of tectonics and seismicity to the design of an engineered facility.

TECTONIC SETTING

The current tectonics of the Pacific Northwest are essentially a function and continuation of tectonic events and processes that have been in operation since the early Tertiary as a result of the interaction of the Juan de Fuca plate system and its predecessors, the Farallon and Kula plates, with the North American plate. This interaction is characterized primarily by the subduction of the Juan de Fuca plate system beneath the North American plate along the Cascadia subduction zone (Figure 1). Examination and evaluation of the characteristics of the Quaternary plate setting provide an understanding of the most geologically recent tectonic processes acting in the Pacific Northwest and assist in the assessment of earthquake hazards. While we cannot avoid discussion of the larger regional picture, we focus mainly on Washington.

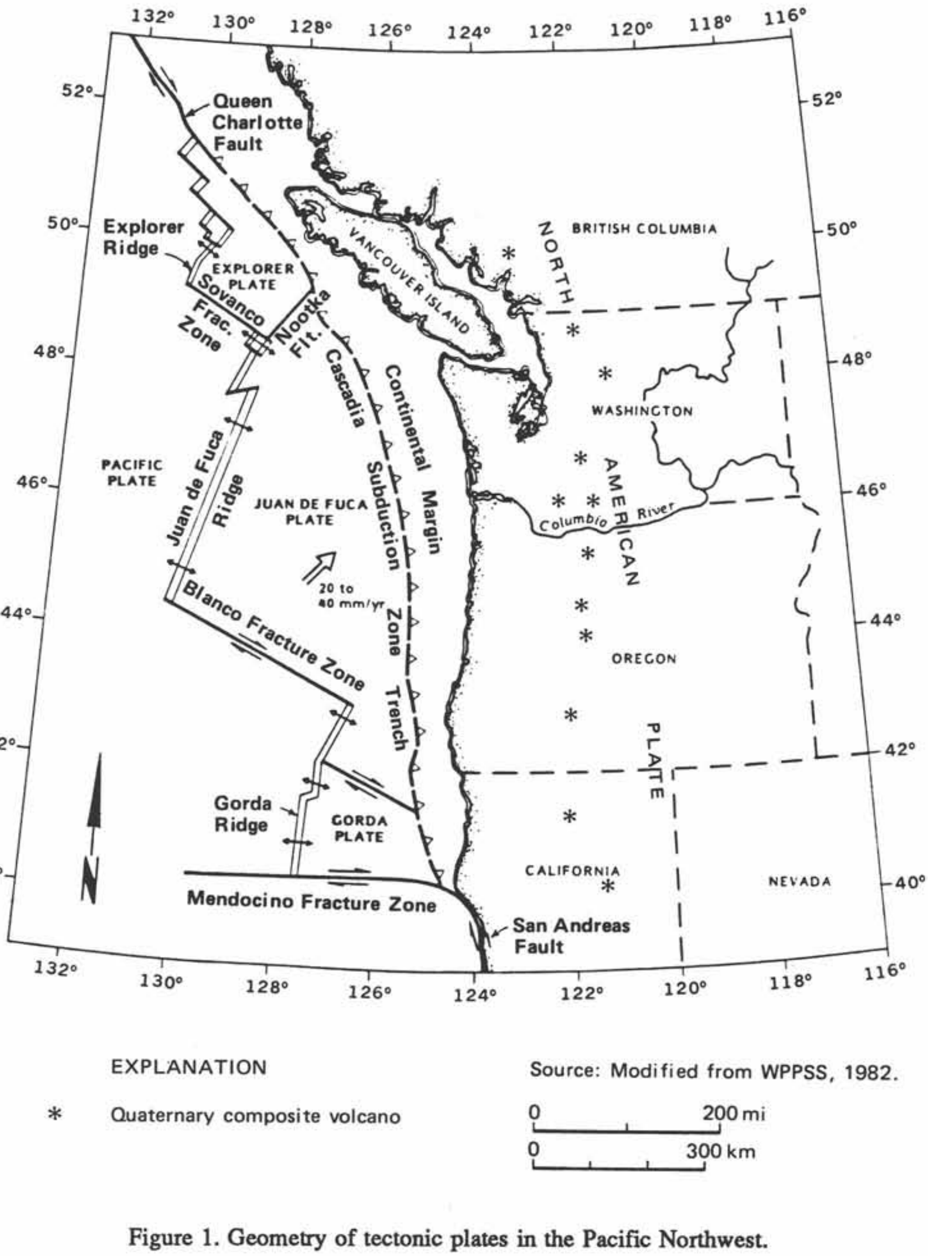

Figure 1. Geometry of tectonic plates in the Pacific Northwest.

Plate Configuration and Geometry

A remnant of the once extensive Farallon plate, the Juan de Fuca plate system lies east of the Juan de Fuca Ridge spreading center. It has been converging with the continental North American plate for at least 30 m.y. (Atwater, 1970). The system consists of three plates that appear to behave differently and somewhat independently from one another. The three plates, from north to south, are Explorer, Juan de Fuca, and Gorda (Figure 1). The Explorer and Gorda plates lie off northern Vancouver Island and northern California, respectively, and their interactions with the North American plate generally affect only those areas. The Juan de Fuca plate lies offshore of (and is subducted beneath) southern Vancouver Island, Washington, and Oregon. Its interaction with the North American continental plate is a major factor in the tectonics and seismicity of Washington.

Studies of oceanic magnetic anomalies have allowed scientists to establish that the direction of convergence between the Juan de Fuca and North American plates is approximately N70°E. The plates have converged at a rate of about 3.5-4.5 cm/yr from the late Quaternary to the present (Riddihough, 1984; Nishimura et al., 1984). The late Quaternary rate of convergence is about one-half to two-thirds the rate during the Pliocene and reflects a decline beginning about 4 Ma (Riddihough, 1984). This plate convergence causes underthrusting (subduction) of the oceanic Juan de Fuca plate beneath the continental North American plate along the Cascadia subduction zone. This subduction results in accretion of sediments and volcanic rocks to parts of the edge of the North American plate, formation of an active volcanic arc, and deformation within the North American plate and the subducted Juan de Fuca plate. The interaction of the two plates gives rise to five general tectonic domains or divisions, each of which has a characteristic structure and location with respect to plate geometry and configuration. These divisions, from west to east, are: the Juan de Fuca plate, the continental margin, the forearc, the volcanic arc, and the back-arc (Figure 2). These divisions comprise Washington and the adjacent region offshore. In addition to these divisions, the northern Rocky Mountains, which lie immediately adjacent to the state's eastern border, contain several tectonic elements that influence the seismicity of the eastern margin of the state. The tectonic elements of the northern Rocky Mountains are apparently unrelated to the present offshore plate boundary. Instead, they represent remnants of a Mesozoic plate boundary, which currently exhibits extensional tectonics along what is now an intraplate zone near the western boundary of the Mesozoic North American plate (Smith and Sbar, 1974).

Juan de Fuca Plate

Composed of the oceanic plate from the Juan de Fuca spreading ridge eastward to the base of the continental slope, the Juan de Fuca plate can also be considered to include the subducted plate extending eastward beneath the North American plate toward the Cascade Range (Figures 1 and 3). The mapped boundary between these two sections of the plate occurs at the base of the continental slope. The suboceanic portion of the Juan de Fuca plate (Figure 1), with an area of about 200,000 sq km, is generally a smooth, featureless plain with only a few isolated seamounts. This contrasts sharply with the Pacific plate, west of the Juan de Fuca Ridge, which has numerous seamounts. The suboceanic part of the Juan de Fuca plate is bounded on the east by the "trench" line, or the toe of the continental slope. In contrast to many (if not most) subduction zones, there is no physical, or even filled, trench along this margin. Reflection profiles (for example, Clowes et al., 1986) indicate that the Juan de Fuca plate slips nearly horizontally beneath the toe of the continental slope and appears to bend downward well east of the trench line.

A layer of marine sediments blankets the Juan de Fuca plate and is underlain by a layer of oceanic basement of basaltic composition and a layer of chemically depleted upper mantle rock. The youngest basalt is along the Juan de Fuca Ridge, while the oldest (about 8 Ma) is generally near the toe of the continental slope. The overlying Miocene to Quaternary marine sediments thicken from west to east and are as much as 2 to 3 km thick at the base of the continental slope (Scholl, 1974; Kulm, 1984).

Dipping eastward beneath the North American plate, the subducted portion of the Juan de Fuca plate extends some 250 to 380 km from the base of the continental slope to about the region of the volcanic arc (the Cascade Range) (Figure 1). Geophysical studies of the subducted slab suggest that (1) its angle of descent is in the range of 10° to 20° as far east as the Puget Sound Basin; (2) the top of the slab is at a depth of about 20 km near the coastline (Taber and Smith, 1985); (3) it dips more steeply (15° to 20°) beneath southwestern Washington to a depth of about 70 km, but appears to dip more shallowly beneath Puget Sound, probably due to an arching of the plate (Crosson and Owens, 1987; Weaver and Baker, 1988); and (4) it is steeply dipping (30° to 50°) in order to be at magma-generating depths (100-200 km) beneath the volcanic arc (Davis, 1981; Dickinson, 1970).

Continental Margin

As the westernmost part of the North American plate, the continental margin includes the continental slope and the continental shelf west of the Washington

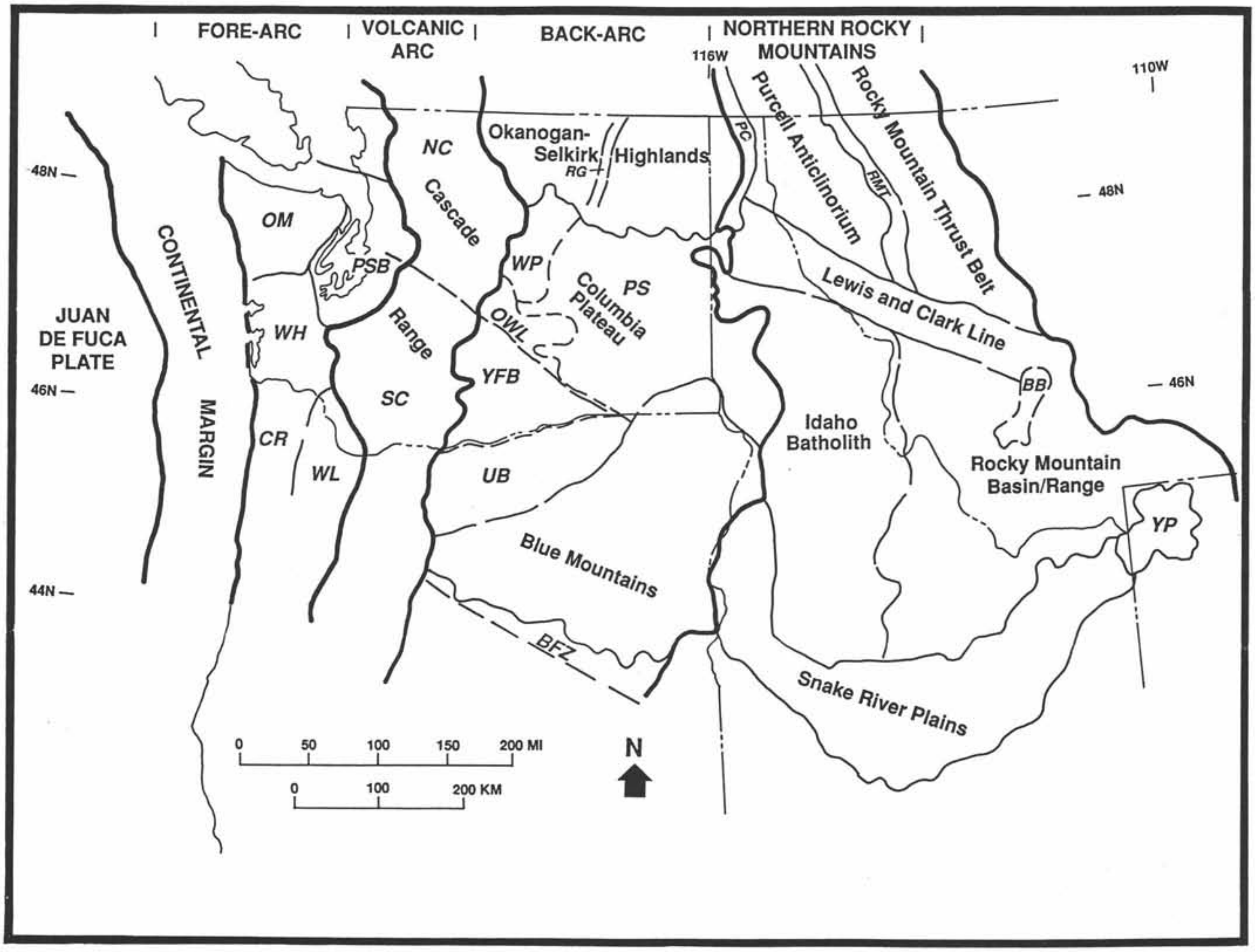

Figure 2. Tectonic provinces of Washington and adjacent areas showing major tectonic terranes influencing Washington seismicity; the Juan de Fuca plate, the fore-arc, the volcanic arc, the back-arc, and the northern Rocky Mountains. BB, Boulder batholith; BFZ, Brothers fault zone; CR, Coast Range; NC, North Cascades; OM, Olympic Mountains; OWL, Olympic-Wallowa lineament; PC, Purcell trench; PS, Palouse slope; PSB, Puget Sound Basin; RG, Republic graben; RMT, Rocky Mountain trench; SC, South Cascades; UB, Umatilla Basin; WH, Willapa Hills; WL, Willamette lowland; WP, Waterville Plateau; YFB, Yakima Fold Belt; YP, Yellowstone Plateau.

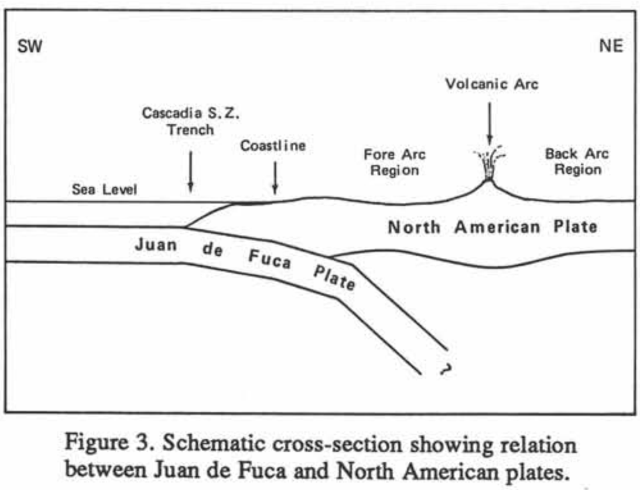

Figure 3. Schematic cross-section showing relation between Juan de Fuca and North American plates.

coastline. The continental slope is the general region in which continental accretion of marine sediments has occurred during the Quaternary, and the process appears to be ongoing, owing to continuing subduction of the Juan de Fuca plate. Off Washington, the continental slope can be divided into an upper slope region that is structurally similar to the outer continental shelf and a lower slope region that exhibits intense deformation owing to subduction and accretion. Within the lower slope is a series of anticlinal ridges, parallel to the trench, that decrease in age toward the west and are separated by sediment-filled valleys. Kulm et al. (1984) have described a style of folding that has both seaward vergence (landward-dipping thrusts) and landward vergence (seaward-dipping thrusts). At the most westerly fold or marginal ridge are folded and faulted Pleistocene and Holocene marine sediments (Carson et al., 1974; Kulm et al., 1984); this is the locus of current deformation associated with subduction.

Along the upper continental slope and outermost shelf are generally broad anticlinal folds and sedimentary basins that raise and deform Miocene to Pleistocene sediments. However, the upper slope Cenozoic sediments off the southern Washington coast are tightly folded and exhibit several unconformities (Kulm et al., 1984). Significant uplift of marine sediments on the upper slope off Washington has not been well documented. In contrast, off the Oregon coast as much as 1,000 m of uplift of late Miocene to Pliocene sediments and as much as 100 m of uplift of Pleistocene sediments has been described (Kulm and Fowler, 1974). Sediments on the continental shelf off Washington are broadly folded and locally faulted, and have local shale/mudstone diapirs (Barnard, 1978; Wagner and Batatian, 1985; Snavely and Wagner, 1982). These diapirs have Pliocene and older Tertiary rocks in their cores. They pierce Quaternary sediments and deform the sea floor (Wagner and Batatian, 1985; Rau and Grocock, 1974). Angular unconformities are present in the Tertiary and Quaternary sediments of the shelf south of latitude 47°N (Grays Harbor) but appear to be lacking to the north (Barnard, 1978). Local faulting of Pleistocene and Holocene marine sediments, as well as the sea floor, has been identified on the Washington continental shelf (Wagner and Batatian, 1985; Snavely et al., 1977), and this, coupled with the presence of young diapirs, suggests that underplating of the shelf may be occurring.

Forearc Region

Within the forearc region of western Washington, we find several tectonic subdivisions. The coast ranges can be distinguished from the Puget Sound Basin; in addition, the coast ranges may be further subdivided into the Olympic Mountains to the north and the Willapa Hills to the south.

As the most topographically prominent component of the coast ranges, the Olympic Mountains contain an arcuate, steeply dipping homocline of Tertiary sedimentary and volcanic rocks that rims the mountain range on the north, east, and south. Within the core rocks of the Olympic Mountains are Tertiary metamorphic rocks that attain their highest grade near Mount Olympus and represent a subduction zone complex that was thrust under oceanic basalt and accreted to the North American continent during the Miocene (Tabor and Cady, 1978). Major deformation within the Olympic Mountains appears to have climaxed in the middle to late Tertiary, as a result of subduction zone accretion, and then waned as the zone of active accretion migrated westward (Silver, 1972). Younger tectonic activity is indicated by folding and faulting of Pleistocene and Holocene glaciofluvial sediments along the northern part of the Olympic Mountains, uplift and warping of an 82-ka Pleistocene marine terrace along the Olympic coast, minor thrust faulting of Pliocene-Pleistocene glaciofluvial sediments north of Grays Harbor, and Holocene faulting in the southeastern part of the mountains (Gower, 1960; Rau, 1973; West and Caldwell, 1987; West and McCrumb, 1988; Moore, 1965; Wilson et al., 1979).

Tectonic features of the Willapa Hills include five major and several minor fault-controlled basement uplifts that expose oceanic basalt at their cores and are surrounded by younger Tertiary marine sediments. The faults are part of a regional rectilinear northwest- and east-northeast-trending pattern that appears to have been the result of northeast-directed near-horizontal compression and shortening during the Tertiary owing to subduction of the Farallon plate and accretion of sediments onto the North American plate (Washington Public Power Supply System, 1982; Drake, 1982). During the Quaternary, the Willapa Hills appear to have experienced some tectonism in the form of broad, uniform, slow uplift. This is evident in uplifted Pliocene-Pleistocene marine terraces (Wagner, 1967a, 1967b; West et al., 1987), fluvial terraces along the Chehalis and Wynoochee rivers (Carson, 1970), and leveling data (Carson, 1970; Ando and Balazs, 1979). Recent work on submerged marsh deposits in Willapa Bay suggests that episodic subsidence of the coast, possibly due to large subduction earthquakes along the Cascadia subduction zone, may have occurred during the late Holocene (Atwater, 1987).

Lying between the Cascade Range and Olympic Mountains, the Puget Sound Basin is historically the most seismically active region in the state. Throughout the Paleogene the region was a subsiding coastal plain; it was uplifted and folded early in the Neogene. Its form as a basin dates from late Miocene to Pliocene time, coincident with accretion of the Olympic Mountain terrane to North America and the uplift of the Cascade Range. The structure beneath the basin is largely concealed by a Quaternary sedimentary cover as much as 1,100 m thick (Hall and Othberg, 1974; Yount et al., 1985). However, geophysical studies have identified large gravity gradients as well as gravity and magnetic lineaments that have been interpreted as faults dividing the rocks beneath the basin into a mosaic of rectilinear "fault" blocks (Danes et al., 1965; Rogers, 1970; Danes, 1985). Tide gage and geodetic data also suggest modern subsidence of the basin (Holdahl et al., 1987).

Volcanic Arc

Subduction of the Juan de Fuca plate beneath the margin of western North America, ongoing in some form for at least the past 38 m.y. (Vance, 1982), is believed to be responsible for the existence of the Cascade volcanic chain. Of the major Quaternary composite volcanoes in the Cascade Range that extend from southern British Columbia to northern California, five are in the state of Washington. These volcanoes are situated in two regions of the Cascade mountains that have distinctive topographic, geologic, and structural characteristics: the North Cascades and the South Cascades (Figure 2). The two regions are separated by a zone of transverse structure related to the Olympic-Wallowa lineament (OWL) (Raisz, 1945) that exhibited considerable tectonism during Paleogene time (Tabor et al., 1984; Walsh, 1986).

Basement rocks of the North Cascades are primarily Paleozoic and Mesozoic metamorphic, plutonic, and marine sedimentary rocks that comprise several accreted terranes. They have been structurally modified by Cretaceous thrust faults, by late Cretaceous and early Tertiary folding, and by strike-slip and normal faults. Quaternary volcanic activity in the North Cascades at Mount Baker and Glacier Peak exhibits recurrent pyroclastic and lava eruptions of andesitic and dacitic composition.

Dominated by volcanic and volcaniclastic rocks of Tertiary age, the South Cascades in Washington also exhibit local intrusions of granitic rocks of Miocene to Pliocene age. These volcanic rocks are folded and faulted into northwest trends and locally interrupted by northeast-trending faults and lineaments (Galster and Mann, 1987). The majority of this deformation appears to have begun during a mid-Miocene orogeny that affected much of western Washington (Washington Public Power Supply System [WPPSS], 1982). The Quaternary composite volcanoes are superimposed on the landscape produced by the earlier orogeny. The 1980 eruption of Mount St. Helens and its record of repeated Pleistocene and Holocene eruptions, as well as the geologic and historic record of eruptions at Mount Rainier and Mount Adams, clearly indicate that volcanism in the South Cascades continues. In addition, Pleistocene and Holocene volcanism, characterized by the development of shield volcanoes, cinder cones, and extensive lava flows, has been centered along the Cascade crest from southeast of Mount Rainier on southward into Oregon.

Back-Arc Region

Situated east of the Cascades volcanic chain, the back-arc region of eastern Washington is composed of the Columbia Plateau to the south and the largely granitic/metamorphic Okanogan-Selkirk Highlands to the north. The Columbia Plateau is underlain almost entirely by basalt of the Miocene Columbia River Basalt Group, which was deposited in voluminous flows between about 17 and 6 Ma (Myers and Price et al., 1979). North-trending fissures in southeastern Washington, northeastern Oregon, and adjacent areas of Idaho that were the main sources of these flows. Subdivision of the plateau into several distinct tectonic elements is possible: the Yakima Fold Belt, Palouse slope, Waterville Plateau, and Blue Mountains (Figure 2).

Located in the western part of the Columbia Plateau, the Yakima Fold Belt consists of a series of east-west- to northwest-trending, narrow, faulted asymmetric anticlines. The trend of the fold belt may be influenced by northwest-trending faults of the Olympic-Wallowa lineament (OWL). Deformation within the Yakima Fold Belt appears to have been under way as early as 16 Ma (Myers and Price et al., 1979; Reidel, 1984) during extrusion of the lava. This deformation climaxed during the Pliocene, and Quaternary fault displacement has been documented for some of the Yakima folds (Campbell and Bentley, 1981; WPPSS, 1981). The Palouse slope occupies the eastern portion of the Columbia Plateau and is largely characterized by relatively undeformed, gently westward-dipping flows. However, the southern part exhibits a series of low-amplitude, north-trending folds and faults which splay from the north flank of the Blue Mountains. Structural/stratigraphic relations within the Palouse province suggest that the majority of the deformation occurred during eruption of the Columbia River basalts (Myers and Price et al., 1979). The Waterville Plateau is the essentially undeformed northwest section of the Columbia Plateau.

Extending into only a small area of southeastern Washington, the Blue Mountains are an anticlinorium more than 250 km long extending northeast from central Oregon. Deformation forming the anticlinorium began prior to the eruption of the Columbia River Basalt Group and continued throughout the eruption of the flows. A north-northeast-trending fault system dominates the northern flank of the Blue Mountains anticlinorium.

At the northern part of the back-arc region, the Okanogan-Selkirk Highlands are a granitic-metamorphic complex with several crystalline tectonic elements of Mesozoic age (Fox and Rinehart, 1988; Fox et al., 1977). The central crystalline mass is flanked on the west by Paleozoic and Mesozoic marine sediments and on the east by Precambrian and Paleozoic metasedimentary rocks, all faulted and folded prior to the end of Cretaceous time.

Northern Rocky Mountains

Immediately east of the eastern border of Washington, the northern Rocky Mountains include several distinct tectonic elements (Figure 2). Much of the region is characterized by linear, north-to-northwest trending, structurally controlled mountain ranges and intervening valleys. From the standpoint of contemporary tectonics the most important of these elements are the Rocky Mountain Basin/Range, the Lewis and Clark Line (LCL), and the Rocky Mountain Trench (RMT). The LCL (Montana lineament) separates the northern Rocky Mountains into two tectonic blocks of contrasting styles across a WNW-trending structural zone 15 to 50 km wide. The RMT appears to be a linear Laramide pull-apart element later modified by normal and strike-slip faults of Tertiary and Quaternary age. The Rocky Mountain Basin/Range is in a state of tectonic extension resulting in contemporary normal faulting over a large area of southwestern Montana and east-central Idaho, north of the Snake River Plains and north and west of the Yellowstone Plateau (Waldron and Galster, 1984; Smith and Sbar, 1974; Qamar and Stickney, 1983).

SEISMICITY

Each year 1,000 to 2,000 earthquakes in Washington and Oregon are located by the Washington Regional Seismographic Network (WRSN). Typically, only 5 to 20 of these are felt because the majority of recorded earthquakes are smaller than magnitude 3. Since 1980, thousands of small earthquakes have occurred in swarms accompanying volcanic activity at Mount St. Helens. Destructive earthquakes are infrequent, the most recent being the 1965 central Puget Sound earthquake (also called the Seattle earthquake). For simplification, this discussion refers to magnitudes in a generic sense, avoiding more precise definitions such as M_L (local or Richter magnitude) and M_S (surface wave magnitude). Magnitudes of early events for which there are no instrumental reports are only roughly estimated from felt reports; magnitudes calculated from the modern seismograph network data are usually equivalent to Richter magnitudes.

Because earthquakes are a reflection of active tectonic processes, it is important to keep in mind the tectonic settings described previously. The process of subduction of the Juan de Fuca plate beneath the North American plate strongly influences the generation of most earthquakes in the western parts of British Columbia, Washington, and Oregon. East of the Cascade Range, however, subduction probably exercises less control on earthquake activity. In western Washington, a zone of earthquakes at depths of 35 to 80 km declines easterly from the coast (Crosson, 1983); this zone has been interpreted as a Benioff zone (Crosson, 1983; Taber and Smith, 1985). Earthquakes within this deep zone occur within the subducting Juan de Fuca plate; they do not define the plate interface itself. Some of the largest earthquakes in the Pacific Northwest since the 1800s have occurred within this deep zone beneath the Puget Sound Basin. A most unusual characteristic of the Cascadia subduction zone that distinguishes it from most subduction zones worldwide is its apparent lack of interface or decoupling thrust earthquakes. This observation has generally been interpreted in one of two ways: (1) either the interface is locked and accumulating strain prior to a major interface earthquake; or (2) the interface is creeping aseismically and strain is released without the necessity for large subduction earthquakes. Resolution of this problem has not yet been reached within the scientific community.

In western Oregon and southwestern British Columbia, there is little or no seismic evidence of a Benioff zone. This need not be taken as evidence of the absence of a subducting slab, but it suggests that physical conditions are somehow different in these regions. In fact, direct evidence from reflection and refraction seismology indicates the presence of the subducted slab beneath western Oregon and Vancouver Island (Keach et al., 1986; Green et al., 1986). Earthquakes at depths of the subducted slab also occur beneath the southern end of Vancouver Island.

Significant Earthquakes

Epicenters of all earthquakes of magnitude 4.0 and greater within the northwestern United States from the National Oceanic and Atmospheric Administration (NOAA) catalog of instrumentally located earthquakes are shown in Figure 4. The NOAA catalog is complete at a magnitude 4 level beginning in 1963, but it also includes a few older historic earthquakes. Figure 4 is thus a fair representation of the regional seismicity. Clearly, the most active part of the entire region is the Blanco fracture zone at the south end of the Juan de Fuca plate adjacent to the Gorda plate. By contrast, the Cascadia subduction zone is nearly devoid of seismicity, and most of the continental seismic activity is at a low level, consisting of relatively isolated clusters. The activity offshore of Vancouver Island is at the north end of the Juan de Fuca Ridge, in the complex transition to the strike-slip Queen Charlotte Island fault system farther to the northwest (Figure 1). Clustered activity in the Puget Sound Basin and near Mount St. Helens is apparent; the latter reflects the active seismicity of this region since the 1980 eruption. Figure 4 also illustrates the remarkable quiescence of the Juan de Fuca Ridge relative to the Blanco fracture zone.

At the scale and magnitude threshold of Figure 4, nearly the entire state of Oregon and the eastern part of Washington are quiescent. The sparse distribution of earthquakes onshore in Washington and Oregon contrasts markedly with seismicity reported for most active subduction zones worldwide, where it is common to have earthquakes of magnitude 4 and larger occurring at the interface between the two plates, within the subducting plate, and within the overriding plate (Uyeda and Kanamori, 1979).

In Idaho and Montana, a south-southeast trend of diffuse seismicity is part of the Intermountain Seismic Belt (ISB) of Smith and Sbar (1974). The Hebgen Lake earthquake in Montana (August 17, 1959, magnitude 7.1) and the Borah Peak, Idaho, earthquake (October 23, 1983, magnitude 7.3) occurred within the ISB and were widely felt throughout the eastern part of Washington state.

Epicenters of the largest earthquakes known (from both historical and instrumental records) to have oc-

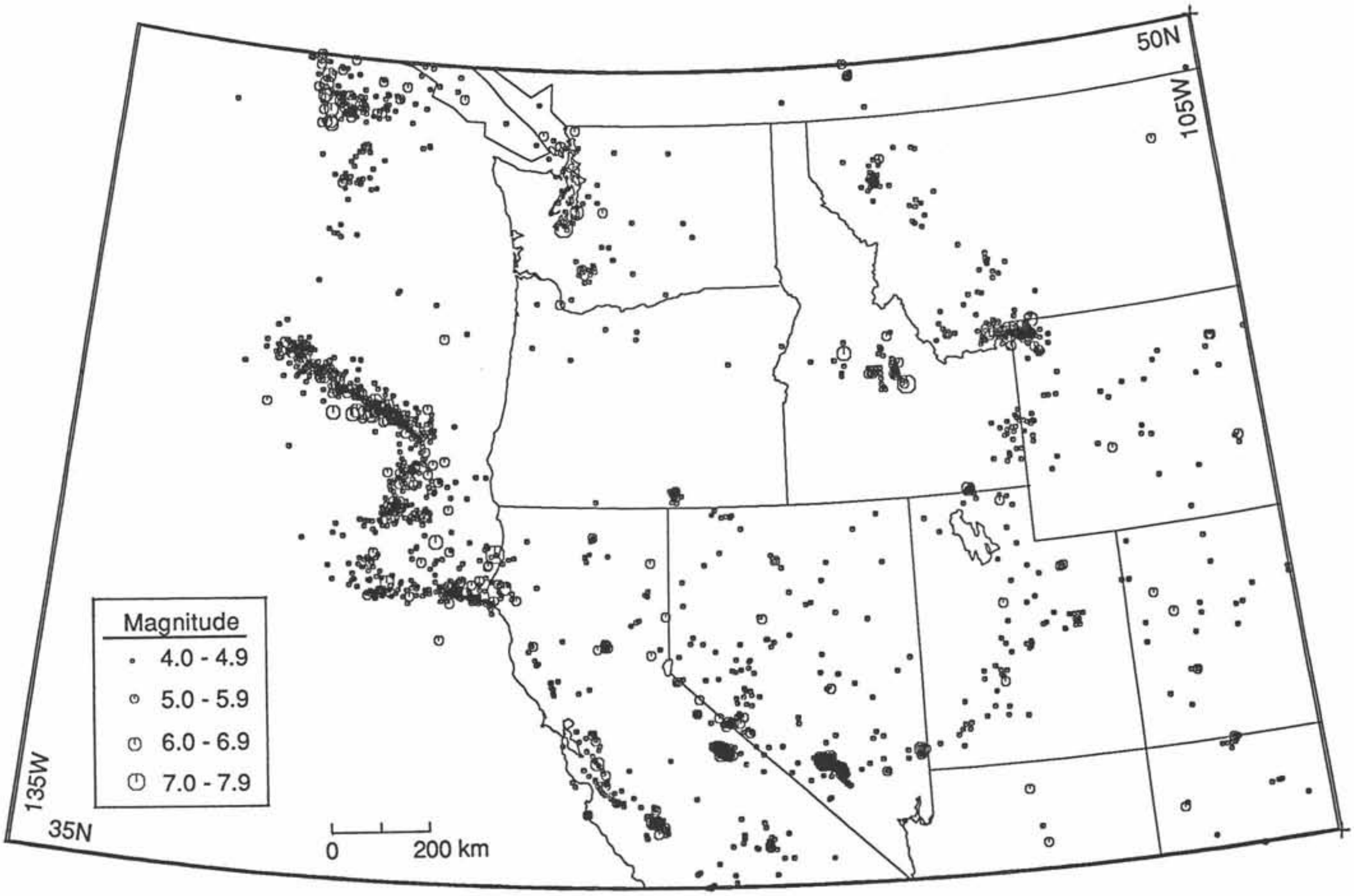

Figure 4. Epicenters of earthquakes with magnitudes greater than 4.0 from NOAA catalog through 1985. This catalog is fairly complete at this magnitude range since 1963. Before that date, the data are not complete. The 1949 Puget Sound earthquake (not in NOAA catalog) has been added to the figure.

curred in or adjacent to Washington are shown in Figure 5. Virtually all instrumentally located earthquakes are shallower than about 90 km. Well-located earthquakes in this region fall into two distinct depth ranges: "shallow", at depths less than 25 km; and "deep", at depths between 35 and 90 km. Comparatively few earthquakes in the region are located between depths of 25 and 35 km. Figure 5 includes the important historical earthquakes of 1872 and 1936, large earthquakes of 1946, 1949, 1962, and 1965 for which limited instrumental data are available, and three smaller (magnitude 5-6) earthquakes that were well recorded instrumentally (1976, 1980, 1981). These earthquakes are critical for discussion of earthquake hazards in Washington. Focal mechanisms for selected earthquakes are also shown on Figure 5. Isoseismal maps for the 1872, 1946, 1949, and 1965 earthquakes are shown in Figure 6, along with isoseismals for the 1959 Hebgen Lake, Montana, and 1983 Borah Peak, Idaho, earthquakes.

With its estimated magnitude of 7.4 (Malone and Bor, 1979), the 1872 North Cascades earthquake is considered to be the largest known earthquake affecting the state. It was felt over more than 1,000,000 sq km (Rogers, 1983), including Washington, central and northern Oregon, northern Idaho, western Montana, and southern British Columbia (Figure 6A). This earthquake was followed by an extensive aftershock sequence (Weston Geophysical Research, Inc., 1976), suggesting a shallow source depth. Study of ground motion effects suggests that the maximum intensity exceeded VII and may have been as high as IX on the Modified Mercalli (MM) Intensity Scale (Table 1). Both the location and depth of the North Cascades earthquake are subject to uncertainty. The location shown in Figure 5 was determined by Malone and Bor (1979) on the basis of the intensity pattern. Other proposed locations are also discussed by Malone and Bor (1979). Algermissen (1983) has suggested a shallow depth based upon intensity contours and the extensive aftershock sequence. Prominent aftershock sequences worldwide only follow earthquakes with depths of 20 km or less (Page, 1968). Furthermore, all instrumentally located earthquakes in this area (since 1970) are shallower than 25 km.

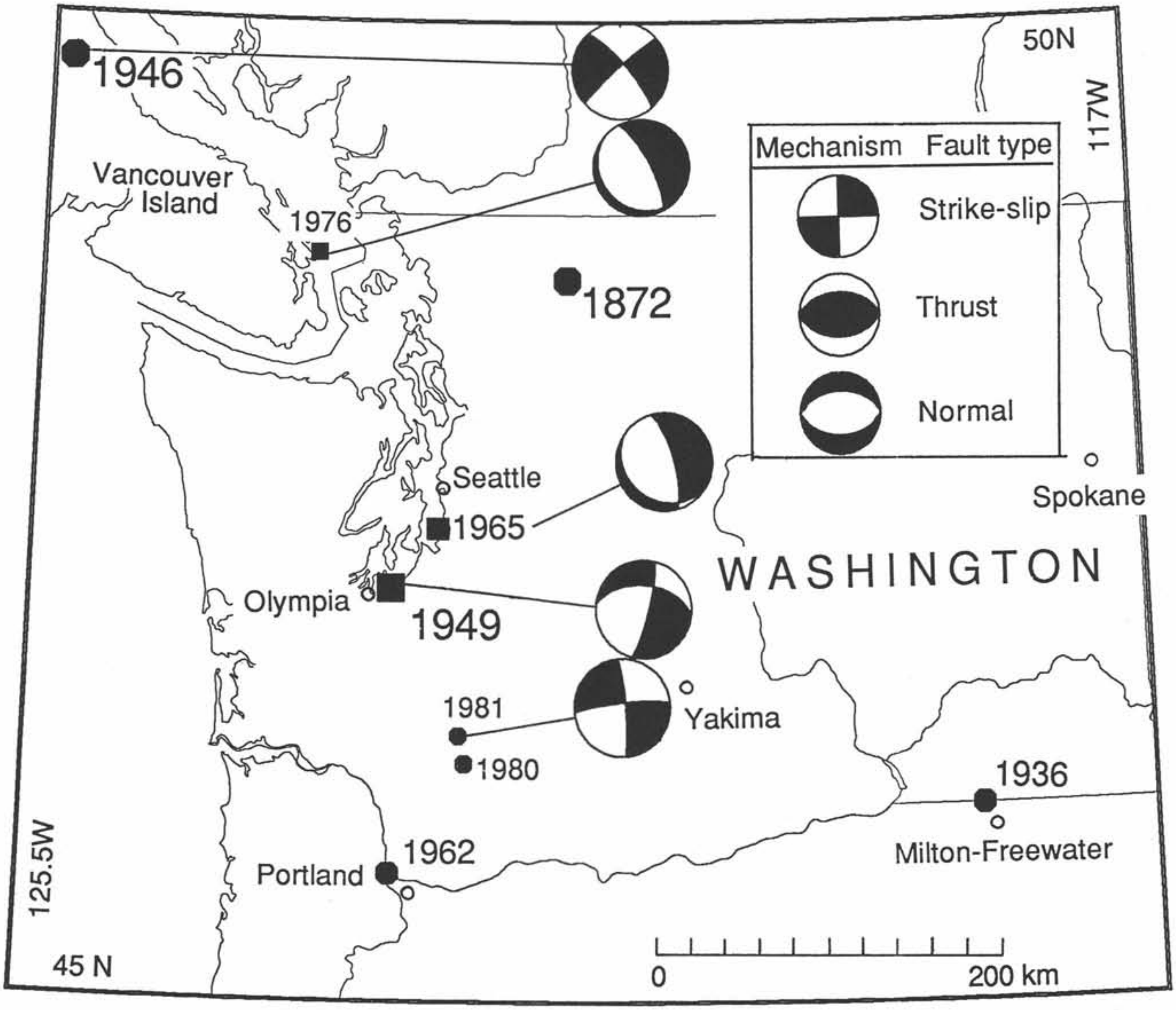

Figure 5. Epicenters of the largest known earthquakes in Washington and adjacent areast; magnitudes greater than 6, and earthquakes larger than magnitude 5 from 1970 through 1986. Lower hemisphere focal mechanisms are indicated where known. Symbol size reflects earthquake magnitude. Square symbols indicate earthquakes with depths greater than 35 km, while octagonal symbols represent shallower earthquakes.

The 1936 Milton-Freewater earthquake in southeastern Washington is significant because it is the largest known event in the eastern Washington region. Its maximum intensity was VII, and the magnitude has been estimated at 5.7 to 5.8. Numerous aftershocks were felt, again suggesting a shallow depth of focus.

Another important earthquake occurred in 1946 to the north of Washington. This magnitude 7.2 to 7.3 earthquake was located on the east side of Vancouver Island in Canada and was widely felt in Washington. It has been interpreted as a crustal, strike-slip earthquake probably due to stresses generated at the transition zone between the Juan de Fuca and Explorer plates (Rogers and Hasegawa, 1978). The focal mechanism determined by Rogers and Hasegawa (1978) is shown on Figure 5, and the isoseismal contours are shown in Figure 6B.

In 1949, a large damaging earthquake occurred beneath the Puget Sound Basin and was felt over approximately 549,000 sq km (Rogers, 1983). Baker and Langston (1987) relocated this magnitude 7.1 earthquake at a depth of 54 km and estimated its focal mechanism. No aftershocks were felt for this earthquake, and at the detection threshold available in 1949 (magnitude 4.0-4.5), none were recorded. The focal mechanism for this event (Figure 5) is strike-slip, with the preferred fault plane striking east-west (Baker and

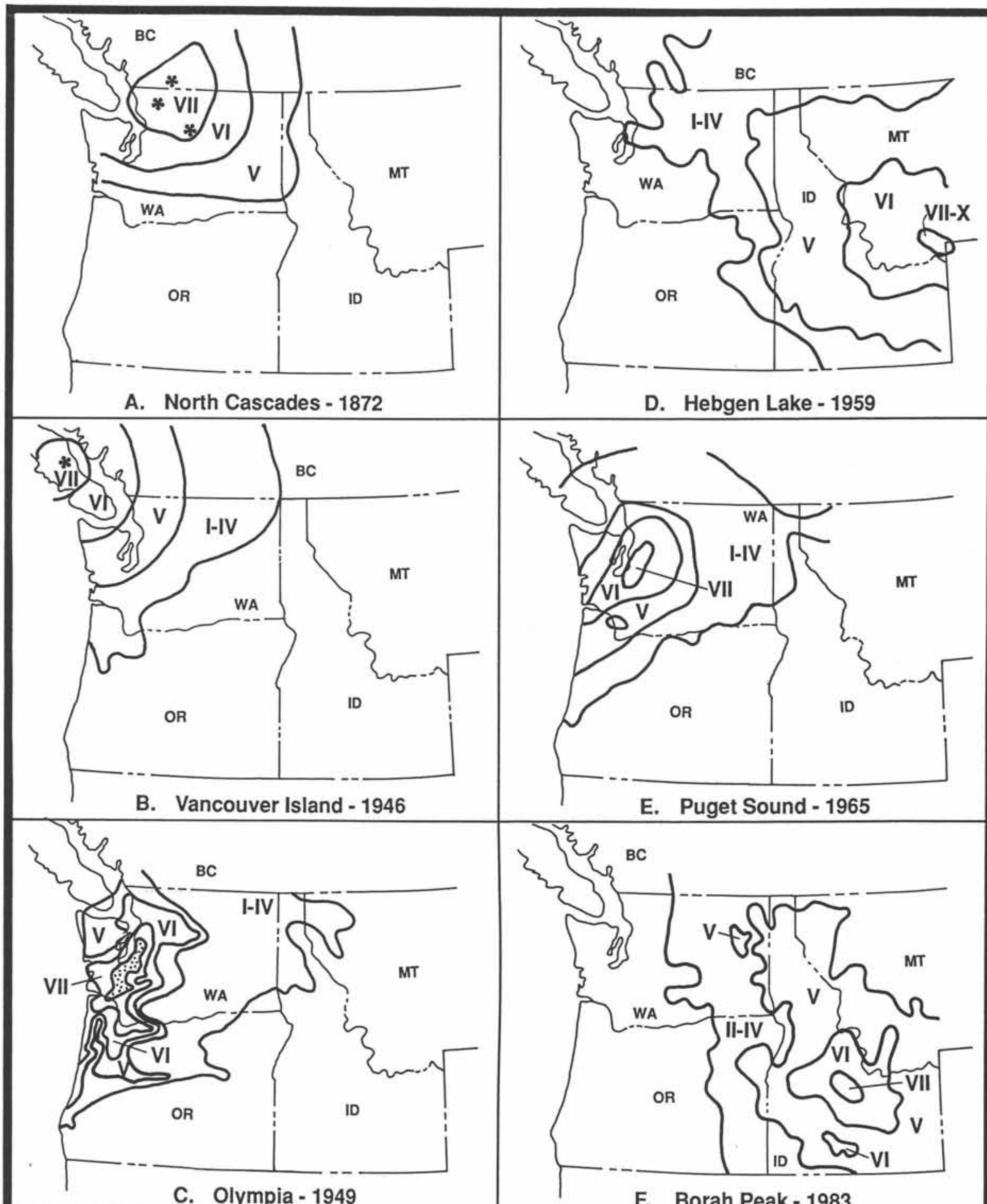

Figure 6. Isoseismal maps of the Pacific Northwest for six major historic earthquakes that have been widely felt in Washington. A. North Cascades earthquake of December 1872 (after Malone and Bor, 1979); limit of felt area (intensity bound I-IV) not shown. B. Vancouver Island earthquake of June 23, 1946 (after Rogers and Hasegawa, 1978). C. Olympia earthquake of April 13, 1949 (after Ulrich, 1949); dotted area is intensity VIII. D. Hebgen Lake earthquake of August 17, 1959 (after Nile, 1960). E. Puget Sound earthquake of April 29, 1965 (after Algermissen et al., 1965). F. Borah Peak earthquake of October 28, 1983 (after Stein and Bucknam, 1985).

Table 1. Modified Mercalli Earthquake Intensity Scale (from Richter, 1956)

I. Not felt. Marginal and long-period effects of large earthquakes.

II. Felt by persons at rest, on upper floors, or favorably placed.

III. Felt indoors. Hanging objects swing. Vibration like passing of light trucks. Duration estimated. May not be recognized as an earthquake.

IV. Hanging objects swing. Vibration like passing of heavy trucks; or sensation of a jolt like a heavy ball striking the walls. Standing motor cars rock. Windows, dishes, doors rattle. Glasses clink. Crockery clashes. In the upper range of IV, wooden walls and frame creak.

V. Felt outdoors; direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters, pictures move. Pendulum clocks stop, start, change rate.

VI. Felt by all. Many frightened and run outdoors. Persons walk unsteadily. Windows, dishes, glassware broken. Knick knacks, boots, etc. off shelves. Pictures off walls. Furniture moved or overturned. Weak plaster and masonry D cracked. Small bells ring (church, school). Trees, bushes shaken (visibly or heard to rustle).

VII. Difficult to stand. Noticed by drivers of motor cars. Hanging objects quiver. Furniture broken. Damage to masonry D, including cracks. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices (also unbraced parapets and architectural ornaments). Some cracks in masonry C. Waves on ponds; water turbid with mud. Small slides and caving in along sand and gravel banks. Large bells ring. Concrete irrigation ditches damaged.

VIII. Steering of motor cars affected. Damage to masonry C; partial collapse. Some damage to masonry B; none to masonry A. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed pilings broken off. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes.

IX. General panic. Masonry D destroyed; masonry C heavily damaged, sometimes with complete collapse; masonry B seriously damaged. General damage to foundations. Frame structures, if not bolted, shifted off foundation. Frames racked. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in ground. In alluviated areas, sand and mud ejected, earthquake fountains, sand craters.

X. Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes, embankments. Large landslides. Water thrown on banks of canals, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat lands. Rails bent slightly.

XI. Rails bent greatly. Underground pipelines completely out of service.

XII. Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown in air.

Langston, 1987). The T-axis is oriented east-southeast and dips at about 20°. Figure 6C shows isoseismal contours.

In 1965, another large damaging earthquake occurred beneath the Puget Sound Basin and was felt over approximately 500,000 sq km (Rogers, 1983). The epicenter of this earthquake was between Tacoma and Seattle at a depth of about 60 km (Algermissen et al., 1965). The focal mechanism (Figure 5), determined from instrumental data worldwide (Isacks and Molnar, 1971), indicates a normal or tensional event with the T-axis oriented at an azimuth of N62°E and plunging 28°. Figure 6E shows isoseismal contours. In 1976 a magnitude 5.6 earthquake, at a similar depth but located near Vancouver Island, Canada, had a focal mechanism nearly identical to that of the 1965 Seattle earthquake (Figure 5) (Rogers, 1983). This is the largest deep earthquake since 1970, when the Washington Regional Seismographic Network was installed. The fact that all three of the larger deep earthquakes have tensional axes that lie approximately in the down-dip direction of the Juan de Fuca slab suggests that down-dip tensional stress within the subducting plate may cause these earthquakes. Observations of smaller earthquakes in the deep suite are generally in agreement (Taber and Smith, 1985; Ma, 1988; Ma et al., 1988).

A magnitude 5.1 earthquake occurred near Portland, Oregon, in 1962. Although damage was minor, the proximity of the epicenter to Portland makes this earthquake significant. Instrumental data were not adequate to provide good depth control, but a 15-20 km depth has been estimated. This depth is also consistent with the numerous aftershocks that were recorded (Dehlinger et al., 1963).

In 1980 two months of intense earthquake activity and large surface deformation preceded the eruption of Mount St. Helens. A few earthquakes were identified in

February 1980, and the number of events increased in March. The first earthquake of significant size (magnitude 4.2) occurred on March 20, 1980. The precursor sequences culminated in the violent eruption of May 18, 1980, when a magnitude 5.1 earthquake initiated a major failure off the volcano's north flank and the resulting north-directed blast removed approximately 2 cu km of the northern side of the volcano, devastating an area of more than 1,000 sq km and causing more than 50 fatalities (Figure 5).

In 1981 a shallow earthquake, magnitude 5.5, occurred near Elk Lake north of Mount St. Helens (Grant et al., 1984). This earthquake was accompanied by many aftershocks, which helped to delineate the seismic zone now called the St. Helens seismic zone (SHZ) (Weaver and Smith, 1983). Previously, a magnitude 5.1 earthquake had occurred in 1961 near Siouxon Peak, along the SHZ south of Mount St. Helens (Grant and Weaver, 1986). Both main shocks were preceded by precursory swarms that contained several magnitude 4 earthquakes and began about 8 months prior to the main shock. Both earthquakes were followed by aftershock sequences. Focal mechanisms for the Elk Lake main shock (Figure 5) and many aftershocks indicate right-lateral, strike-slip motion with a northeast-southwest axis of apparent maximum principal stress (Grant et al., 1984; Grant and Weaver, 1986). Earthquakes along this zone have hypocenters generally shallower than 14 km, except under Mount St. Helens, where depths as great as about 20 km have been detected.

Network Investigations

A modern telemetered regional seismograph network in western Washington was begun in 1969 (Crosson, 1972, 1974) and at approximately the same time in eastern Washington in the vicinity of Richland. In subsequent years, these installations have merged into a statewide network extending into northern Oregon, including more than 110 telemetered stations. Data from all these stations are now recorded digitally at the University of Washington in Seattle. Because this development has significantly changed the character and quality of our observational capability, it is appropriate to discuss recent observations from this high-density network separately from historical observations and pre-network instrumental observations.

Instrumentally located earthquakes of magnitude greater than 2.5 since 1970, including a few significant earlier earthquakes that have adequate instrumental locations, are shown in Figure 7. Since 1970 the catalog of earthquakes larger than magnitude 2.5 is reasonably complete. The Mount St. Helens region has been the site of intense earthquake activity since the renewal of eruptive activity there in 1980. Thus, for clarity, earthquakes near the cone of Mount St. Helens have been excluded, except for the May 18, 1980, earthquake that triggered the catastrophic eruption. Aftershocks of the 1981 Elk Lake earthquake (northwest of Mount St. Helens) smaller than magnitude 4 are not shown.

Western Washington Seismicity

The deepest earthquakes in the conterminous United States, with depths as great as 90 km, occur within the subducting Juan de Fuca plate beneath western Washington (Crosson, 1983; Taber and Smith, 1985). Of all earthquakes along the entire Cascadia subduction zone, those beneath Puget Sound offer the clearest direct evidence of the existence of the subducted Juan de Fuca plate. Although the reasons are not entirely understood, there is a concentration of both crustal and subcrustal earthquakes in the Puget Sound region (Figures 7 and 8). Hypocenters of Puget Sound earthquakes cluster into two distinct depth groups: those deeper than 30 to 35 km, and those shallower than 20 to 25 km. In an east-west cross-section (Figure 8), the suite of deep earthquakes approximately defines a planar surface dipping eastward at an angle of about 10°. These earthquakes are interpreted to lie within the descending Juan de Fuca plate (Crosson, 1983; Taber and Smith, 1985). From the depths of the 1949 and 1965 Puget Sound events, which occurred before high-quality network data were available, we infer that they too were within the subducted Juan de Fuca plate. Hypocenters of the 1949 and 1965 earthquakes are shown on Figure 8. It is reasonable to expect future earthquakes in the magnitude range of 6 to 7.5 from this source region within the subducted plate.

Several characteristics distinguish the deep from the shallow earthquake zones beneath Puget Sound. The shallow earthquakes tend to cluster in space and time. For example, a distinct swarm of crustal earthquakes near Seattle in the early 1970s was reported by Yelin (1982). By contrast, the deep earthquakes are more uniformly distributed in both space and time. Within the Puget Sound Basin, at lower magnitude levels, shallow earthquakes substantially outnumber deeper quakes. However, both network data since 1970 and historical observations of the 1949 and 1965 deep Puget Sound earthquakes indicate that the larger earthquakes are more likely to occur in the deep suite (Crosson, 1983). In the Puget Sound Basin since 1970 although deep earthquakes account for only about 20 percent of events with magnitudes from 2.5 to 4.0, almost half the earthquakes of magnitude 4 and larger are in the deep suite. Another important difference between deep and shallow earthquakes is the orientation of tectonic stress as interpreted from focal mechanisms. Crustal earthquakes in western Washington have focal mechanisms that are consistent with dominant north-south compressive stress, whereas the subcrustal earthquakes appear to result from tensional slab forces and related effects. This difference was documented by Yelin (1982) and recently re-examined by Ma et al. (1988).

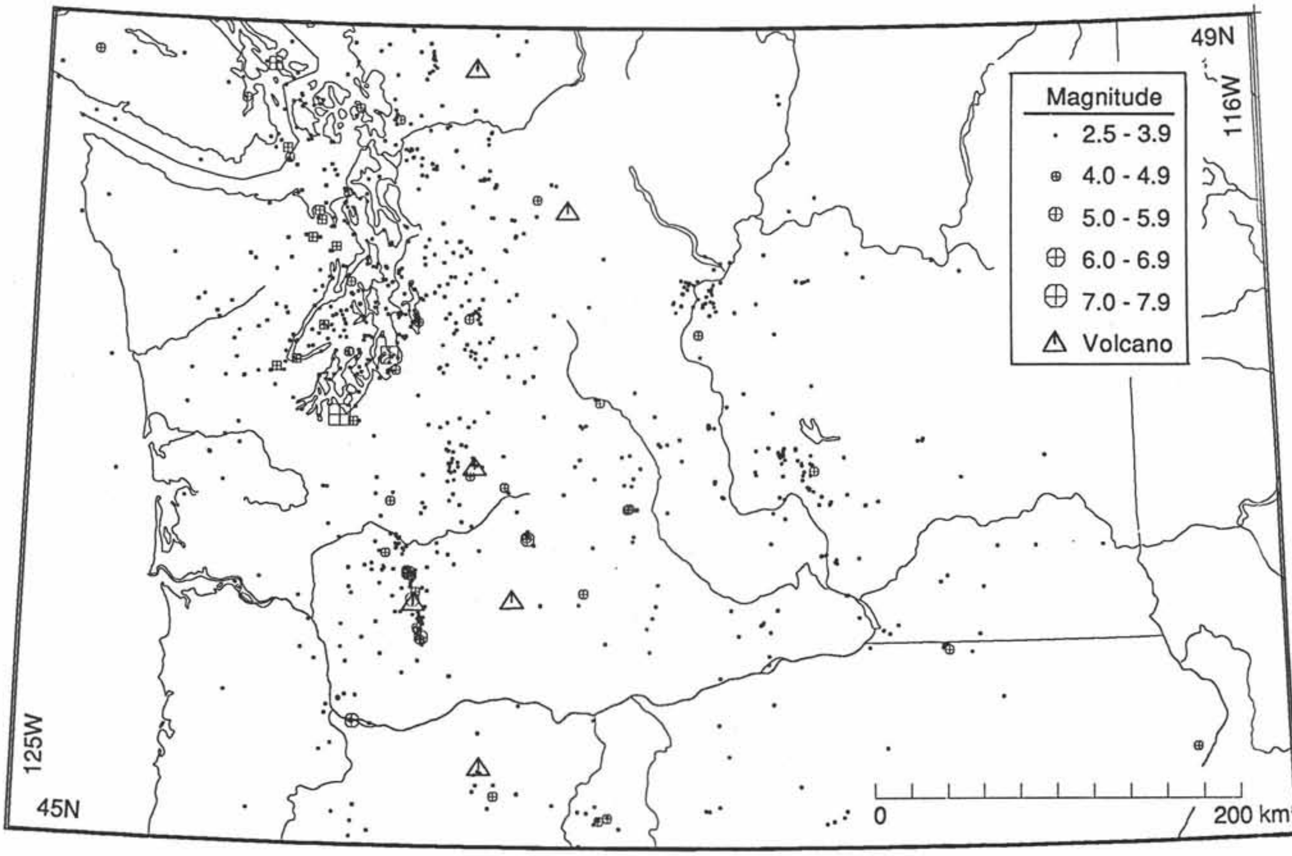

Figure 7. Instrumentally located earthquakes in Washington and northern Oregon. Symbols are scaled proportionally to earthquake size for events greater than 4.0, while from magnitude 2.5 to 3.9, all events have the same symbol size. Earthquakes shallower than 35 km have hexagonal symbols, while deeper earthquakes are shown as squares. All events since 1970 located by the WRSN with magnitudes greater than 2.5 are included. Some earlier earthquakes greater than magnitude 4.0 also have adequate instrumental locations. These include the 1949 Olympia and 1965 Puget Sound earthquakes, the 1962 Portland earthquake, and the Swift Reservoir earthquakes south of Mount St. Helens in 1960 and 1961. Volcanic earthquakes at Mount St. Helens have not been plotted. Aftershocks of the 1981 Elk Lake earthquake less than magnitude 4.0 also have been omitted.

Within western Washington, there has been little or no association of shallow earthquake hypocenters with known or suspected shallow faults. In some respects, this is not surprising since many of the earthquakes occur at mid-crustal depths (15 to 25 km depth). In addition, surface exposure of faults is generally poor in western Washington owing to thick Quaternary deposits and vegetative cover. Consequently, with the possible exception of the St. Helens seismic zone (SHZ), no well established hypocenter lineations in western Washington can be interpreted unequivocally to reflect shallow faulting. Near Mount St. Helens, a prominent alignment of epicenters of about 60 km length can be seen along the SHZ (Figure 7). This includes aftershocks larger than magnitude 4 of the 1981 magnitude 5.5 Elk Lake earthquake. Clear association of the SHZ with surface faulting has not been established. A possible surface expression of the SHZ has been identified by Galster and Mann (1987).

Since 1980 more than 6,000 volcanic earthquakes have been located in the vicinity of Mount St. Helens. Many additional earthquakes have been detected but not located. Swarms of earthquakes preceded and accompanied the eruptions, and short-term prediction of eruptions has been possible in many instances owing to the rapid increase of seismic energy release from 12 hr to a day before magma was actually extruded at the surface (Swanson et al., 1983).

Eastern Washington Seismicity

In eastern Washington all seismicity occurs at depths less than 25 km, in contrast to the two distinct depth zones for earthquakes in western Washington. More than 90 percent of this activity occurs at depths of less than 8 km, often in swarms of small earthquakes (magnitudes 2.0 or less) that are isolated in both space and time and only a few kilometers in maximum spatial extent (Malone et al., 1975). The duration of swarm ac-

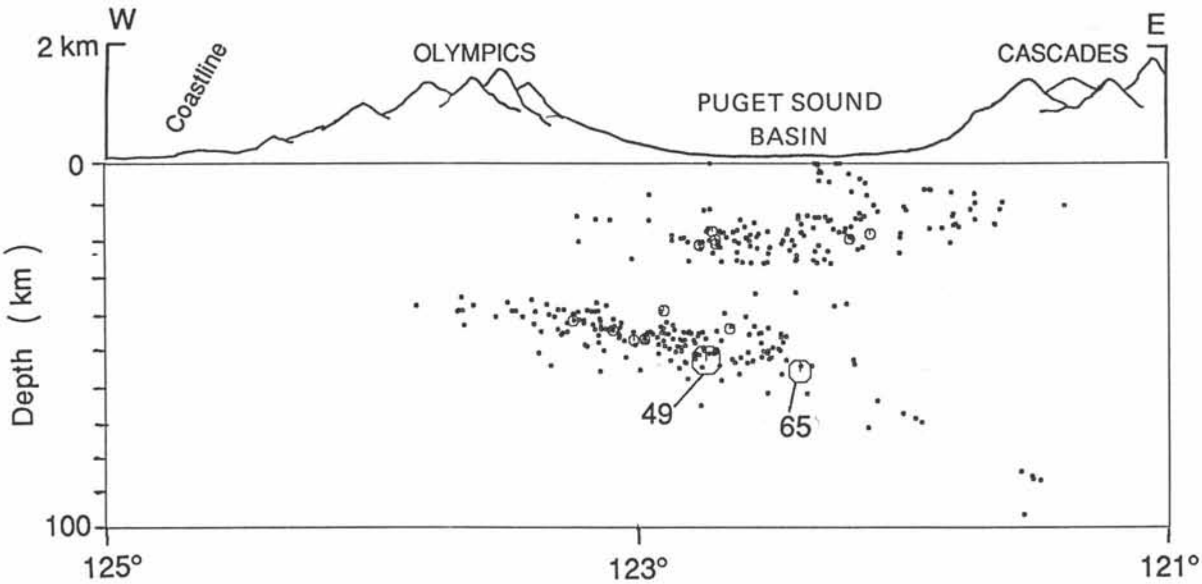

Figure 8. East-West cross-section from 121° to 125° W longitude for the area between 47 and 49° N latitude, with no vertical exaggeration. Approximate topography is shown above the cross-section at 10:1 vertical exaggeration. Data used in this figure are the best-located (by WRSN) earthquakes since 1970, plus the damaging 1949 and 1965 earthquakes. Events shown have WRSN quality factors "B" or higher (Qamar et al., 1987) and no problem depths (for example, depth fixed or iterations exceeded without convergence). Because fewer earthquakes occur in the deep suite, deep (>35 km) events greater than magnitude 1.0 that met the criteria were included, while shallow (≤35 km) events below magnitude 2.5 were excluded. One symbol size was used for all earthquakes smaller than magnitude 4.0. Symbol sizes for earthquakes of magnitude 4.0 or greater are scaled by magnitude.

tivity may be only a few weeks or may continue for many months. Some of these swarms appear to be spatially associated with the west-trending anticlines of the Yakima Fold Belt, although no clear association of earthquakes and mapped surface faults or other geologic structures has been made.

At source depths of less than 8 km, most earthquakes in the Columbia Plateau region have hypocenters within the Columbia River basalt. Focal mechanisms of selected earthquakes and composite mechanisms from swarms indicate a common maximum compressive stress axis that is nearly horizontal and oriented approximately north-south (Malone et al., 1975). The minimum compressive stress axis ranges in orientation from east-west to nearly vertical. This tectonic stress distribution is consistent with the west-trending anticlines as well as with geodetic deformation measurements, which suggest very slow overall contraction in a north-south direction (Savage et al., 1981). Thus there is general similarity between tectonic stress orientations in the crust in both western and eastern Washington, as interpreted from earthquake data.

TECTONIC IMPLICATIONS

Plate Geometry

To understand regional tectonics, a clear picture of the three-dimensional geometry of the subducted slab along the Cascadia subduction zone is needed. Recent research has improved our understanding of this geometry. Evidence is provided mainly by seismic refraction and reflection studies, analysis of earthquake hypocenters, and observations of distant earthquakes made at surface seismograph stations.

Although there is no physical trench associated with the Cascadia subduction zone, the surface location of the boundary between the North American and Juan de Fuca plates lies at the toe of the continental slope off Washington and Oregon. There is a natural tendency for subduction zones to arc in a concave sense in the direction of underthrusting, and this is understood to result from minimization of the in-plane strain or deformation within the subducted plate. However, in the case of Cascadia, the subduction zone is forced to bend convexly in the direction of underthrusting owing to the configuration of the relatively rigid North American plate boundary (Figure 1). Most of this curvature is concentrated in the region near 47° N latitude, where the trend of the subduction zone changes from nearly north-south to approximately N30°W. This configuration requires that the subducted Juan de Fuca plate undergo internal deformation, namely compression parallel to the subduction zone.

Several possible ways in which this deformation could be accomplished have been considered, including crenulations, tears, and thickening of the subducted plate (Rogers, 1983), and plate segmentation (Michaelson and Weaver, 1986). From hypocenter distribution and analysis of teleseismic converted waves, a simple uparching of the subducted plate beneath Puget Sound is suggested (Crosson and Owens, 1987; Owens et al., 1987; Weaver and Baker, 1988) (Figure 8). The crest of the arch lies directly beneath the concentration of shallow and deep seismicity beneath the Puget Sound basin (Crosson and Owens, 1987). Along the crest of the arch the angle of subduction is approximately 10° to the east, as shown by the earthquake hypocenter distribution beneath the Puget Sound Basin (Figure 9). Away from the arch, the angle of subduction appears to be on the order of 16° to 20°, carrying the slab more rapidly to greater depths and higher temperatures compared with the arch region.

Some observed characteristics of the seismicity pattern and structure may be explained by the concept of an arched plate. When the subducted Juan de Fuca plate reaches depths of 30 to 40 km or more, an asthenospheric wedge of upper mantle material overlies the slab, accounting for the anomalously low upper mantle velocity observed from a number of measurements (for example, Zervas and Crosson, 1986). Most of the subcrustal earthquakes located within the Juan de Fuca plate lie in the uplifted arch structure, suggesting a causal relationship. The mechanism of control could be either pressure/temperature conditions within the subducting slab, owing to the decreased rate of descent in the vicinity of the arch, or simply to bending stresses induced within the slab by the arch structure (Crosson and Owens, 1987). Because the plate convergence direction is not exactly down the axis of the induced arch, but is inclined at a slight angle, localized bending stresses may exist at the south limb of the structure. This may explain the concentration of larger (that is, 1949 and 1965) deep earthquakes toward the southern Puget Sound region.

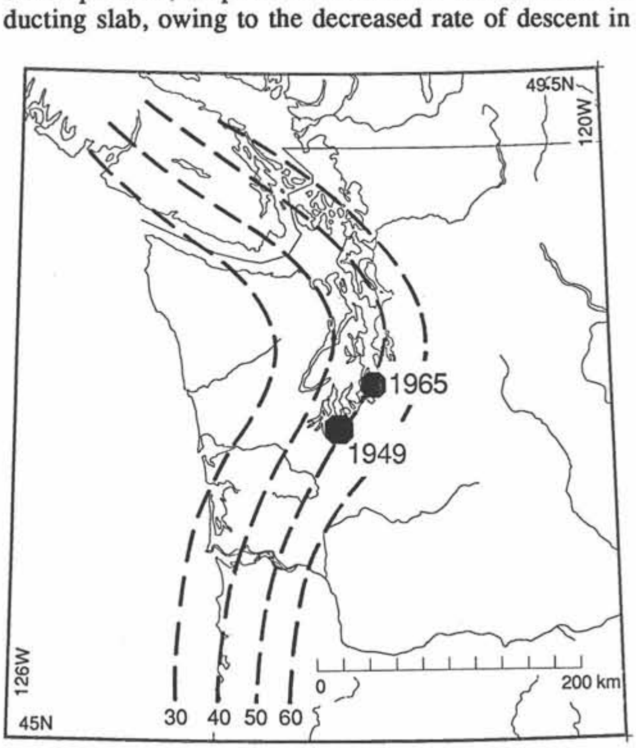

Figure 9. 10-km depth contours of the subducted Juan de Fuca slab. The positions of the 1949 and 1965 earthquake hypocenters are indicated.

Shallow continental seismicity also is concentrated at the axis of the slab arch. This suggests a causative mechanism, perhaps through chemical, thermal, or mechanical means. One possibility is that the arch induces a thinning of the elastic portion of the overlying lithosphere, leading to a low strength region of stress concentration relative to surrounding regions. The structure of the Olympic Mountains uplift mimics the arch structure in the subducted plate in a gross manner, and this similarity seems more than coincidental. It is possible that the uplift of the Olympic Mountains is related to the uparch of the underlying subducted Juan de Fuca plate.

Regional Stress

To understand regional tectonics we must ultimately understand the state of stress in the Earth's lithosphere. Seismology, through the study of focal mechanisms, provides information on stress directions where earthquakes are abundant. Horizontal geodetic measurements can provide strain information in the Earth's surface plane, which indirectly reflects changes in stress. Vertical leveling measurements provide important constraints. Other direct stress measurements, such as borehole hydrofracture measurements and overcoring measurements, can also be used. In the Pacific Northwest, earthquake focal mechanisms and horizontal geodetic strain measurements have been used to interpret regional stress and strain.

From earthquake focal mechanisms it has been noted that a pervasive north-south compression holds throughout the continental lithosphere (earthquakes having depths of 30 km or less). In the Puget Sound region, where the greatest concentration of earthquakes has occurred since 1970, a very consistent picture of north-south compression has emerged (Yelin, 1982; Crosson, 1972, 1983; Ma, 1988; Ma et al., 1988). A similar picture is found in southern British Columbia (Rogers, 1983) and in eastern Washington (Malone et al., 1987).

Horizontal strain data yield an apparently different result from seismic observations. Savage et al. (1981) interpreted strain data from the Puget Sound region to include compression in an east-northeasterly direction and proposed, on this basis, that the subduction zone was locked and a major earthquake, therefore, was possible. However, the data showed a strong time-dependent dilational component (Crosson, 1986) that may have caused Savage et al. (1981) to overestimate the northeastward compression. In any case, the rate of deformation near Puget Sound was found to be low, and Lisowski et al. (1987) found even lower rates of northeastward compression in data from the Puget Sound Basin and Olympic Mountains networks, although they interpret strain measured in the vicinity of the Strait of Juan de Fuca to be consistent with that expected from locked subduction. Since the strain and stress accumulation expected from locked subduction with episodic slip has its principal compression axis nearly east-west, while earthquake focal mechanisms are consistent with north-south compressive stress, these two sets of measurements are obviously not consistent. Still, an explanation is possible. Horizontal strain data from geodetic measurements provide information only on incremental changes in strain and stress. By contrast, earthquake focal mechanisms may be interpreted to reflect the dominant ambient state of stress. If the earthquakes respond to the large ambient tectonic stress, whereas the strains result from much smaller incremental changes in stress, then the two sets of observations may be perfectly compatible (Sbar, 1983). If so, we can conclude that the magnitude of plate-coupling stress must only be a small fraction of the regional tectonic stress.

In contrast to the results from crustal earthquakes, focal mechanism observations of subcrustal earthquakes suggest that stress orientation in the subducted slab is complex (Crosson, 1983; Taber and Smith, 1985; Ma et al., 1988). The modification of normal slab driving stresses by plate-bending in the vicinity of the arch (where earthquakes are observed) may at least partly explain this complication.

In summary, seismic observations provide a consistent picture of dominant north-south compression in the continental lithosphere adjacent to the Cascadia subduction zone. If the plates are coupled across the megathrust, the modification of the stress field owing to this coupling must be small, leading to uncertainty about the capability of the subduction system to produce a major earthquake. Still, the driving stresses in subduction earthquakes are not well understood, and these observations do not provide definitive evidence on the subduction earthquake hazard. In any case, the regional north-south crustal compression is probably due to the interaction between the Pacific and North American plates at a scale much larger than that of the Juan de Fuca plate. The earthquake focal mechanism evidence may be consistent with weak coupling across the Cascadia subduction zone.

Subduction Zone Tectonics

Between the two zones of observed seismic activity lies an inferred megathrust, which is the actual boundary between the two adjacent plates. Heaton and Kanamori (1984) and Heaton and Hartzell (1987) have argued, on the basis of a general comparison of the Cascadia subduction zone to other subduction zones worldwide, that great thrust-type earthquakes (magnitude 8+) could occur on the megathrust. No thrust earthquakes on the Juan de Fuca/North American plate interface have yet been identified, but our historical records extend back at most only 200 years (Heaton and Snavely, 1985), and the recurrence interval for such earthquakes could be very long (500-1,000 yr or more). Heaton and Kanamori (1984) base their argument on the observation that subduction earthquake size is related to slab age and convergence rate. The largest earthquakes occur in subduction zones where young material is being subducted at a high rate of convergence (8-12 cm/yr). Although the Juan de Fuca plate is composed of extremely young material (10-15 Ma), it has a low convergence rate (3.5 cm/yr; Riddihough, 1977) and represents an end member when compared to subduction zones worldwide. While the Juan de Fuca plate is small compared to other plates, if the megathrust were to break along its entire length from southern Oregon to mid-Vancouver Island over a width of 100 km, an earthquake of magnitude 9.0 or larger could be generated.

Searches for geologic evidence of great Holocene earthquakes along the west coast from Vancouver Island to northern California have been conducted by several investigators (Atwater, 1987; Hull, 1987; Reinhart and Bourgeois, 1987; Darienzo and Peterson, 1987; Grant and McLaren, 1987; Nelson, 1987). Major subduction earthquakes are normally accompanied by vertical deformation. This deformation consists of belts of uplift and subsidence parallel to the trench (Plafker, 1969; Plafker and Savage, 1970; Thatcher, 1984). Evidence interpreted as due to subsidence has been found along the coast of Washington (Atwater, 1987), where densely vegetated fresh-water lowland horizons are found in the intertidal zone; this change in elevation has resulted in vegetation kill and subtidal peat horizons. Sand deposits interpreted as tsunami-generated overlie some of these horizons. In some locations, eight or more peat horizons can be found; several may correlate between localities near the mouth of the Columbia River and Grays Harbor, Washington, a distance of 100 km. These observations and the plate comparative studies have focused serious attention on the possibility that large subduction earthquakes may have occurred off the coast of the Pacific Northwest (Heaton and Kanamori, 1984; Heaton and Hartzell, 1987; Atwater, 1987). However, considerable investigation remains before this question can be satisfactorily resolved.

ENGINEERING SEISMOLOGY

Engineering seismology combines the applications of seismology, geology, and tectonics to engineering projects. Of special importance is the analysis of the upper Tertiary and Quaternary geologic record for evidence of faulting and other features that may reflect the occurrence of large earthquakes. The analysis of the past geologic record of seismicity, of the historic record, and of the contemporary instrumental geodetic and seismologic record produces the basis for a deterministic evaluation of earthquake hazard and the selection of an appropriate maximum design earthquake for a given area or engineering structure. The historic seismologic record may also be used to develop a probabilistic evaluation of hazard and risk. The potential influence of earthquake-related effects, such as tsunamis, seiches, landslides, and soil liquefaction, also falls within the scope of engineering seismology. Whether employing deterministic or probabilistic methods, the goal of the engineering geologist is to produce estimates of earthquake ground motions in terms useful to the design engineer. This allows the engineering community an opportunity to incorporate earthquake-resistant design and to avoid placing structures where earthquake-related effects may result in damage.

Earthquake Hazards

Hazards to structures resulting from earthquakes include surface faulting, ground shaking, ground failure, tsunamis, and seiches. Two relatively recent earthquakes in western Washington have demonstrated the susceptibility of at least some areas to seismic hazards. The 1949 and 1965 earthquakes in the Puget Sound area were moderate events, with magnitudes of 7.1 and 6.5, respectively, that caused considerable damage. The 1949 Olympia earthquake resulted in some $150 million damage (1984 dollars) and eight deaths. The 1965 Seattle-Tacoma earthquake resulted in some $50 million damage (1984 dollars) and seven deaths (Washington State Seismic Safety Council, 1986).

Surface Faulting

Surface faulting can cause rupture of lifelines, render roadways impassable, and severely damage structures that span or are situated close to fault zones. No surface fault movement has been recorded in Washington within historic time. This reflects the subcrustal nature of the largest historical events occurring in the Puget Sound region and the historic absence of very large crustal earthquakes within the state. There are, however, numerous instances of Quaternary faulting within the state that require evaluation during the siting and design of critical structures.

Ground Shaking and Ground Failure

Ground shaking intensities generated by six major earthquakes are shown in Figure 6. The Modified Mercalli (MM) Scale is given in Table 1. Types of ground failure observed from past Washington earthquakes have included landslides, liquefaction (including bearing loss below the water table), ground lurching, settlements, and boils (Thorsen, 1986; Noson et al., 1988). A general review of earthquake hazards in Washington is given in Noson et al. (1988). Eastern Washington, except for the 1872 North Cascades event, has not been as prone to such failures. On the other hand, in western Washington, an area of greater seismic potential, it has been repeatedly demonstrated that these types of failures should be of major concern to engineers. During every major historic seismic event in Washington, landslides have occurred. Major landslides and numerous minor roadbed slide failures were associated with both the 1949 Olympia earthquake (Thorsen, 1986; Noson et al., 1988) and the 1872 North Cascades event.

Ground shaking and ground failure most often are the phenomena that cause the greatest damage during an earthquake. During the 1949 and 1965 earthquakes in the Puget Sound Basin, major damage occurred, particularly on alluvium and fill. In 1949 high ground near the epicentral area, composed of sand and gravel, also experienced failure and large induced ground motions, as evidenced by damage to buildings on the State Capitol campus in Olympia. Other buildings in the Puget Sound region also suffered significant structural damage. In the southern Puget Sound Basin, shaking of water-saturated tide flats produced foundation failures. Even where structures were built on piles, damage due to violent ground shaking and settling occurred. Locally, areas generally considered to have excellent foundation ground also experienced damage. For example, in West Seattle the bedrock geometry and overburden characteristics produced considerable focusing of seismic energy resulting in localized chimney collapse during both the 1949 and 1965 earthquakes. Ground shaking has also caused rock slides and failure of consolidated soil on roadways and other facilities.

Tsunamis and Seiches

Tsunamis (seismic sea waves) generated by major subduction earthquakes, especially on the northern and western margins of the Pacific rim, are a factor that must be considered in design of facilities along Washington's coast. The Pacific Tsunami Warning System, operated by the National Ocean and Atmospheric Administration in Hawaii, now provides forecasts of arrival times of tsunamis from major earthquakes around the Pacific rim to appropriate civil defense officials. Tsunami damage is strongly controlled by submarine topography adjacent to the coastline as well as the topography of the immediate onshore area. The protected inland waters of western Washington, although not immune to tsunami action, tend to dampen the wave action, greatly reducing the hazard.

Although there are no recorded fatalities from tsunamis reaching the Washington coast, Oregon and northern California have had fatalities from tsunamis whose effects were noted along Washington coastal areas. The focusing tendency of tsunamis was well illustrated as a result of the 1964 Alaska earthquake.

Three tsunami waves struck the Washington coast about 8 hours after the Alaska earthquake, inflicting considerable damage on private and public property in low-lying coastal areas north of Grays Harbor. Three homes were destroyed, and two highway bridges, as well as a number of vehicles and trailers, were damaged. Much of the damage was due to large tsunami-transported debris acting as battering rams. In contrast, no damage farther south along the Washington coast was reported, yet considerable damage was suffered on the Oregon and northern California coastlines; there were three fatalities in Oregon and 12 in California. The tide gage at Neah Bay recorded a rise of a maximum of 4.7 ft as the tsunami arrived (Spaeth and Berkman, 1969). However, little wave energy reached the inland waters. For example, the tide gage at Seattle exhibited less than 1 ft of change as a result of the tsunami (Spaeth and Berkman, 1969). Seiches on Lake Union in Seattle caused minor damage to small craft. The experience during the 1964 Alaska earthquake confirms that tsunamis generated by distant sources need to be considered in the siting of coastal facilities.

Engineering Implication of Potential Earthquake Sources

From the foregoing description of seismicity and tectonics, we can establish a general seismic zonation in Washington. In this section we will review the engineering implications for each of the tectonic provinces of or adjacent to Washington.

Juan de Fuca Plate

Historic seismicity of the Juan de Fuca plate is concentrated along the Blanco fracture zone and the Sovanco fracture zone (Figures 1 and 4). The nearest concentration of earthquakes on these features lies 200 km west of Cape Flattery. Hence, they are too distant to be of significance to engineered structures in Washington. Although earthquakes greater than magnitude 6.5 may occur along the Blanco fracture zone, at more than 400 km distance, they will not produce strong ground shaking in Washington. Furthermore, there is no significant tsunami hazard from these earthquakes.

Continental Margin

In the state's 200-yr historical record no earthquake has occurred along the boundary between the converging Juan de Fuca and North American plates that could be interpreted as a large, thrust-faulting event such as are typically associated with active subduction zones. Instrumentally recorded seismicity at the continental margin is also sparse. Seismicity from this area has historically had no effect onshore in Washington and has not been considered to be a viable seismogenic source from the standpoint of engineering seismology. However, as noted previously, several recent investigations have raised the possibility of large subduction earthquakes along this margin (for example, Heaton and Kanamori, 1984; Heaton and Hartzell, 1987; Atwater, 1987). At the time of this writing, this question is still the subject of intense investigation and active debate within the earth science community. If further investigations clearly demonstrate the potential for great subduction earthquakes along the Cascadia zone, a significant hazard would then exist in western Washington, and re-evaluation for engineering purposes would be required.

Forearc Region

The subcrustal zone beneath the Puget Sound Basin may be capable of generating an earthquake somewhat greater than the 1949 magnitude 7.1 event. In subduction zones worldwide, similar tensional earthquakes within the subducting plate have magnitudes as large as 8.0 (Astiz et al., 1988). However, the Juan de Fuca plate is somewhat thinner than most subducting slabs, and an earthquake of magnitude 7.5 is usually considered to be a conservative feasible event. The development of the concept of the arch in the subducted plate beneath Puget Sound provides a stronger basis for localizing the larger slab earthquakes in the vicinity of the arch. If true, the hazard for subcrustal (intraplate) earthquakes within the subducted Juan de Fuca slab is in the vicinity of Puget Sound, not the crest or flanks of the arch in the plate.

Crustal seismicity is somewhat diffuse throughout the Puget Sound Basin–San Juan–Georgia Strait area and sparse in the Olympic Mountains–Coast Range area. Focal mechanisms of these generally moderate to low magnitude events (less than 5.5) indicate north-south compression, consistent with the large-scale relative North American/Pacific plate motions. Many crustal events are concentrated in the central section of the Puget Sound Basin, which is also characterized by major gravity gradients considered by many workers to be crustal fault zones (Gower et al., 1985). The selection of candidate faults in the fore-arc crustal zone is problematical. Although there are numerous bits of local evidence for postglacial faulting, the continuity of surface faulting is difficult to trace. An effort is usually made to tie the design event to the closest major fault zone, geophysical anomaly, or lineament determined by remote-sensing analysis. Weaver and Smith (1983) proposed a maximum magnitude as large as 7.0 for the SHZ in the adjacent volcanic arc region. Whether earthquakes this large can occur in the forearc region is uncertain. No crustal earthquakes within one magnitude unit of this size have yet been observed in the forearc region.

Volcanic Arc

The largest historic event for the North Cascades was the December 14, 1872, earthquake. Epicentral intensities of MM VII to IX may have resulted from this earthquake, and a magnitude of 7.4 has been assigned to this event (Malone and Bor, 1979). Although poorly constrained with respect to location, this event appears unique when compared with the relative paucity of subsequent historic seismicity in the North Cascades. The only important exception is a zone of shallow seismicity in the Chelan area. A maximum event of magnitude 5.8 has been calculated for this zone (Bor, 1977), which spans the boundary between the North Cascades (forearc) and Columbia Plateau (back-arc). The 1872 earthquake is a reasonable maximum event for the North Cascades.

The recent crustal seismicity of the southern Cascade Range is dominated by the SHZ (Weaver and Smith, 1983). Notable is the lack of historic seismicity in the Mount Adams–Simcoe volcanic area along the southeastern flank of the South Cascades. Focal mechanism solutions of earthquakes on the SHZ show north-northwest right-lateral strike-slip motion, consistent with the north-south crustal compression observed elsewhere in the state (Ma et al., 1988). Weaver and Smith (1983) have suggested a magnitude as large as 7.0 for the SHZ, but the zone now appears more constrained than originally envisioned. Since a magnitude 5.5 was recently observed on the SHZ (Grant et al., 1984), we estimate that earthquakes in the range of 5.5 to 6.5 may occur in the South Cascades of southern Washington.

Back-Arc Region

The presence of major structures such as nuclear power plants, a proposed nuclear waste repository, and major dams has focused attention on the seismic hazard of the Columbia Plateau region. Most of the seismicity within the plateau is low-level and apparently associated with minor northward compression continuing in the Yakima Fold Belt, producing low-level thrust activity. Applying fault length-displacement relations from other regions to some observed faults and lineaments within the plateau results in magnitudes ranging from 5.0 to 6.5. Historic records do not indicate any earthquakes larger than the magnitude 5.7 (estimated) Milton-Freewater earthquake of 1936.

Northern Rocky Mountains

Although the principal region of earthquake activity in the northern Rocky Mountains lies at considerable distance from the state's eastern border, large historic earthquakes (magnitude 7.1-7.5) from this source have resulted in ground motion intensities as high as MM V near the state's eastern margin (Figure 6D, 6F). This source area is not usually considered in engineering design in Washington; however, the effects of long-period wave motions should be considered for some structures, and some minor damage, such as cracked plaster, also may occur from this source area.

Design Earthquake Determination

The selection of appropriate earthquake motions for the design of an engineered structure requires consideration of the consequence of the failure of the structure in terms of lives and property damage. The failure of a large building, a nuclear plant, or a large hydroelectric dam has a consequence that differs from that of the failure of a two-lane road or single dwelling. Structural engineers have established building codes based on historic records of seismicity and on damage experience to be applied to various structures. Some general guidance on peak acceleration values is shown on Figure 10,. Figure 10B shows the National Bureau of Standards (1978) values for effective peak acceleration for Washington. These values are equivalent to Uniform Building Code values established by the Applied Technology Council. A building code such as this one may be acceptable for lesser structures, but for critical or major structures whose failure would be of great consequence, more rigorous site-specific analysis is warranted. In such cases, a "design earthquake" is usually selected to provide the basis for estimating ground motions at the structure. The location of the design earthquake, together with its attenuation relation, and the correction for site response must be used in the final estimation of ground motion.

Specification of the design earthquake can be based on identification of an "active" fault in the vicinity of the structure. If such a structure cannot be identified, a variable or "floating" source location is sometimes used in conjunction with a statistical model for earthquake recurrence and location.

Attenuation and Range of Earthquake Motions

Attenuation, in its engineering usage, describes the reduction of earthquake motion with distance from the source. Normally, either peak acceleration, velocity, or displacement, as a function of frequency, at different frequencies is used to describe ground motion at a site. The use of an appropriate attenuation factor between source and site is critical in obtaining a valid estimate of site ground motion. The amplitude of seismic waves decreases with distance owing to geometrical spreading and anelastic attenuation. Local site conditions, such as topography, soil properties, ground-water table, and subsurface structure, play important roles in determining ground motion. Most attenuation formulas are empirically derived, from both intensity data and accelerograph records.

Brazee (1976) developed an attenuation relation using intensity data for 91 earthquakes in Washington and Oregon. These events were located west of the Cascade Range. Rassmussen et al. (1974) developed attenuation curves for hazard evaluation in the Puget Sound region; these incorporated travel path and local conditions. Specific attenuation and strong motion studies have been conducted for Washington by several investigators (U.S. Army Corps of Engineers, 1981, 1982; Johnson, 1980; Langston, 1981; Langston and Lee, 1986; Woodward-Clyde Consultants, 1980). In addition, several excellent guides are available for

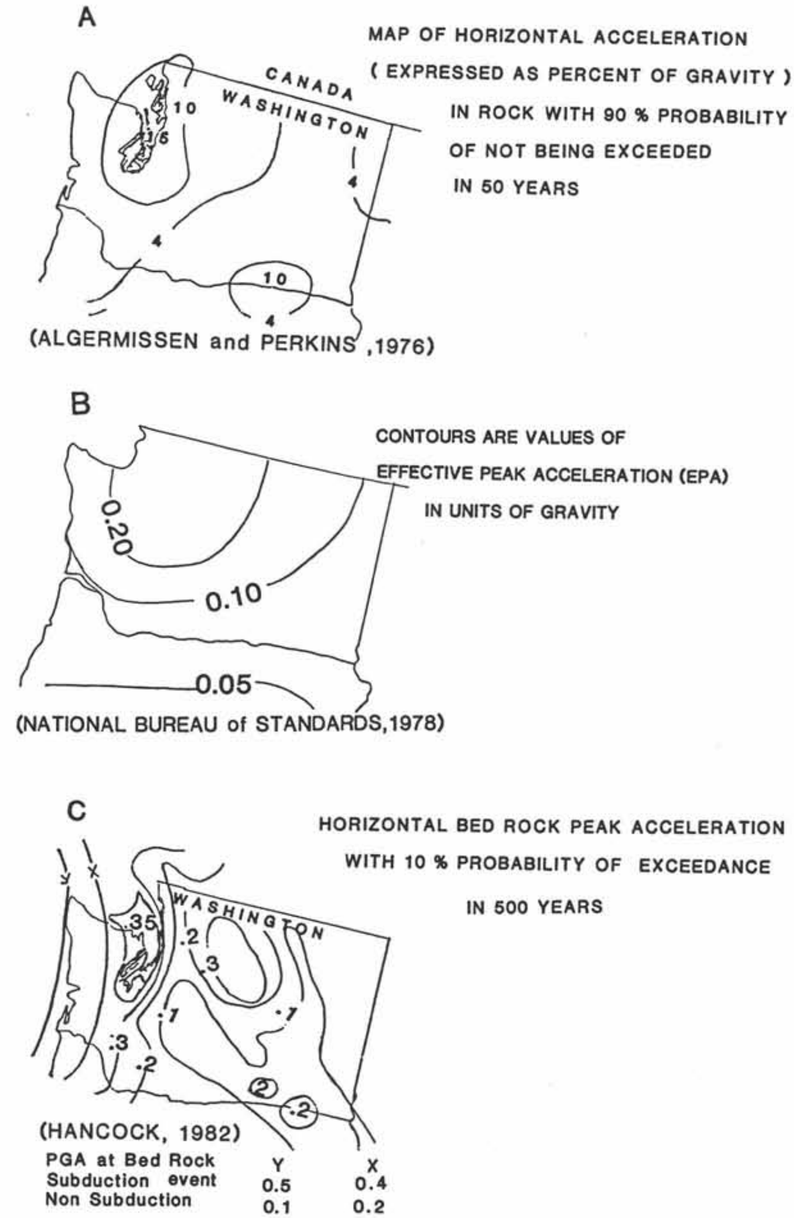

Figure 10. Range of peak bedrock acceleration in Washington.

developing site-specific seismic design parameters. These include: Seismic Design Guidelines for Essential Buildings (U.S. Department of the Army, 1986); Guidelines for Developing Design Earthquake Response Spectra (Hays et al., 1975); and Procedures for Estimating Earthquake Ground Motions (Hays, 1980).

REFERENCES

Algermissen, S. T., 1983, *An Introduction to the sesimicity of the United States*: Earthquake Engineering Research Institute [Engineering monographs on earthquake criteria, structural design and strong motion records, Berkeley, CA], 148 p.

Algermissen, S. T.; Harding, S. T.; Steinbrugge, L. V; and Cloud, W. K., 1965, *The Puget Sound, Washington Earthquake of April 29, 1965*: U.S. Department of Commerce, Coast and Geodetic Survey, 51 p.

Algermissen, S. T. and Perkins, D. M., 1976, *A Probabilistic Estimate of Maximum Acceleration in Rock in the Contiguous United States*: U.S. Geological Survey Open-File Report 76-416, 45 p.

Ando, M. and Balazs, E. J., 1979, Geodetic Evidence for Aseismic Subduction of the Juan de Fuca Plate: *Journal of Geophysical Research*, Vol. 84, No. B6, pp. 3023-3027.

Astiz, L.; Lay, T.; and Kanamori, H., 1988, Large intermediate depth earthquakes and the subduction process: *Physics of the Earth and Planetary Interiors*, Vol. 53, No. 1 and 2, pp. 80-166.

Atwater, B. F., 1987, Evidence for great Holocene earthquakes along the outer coast of Washington State: *Science*, Vol. 236, No. 4804, pp. 942-944.

Atwater, T., 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western North America: *Geological Society of America Bulletin*, Vol. 81, No. 12, pp. 3513-3535.

Baker, G. E. and Langston, C. A., 1987, Source parameters of the 1949 magnitude 7.1 South Puget Sound, Washington, earthquake as determined from long-period body waves and strong ground motions: *Bulletin of the Seismological Society of America*, Vol. 77, No. 5, pp. 1530-1557.

Barnard, W. D., 1978, The Washington continental slope–Quaternary tectonics and sedimentation: *Marine Geology*, Vol. 27, No. 1-2, pp. 79-114.

Bor, S. S., 1977, *Scaling for Seismic Source Spectra and Energy Attenuation in the Chelan Region, Eastern Washington* [M.S. thesis]: University of Washington, Seattle, WA, 76 p.

Brazee, R. S., 1976, *Final Report–An Analysis of Earthquake Intensities with Respect to Attenuation, Magnitude, and Rate of Recurrence*: National Oceanic and Atmospheric Administration, Technical Memorandum EDS NGS DC-2, 53 p., 3 appendices.

Campbell, N. P. and Bentley, R. D., 1981, Late Quaternary deformation of the Toppenish Ridge uplift in south-central Washington: *Geology*, Vol. 9, No. 11, pp. 519-524.

Carson, R. J., 1970, *The Quaternary Geology of the South-Central Olympic Peninsula, Washington* [Ph.D. thesis]: University of Washington, Seattle, WA, 67 p.

Carson, B.; Yuan, J.; Myers, P. B. Jr.; and Bernard, W.D., 1974, Initial deformation at the base of the Washington continental slope–A response to subduction: *Geology*, Vol. 3, No. 11, pp. 561-564.

Clowes, R. M.; Yorath, C. J.; and Hyndman, R. D., 1986, Reflection mapping across the convergent margin of western Canada: *Geophysical Journal of the Royal Astronomical Society*, Vol. 89, No. 1, pp. 79-84.

Crosson, R. S., 1972, Small earthquakes, structure, and tectonics of the Puget Sound region: *Bulletin of the Seismological Society of America*, Vol. 62, No. 5, pp. 1133-1171.

Crosson, R. S., 1974, *Compilation of Earthquake Hypocenters in Western Washington July 1970-Dec. 1972*: Washington Division of Geology and Earth Resources, Information Circular 53, Olympia, WA, 25 p.

Crosson, R. S., 1983, Review of seismicity in the Puget Sound region from 1970 through 1978. In Yount, J. C. and Crosson, R. S. (editors), *Proceedings of Conference XIV, Earthquake Hazards of the Puget Sound Region, Washington*: U.S. Geological Survey Open-File Report 83-19, pp. 6-18.

Crosson, R. S., 1986, Comment on "Geodetic strain measurements in Washington" by J. C. Savage, M. Lisowski, and W. H. Prescott: *Journal of Geophysical Research*, Vol. 91, No. B7, pp. 7555-7557.

Crosson, R. S. and Owens, T. J., 1987, Structure of the subducted Juan de Fuca plate beneath western Washington from earthquake hypocenters and teleseismic converted waves: *Geophysical Research Letters*, Vol. 14, No. 8, pp. 824-827.

Danes, Z. F., 1985, *Sedimentary Thickness in the Puget Sound Area, Washington, Derived from Aeromagnetic Data*: Washington Division of Geology and Earth Resources Open-File Report 85-5, Olympia, WA, 15 p.

Danes, Z. F.; Bonno, M.; Brau, E.; Gilham, W. D.; Hoffman, T. F.; Johansen, D.; Jones, M. H..; Malfait, B.; Masten, J.; and Teague, G. O., 1965, Geophysical investigations of the southern Puget Sound area, Washington: *Journal of Geophysical Research*, Vol. 70, No. 22, pp. 5573-5580.

Darienzo, M. and Peterson, C., 1987, Episodic tectonic subsidence recorded in late-Holocene salt-marshes, northwest Oregon [abstract]: *Eos (Transactions of the American Geophysical Union)*, Vol. 68, No. 44, p. 1469.

Davis, G. A., 1981, *Late Cenozoic Tectonics of the Pacific Northwest with Special Reference to the Columbia Plateau*: Washington Public Power Supply System, WNP-2 Final Safety Analysis Report, Appendix 2.5M, Amendment No. 18, 48 p., 11 figs.

Dehlinger, P.; Bowen, R. G.; Chiburis, E. F.; and Westphal, W. H., 1963, Investigations of the earthquake of November 5, 1962 near Portland: *Ore Bin*, Vol. 25, No. 4, pp. 53-68.

Dickinson, W. R., 1970, Relations of andesites, granites, and derivative sandstones to arc-trench tectonics: *Reviews of Geophysics*, Vol. 8, No. 4, pp. 813-860.

Drake, E. T., 1982, Tectonic evolution of the Oregon continental margin: *Oregon Geology*, Vol. 44, No. 2, pp. 15-21.

Fox, K. F., Jr.; Rinehart, C. D.; and Engels, J. C., 1977, *Plutonism and Orogeny in North-Central Washington–Timing and Regional Context*: U.S. Geological Survey Professional Paper 989, 27 p.

Fox, K. F., Jr. and Rinehart, C. D., 1988, Okanogan gneiss dome, a metamorphic core complex in north-central Washington: *Washington Geologic Newsletter*, Vol. 16, No. 1, pp. 3-12.

Galster, R. W. and Mann, L. V., 1987, Radar analysis of western Washington structural fabric [abstract]: *Geological Society of America Abstracts with Programs*, Vol. 9, No. 6, p. 380.

Gower, H. D., 1960, *Geology of the Pysht Quadrangle*: U.S. Geological Survey Geological Quadrangle Map GQ-129, 1 sheet, scale 1:62,500.

Gower, H. D.; Yount, J. C.; and Crosson, R. S., 1985, *Seismotectonic Map of the Puget Sound Region, Washington*: U.S. Geological Survey Miscellaneous Investigations Series Map I-1613, 15 p., 1 plate, scale 1:250,000.

Grant, W. C. and McLaren, D. D., 1987, Evidence for Holocene subduction earthquakes along the northern Oregon coast [abstract]: *Eos (Transactions of the American Geophysical Union)*, Vol. 68, No. 44, p. 1239.

Grant, W. C. and Weaver, C. S., 1986, Earthquakes near Swift Reservoir, Washington, 1958-1963–Seismicity along the southern St. Helens seismic zone: *Bulletin of the Seismological Society of America*, Vol. 76, No. 6, pp. 1573-1587.

Grant, W. C.; Weaver, C. S.; and Zollweg, J. E., 1984, The 14 February 1981 Elk Lake earthquake sequence: *Bulletin of the Seismological Society of America*, Vol. 74, No. 4, pp. 1289-1309.

Green, A. G.; Clowes, R. M.; Yorath, C. J.; Spencer, C.; Kanasewich, E. R.; Brandon, M. T.; and Brown, A. S., 1986, Seismic reflection imaging of the subducting Juan de Fuca plate: *Nature*, Vol. 319, No. 6050, pp. 210-213.

Hall, J. B. and Othberg, K. L., 1974, *Thickness of Unconsolidated Sediments, Puget Lowland, Washington*: Washington Division of Geology and Earth Resources Geologic Map GM-12, Olympia, WA, 3 p., 1 plate, scale 1:250,000.

Hancock, W. E., 1982, Seismic hazard analysis and regionalization studies for the upper Columbia River, U.S. In Sherif, Memet (chairman), *Third International Earthquake Microzonation Conference Proceedings*: National Science Foundation, Vol. III, pp. 1296-1306.

Hays, W. W., 1980, *Procedures for Estimating Earthquake Ground Motions*: U.S. Geological Survey Professional Paper 1114, 77 p.

Hays, W. W.; Algermissen, S. T.; Estinosa, A. F.; Perkins, D. M.; and Rinehart, W. A., 1975, *Guidelines for Developing Design Earthquake Spectra*: U.S. Army Corps of Engineers, Construction Engineering Research Laboratory, Technical Report M-114, Champaign, IL, 349 p.

Heaton, T. H. and Hartzell, S. H., 1987, Earthquake hazards on the Cascadia subduction zone: *Science*, Vol. 236, pp. 162-168.

Heaton, T. H. and Kanamori, H., 1984, Seismic potential associated with subduction in the northwestern United States: *Bulletin of the Seismological Society of America*, Vol. 74, No. 3, pp. 933-941.

Heaton, T. H. and Snavely, P. D., Jr., 1985, Possible tsunami along the northwestern coast of the United States inferred from Indian traditions: *Bulletin of the Seismological Society of America*, Vol. 75, No. 5, pp. 1455-1460.

Hohldahl, S. R.; Faucher, F.; and Dragert, H., 1987, Recent vertical crustal motion in the Pacific Northwest [abstract]: *Eos (Transactions of the American Geophysical Union)*, Vol. 68, No. 44, p. 1240.

Hull, A. G., 1987, Buried lowland soils from Willapa Bay, southwest Washington–Further evidence for recurrence of large earthquakes during the last 5,000 years [abstract]: *Eos (Transactions of the American Geophysical Union)*, Vol. 68, No. 44, p. 1468-1469.

Isacks, S. M. and Molnar, P., 1971, Distribution of stresses in the descending lithosphere from a global survey of focal-mechanism solutions of mantle earthquakes: *Reviews of Geophysics and Space Physics*, Vol. 9, No. 1, pp. 103-174.

Johnson, D. M., 1980, *An Estimate of Seismic Q from the Walla Walla Earthquake of April 8, 1979*: Report prepared for the U.S. Army Corps of Engineers, Seattle District, Seattle, WA, 7 p.

Keach, R. W.; Potter, C. J.; Oliver, J. E.; and Brown, L. D., 1986, Cenozoic active margin and shallow Cascades structure–COCORP results from western Oregon [abstract]: *Geological Society of America Abstracts With Programs*, Vol. 18 , p. 652.

Krinitsky, E. L. and Chang, F. K., 1988, Intensity related earthquake ground motions: *Bulletin of the Association of Enginnering Geologists*, Vol. 25, No., 4, pp. 425-435.

Krinitsky, E. L.; Chang, F. K.; and Nuttli, O. W. 1988, Magnitude-related earthquake ground motions: *Bulletin of the Association of Engineering Geologists*, Vol. 25, No. 4, pp. 399-423.

Kulm, L. D. (editor), 1984, *Western North American Continental Margin and Adjacent Ocean Floor off Oregon and Washington, Atlas 1 Ocean Margin Drilling Program, Regional Atlas Series*, Marine Science International, Woods Hole, MA, 32 sheets.

Kulm, L. D. and Fowler, G. A., 1974, Cenozoic sedimentary framework of the Gorda-Juan de Fuca plate and adjacent continental margin–A review. In Dott, R. H., Jr., and Shaver, R. H. (editors), *Modern and Ancient Geosynclinal Sedimentation*: Society of Economic Paleontologists and Mineralogists Special Publication 99, pp. 212-229.

Langston, C. A., 1981, A study of Puget Sound strong motion: *Bulletin of the Seismological Society of America*, Vol. 71, No. 3, pp. 883-903.

Langston, C. A. and Lee, J. J., 1986, Effects of structure geometry on strong ground motions–The Duwamish River valley, Seattle, Washington: *Bulletin of the Seismological Society of America*, Vol. 73, No. 6, pp. 1851-1863.

Lisowski, M.; Savage, J. C.; and Prescott, W. H., 1987, Strain accumulation along the Cascadia subduction zone in western Washington [abstract]: *Eos (Transactions of the American Geophysical Union)*, Vol. 68, No. 44, p. 1240.

Ma, L., 1988, *Regional Tectonic Stress in Western Washington from Focal Mechanisms of Crustal and Subcrustal Earthquakes* [M.S. thesis]: University of Washington, Seattle, WA, 84 p.

Ma, L.; Crosson, R. S.; and Ludwin, R. S., 1988, Regional tectonic stress in western Washington from focal mechanisms of crustal and subcrustal earthquakes [abstract]: *Seismological Research Letters*, Vol. 59, No. 1, p. 16.

Malone, S. D., 1979, *Earthquake Monitoring in Eastern Washington, Annual Technical Report 1978*: Report prepared for U.S. Department of Energy and Washington Public Power Supply System, Richland, WA, 12 p.

Malone, S. D. and Bor, S. S., 1979, Attenuation patterns in the Pacific Northwest based on intensity data and the location of the 1872 North Cascades earthquake: *Bulletin of the Seismological Society of America*, Vol. 69, No. 2, pp. 531-546.

Malone, S. D.; Johnson-Browne, P.; McClurg, D.; Qamar, A. I.; Ramey, J.; and Thompson, K., 1987, *Annual Technical Report 1987, U.S. Dept. of Energy Contract No. EY-76-S-06-2225 Task Agreement 39*: University of Washington Geophysics Program, Seattle, WA, 80 p.

Malone, S. D.; Rothe, G. H. III; and Smith, S. W., 1975, Details of micro-earthquake swarms in the Columbia Basin, Washington: *Bulletin of the Seismological Society of America*, Vol. 65, No. 4, pp. 855-864.

Michaelson, C. A. and Weaver, C. S., 1986, Upper mantle structure from teleseismic P-wave arrivals in Washington and northern Oregon: *Journal of Geophysics Research*, Vol. 91, No. B2, pp. 2077-2094.

Moore, J. L., 1965, *Surficial Geology of the Southwestern Olympic Peninsula* [M.S. thesis]: University of Washington, Seattle, WA, 63 p.

Myers, C. W. and Price, S. M. et al., 1979, *Geologic Studies of the Columbia Plateau–A Status Report*: Rockwell Hanford Operations, Richland, WA, Report No. RHO-BWI-ST-4, 541 p., 53 plates.

National Bureau of Standards, 1978, *Tentative Provisions for Development of Seismic Regulations for Buildings, ATC-3-06*: National Bureau of Standards Special Publication 510, Washington, DC, p. 55, 68.

Nelson, A. R., 1987, Apparent gradual rise in relative sea level on the south-central Oregon coast during the late Holocene–Implications for the great Cascadia earthquake hypothesis [abstract]: *Eos (Transactions of the American Geophysical Union)*, Vol. 68, No. 44, p. 1240.

Nile, S. W., 1960, The Hebgen Lake earthquakes: *Billings Geological Society, 11th Annual Field Conference*, Billings, MT, pp. 24-30.

Nishimura, C.; Wilson, D. S.; and Hey, R. N., 1984, Pole of rotation analysis of present-day Juan de Fuca plate motion: *Journal of Geophysical Research*, Vol. 89, No. B12, pp. 10283-10290.

Noson, L. L.; Qamar, Anthony; and Thorsen, G. W., 1988, *Washington State Earthquake Hazards*: Washington Division of Geology and Earth Resources Information Circular 85, Olympia, WA, 77 p.

Owens, T. J.; Crosson, R. S.; and Hendrickson, M. A., 1988, Constraints on the subduction geometry beneath western Washington from broadband teleseismic waveform modeling: *Bulletin of the Seismological Society of America*, Vol. 78, No. 3, pp. 1319-1334.

Page, R., 1968, Focal depths of aftershocks: *Journal of Geophysical Research*, Vol. 73, No. 12, pp. 3897-3903.

Plafker, G., 1969, *Tectonics of the March 27, 1964 Alaska Earthquake*, [Chapter I of] The Alaska Earthquake, March 27, 1964—Regional Effects: U.S. Geological Survey Professional Paper 543-I, pp. I1-I17.

Plafker, G. and Savage, J. C., 1970, Mechanism of the Chilean earthquakes of May 21 and 22, 1960: *Geological Society of America Bulletin*, Vol. 81, No. 4, pp. 1001-1030.

Qamar, Anthony; Ludwin, R. S.; Crosson, R. S.; and Malone, S. D., 1987, *Earthquake Hypocenters in Washington and Northern Oregon–1982-1986*: Washington Division of Geology and Earth Resources Information Circular 84, Olympia, WA, 78 p.

Qamar, A. I. and Stickney, M. C., 1983, *Montana earthquakes 1869-1979*: Montana Bureau of Miners and Geology Memoir 51, 79 p., 3 plates.

Raisz, E., 1945, The Olympic-Wallowa lineament: *American Journal of Science*, Vol. 243A, pp. 479-485.

Rasmussen, N. H.; Millard, R. C.; and Smith, S. W., 1974, *Earthquake Hazard Evaluation of Puget Sound Region, Washington State*: University of Washington Geophysics Program Seattle, WA, 99 p.

Rau, W. W., 1973, *Geology of the Washington Coast between Point Grenville and the Hoh River*: Washington Division of Geology and Earth Resources Bulletin 66, Olympia, WA, 58 p.

Rau, W. W. and Grocock, G. R., 1974, *Piercement Structure Outcrops along the Washington Coast*: Washington Division of Geology and Earth Resources Information Circular 51, Olympia, WA, 7 p.

Reidel, S. P., 1984, The Saddle Mountains–The evolution of an anticline in the Yakima fold belt: *American Journal of Science*, Vol. 284, No. 8, pp. 942-978.

Reinhart, M. A. and Bourgeois, J., 1987, *Distribution of anomalous sand at Willapa Bay, Washington–Evidence for large-scale landward-directed processes [abstract]*: Eos (Transactions of the American Geophysical Union), Vol. 68, No. 44, p. 1469.

Richter, C. F., 1956, *Elementary Seismology*: W.H. Freeman and Company, Inc., San Francisco, CA, 768 p.

Riddihough, R. P., 1977, A model for recent plate interactions off Canada's West Coast: *Canadian Journal of Earth Sciences*, Vol. 14, No. 3, pp. 384-396.

Riddihough, R. P., 1984, Recent movements of the Juan de Fuca plate system: *Journal of Geophysical Research*, Vol. 83, No. B8, pp. 6980-6994.

Rogers, G. C., 1983, *Seismotectonics of British Columbia* [Ph.D. thesis]: University of British Columbia, Vancouver, BC, Canada, 247 p.

Rogers, G. C. and Hasegawa, H. S., 1978, A second look at the British Columbia earthquake of June 23, 1946: *Bulletin of the Seismological Society of America*, Vol. 68, No. 3, pp. 653-675.

Rogers, W. P., 1970, *A Geological and Geophysical Study of the Central Puget Sound Lowland* [Ph.D. thesis]: University of Washington, Seattle, WA, 123 p.

Savage, J. C.; Lisowski, M.; and Prescott, W. H., 1981, Geodetic strain measurements in Washington: *Journal of Geophysical Research*, Vol. 86, No. B6, pp. 4929-4940.

Sbar, M. L., 1983, An explanation for contradictory geodetic strain and fault plane solution data in western North America: *Geophysical Research Letters*, Vol. 10, No. 3, pp. 177-180.

Scholl, D. W., 1974, Sedimentary sequences in the north Pacific trenches. In Burk, C. and Drank, L. (editors), *The Geology of Continental Margins*: Springer-Verlag, New York, NY, pp. 493-504.

Silver, E. A., 1972, Pleistocene tectonic accretion of the continental slope off Washington: *Marine Geology*, Vol. 13, No. 4, pp. 239-249.

Smith, R. B. and Sbar, M. L., 1974, Contemporary tectonics and seismicity of the western United States with emphasis on the intermountain seismic belt: *Geological Society of America Bulletin*, Vol. 85, No. 8, pp. 1205-1218.

Snavely, P. D., Jr.; Pearl, J. E.; and Lander, D. L., 1977, *Interim Report on Petroleum Resources Potential and Geologic Hazards in the Outer Continental Shelf; Oregon and Washington Tertiary Province*: U.S. Geological Survey Open-File Report 77-282, 64 p.

Snavely, P. D., Jr. and Wagner, H. C., 1982, *Geologic Cross-Section across the Continental Margin of Southwestern Washington*: U.S. Geological Survey Open-File Report 82-459, 10 p., 1 sheet.

Spaeth, M. G. and Berkman, S. C., 1969, The tsunami of March 28, 1964, as recorded at tide stations. In *The Prince William Sound Alaska Earthquake of 1964 and Aftershocks, Vol. II*: U.S. Department of Commerce, Environmental Science Services Administration, Coast and Geodetic Survey, Washington, DC, pp. 223-307.

Stein, R. S. and Bucknam, R. C., 1965, The Basin and Range reviewed from Borah Peak, Idaho: *Earthquake Information Bulletin*, Vol. 17, No. 3, pp. 98-105.

Swanson, D. A.; Casadevall, T. J.; Dzurisin, D.; Malone, S. D.; Newhall, C. G.; and Weaver, C. S., 1983, Predicting Eruptions at Mount St. Helens, June 1980 through December 1982: *Science*, Vol. 221, No. 4618, pp. 1369-1376.

Taber, J. J., Jr. and Smith, S. W., 1985, Seismicity and focal mechanisms associated with the subduction of the Juan de Fuca plate beneath the Olympic Peninsula, Washington: *Bulletin of the Seismological Society of America*, Vol. 75, No. 1, pp. 237-249.

Tabor, R. W. and Cady, W. M., 1978, *The structure of the Olympic Mountains, Washington–Analysis of a subduction zone:* U.S. Geological Survey Professional Paper 1033, 38 p.

Tabor, R. W.; Frizzell, V. A., Jr.; Vance, J. A.; and Naeser, C. W., 1984, Ages and stratigraphy of lower and middle Tertiary sedimentary and volcanic rocks of the central Cascades, Washington–Application to the tectonic history of the Straight Creek fault: *Geological Society of America Bulletin*, Vol. 95, No. 1, pp. 26-44.

Thatcher, W., 1984, The earthquake deformation cycle at the Nankai trough, southwest Japan: *Journal of Geophysical Research*, Vol. 89, No. B5, pp. 3087-3101.

Thorsen, G. W., 1986, *The Puget Lowland Earthquakes of 1949 and 1965*: Washington Division of Geology and Earth Resources Information Circular 81, Olympia, WA, 113 p.

Tocher, D., 1975, On crustal plates: *Bulletin of the Seismological Society of America*, Vol. 65, No. 5, pp. 1495-1500.

Ulrich, F. P., 1949, Reporting the Northwest earthquake from the scientific point of view: *Building Standard Monthly*, Vol. 18, No. 6, pp. 8-16.

U.S. Army Corps of Engineers, 1981, *Earthquake Analysis of Chief Joseph Dam*: U.S. Army Corps of Engineers, Seattle District, Seattle, WA, 168 p., 3 plates.

U.S. Army Corps of Engineers, 1982, *Madigan Army Medical Center, Ft. Lewis, Washington, Geotechnical Report*: U.S. Army Corps of Engineers, Seattle District, Seattle, WA, 52 p., 3 plates.

U.S. Department of the Army, 1986, *Seismic Design Guidelines for Essential Buildings*: U.S. Department of the Army, Technical Manual TM-809-10-1, Washington, DC, 303 p.

Uyeda, S. and Kanamori, H., 1979, Back-arc opening and the mode of subduction: *Journal of Geophysical Research*, Vol. 84, No. B3, pp. 1049-1061.

Vance, J. A., 1982, Cenozoic stratigraphy and tectonics of the Washington Cascades [abstract]: Geological Society of America Abstracts With Programs, Vol. 14, No. 4, p. 241.

Wagner, H. C., 1967a, *Preliminary Geologic Map of the Raymond Quadrangle, Pacific County, Washington*: U.S. Geological Survey Open-File report 67-265, 1 sheet, scale 1:62,500.

Wagner, H. C., 1967b, *Preliminary Geologic Map of the South Bend Quadrangle, Pacific County, Washington*: U.S. Geological Survey Open-File Report 67-266, 1 sheet, scale 1:62,500.

Wagner, H. C. and Batatian, L. D., 1985, *Preliminary Geologic Framework Studies Showing Bathymetry, Locations of Geophysical Tracklines and Exploratory Wells, Sea Floor Geology and Deeper Geologic Structures, Magnetic Contours, and Inferred Thickness of Tertiary Rocks on the Continental Shelf and Upper Slope off Southwestern Washington between Latitudes 46° N and 47°30′ N and from the Washington Coast to 125°21′ W*: Washington Division of Geology and Earth Resources Open File Report 85-1, Olympia, WA, 6 p., 5 plates.

Waldron, H. H. and Galster, R. W., 1984, Comparative seismic hazards study of western Montana: *Proceedings of the Eighth World Conference on Earthquake Engineering*, San Francisco, CA: Vol. 1, Prentice-Hall, Inc., Englewood Cliffs, NJ, pp. 31-38.

Walsh, T. J., 1986, Age of deformation along the Olympic-Wallowa Lineament near Seattle, Washington [abstract]: Geological Society of America Abstracts with Programs, Vol. 18, No. 2, p. 195.

Washington Public Power Supply System, 1981, *WNP-1 Final Safety Analysis Report, Section 2.5, Geology and Seismology*: Washington Public Power Supply System, Richland, WA, Vol. 3, 11 p.

Washington Public Power Supply System, [1982-1986], *Supply System nuclear project No. 3, Final Safety Analysis Report, Section 2.5 Geology and Seismology*: Washington Public Power Supply System, Richland, WA, Vol. 4, 233 p., references, glossary, and 124 figs.

Washington State Seismic Safety Council, 1986, *Washington State Seismic Safety Council policy recommendations*; Washington State Seismic Safety Council, 2 v. [Available from Washington Division of Emergency Management]

Weaver, C. S. and Baker, G. E., 1988, Geometry of the Juan de Fuca plate beneath Washington and northern Oregon from seismicity: *Bulletin of the Seismological Society of America*, Vol. 78, No. 1, pp. 264-275.

Weaver, C. S. and Smith, S. W., 1983, Regional tectonic and earthquake hazard implications of a crustal fault zone in southwestern Washington: *Journal of Geophysical Research*, Vol. 88, No. B12, pp. 10371-10383.

West, D. O. and Caldwell, D. M., 1987, Nature of shallow Cascadia subduction zone paleoseismicity inferred from characteristics of Washington-Oregon coastline uplift [abstract]: *Eos (Transactions of the American Geophysical Union)*, Vol. 68, No. 44, p. 1468.

West, D. O. and McCrumb, D. R., 1988, Coastline uplift in Oregon and Washington and the nature of Cascadia subduction-zone tectonics: *Geology*, Vol. 16, No. 2., pp. 169-172.

West, D. O.; McCrumb, D. R.; and Kiel, W. A., 1987, Geomorphology, convergent margins, and earthquakes. In *Coastal '87–Proceedings of the Fifth Symposium on Coastal and Ocean Management*: American Society of Civil Engineers, New York, NY, pp. 3320-3331.

Weston Geophysical Research, Inc., 1976, *The 1872 earthquake–Significant data and conclusions*: Prepared under contract for United Engineers and Constructors, Inc., 5 p., and 5 appendices.

Wilson, J. R.; Bartholomew, M. J.; and Carson, R. J., 1979, Late Quaternary faults and their relationship to tectonism in the Olympic Peninsula, Washington: *Geology*, Vol. 7, No. 5, pp. 235-239.

Woodward-Clyde Consultants, 1980, *Seismic Attenuation Study for the Walla Walla Basin, Washington*: Report prepared for the U.S. Army Corps of Engineers, Seattle District, Seattle, WA, 28 p.

Yelin, T. S., 1982, *The Seattle Earthquake Swarms and Puget Basin Focal Mechanisms and Their Tectonic Implications* [M.S. thesis]: University of Washington, Seattle, WA, 96 p.

Yount, J. C.; Danbroff, G. R.; and Barats, G. M., 1985, *Map Showing Depth to Bedrock in the Seattle 30′ x 60′ Quadrangle, Washington:* U.S. Geological Survey Miscellaneous Field Studies Map MF-1692, 1 sheet, scale 1:100,000.

Zervas, C. E. and Crosson, R. S., 1986, P_n observations and interpretations in Washington: *Bulletin of the Seismological Society of America*, Vol. 76, No. 2, pp. 521-546.

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Land Subsidence in Washington

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INTRODUCTION

The occurrence of subsidence, or the lowering of the ground surface with respect to a datum plane, is classified into two broad categories: endogenic and exogenic (Prokopovich, 1979). Endogenic subsidence involves large areas of the Earth's crust and is of tectonic origin. Exogenic subsidence involves only the outermost portion of the Earth's surface and is commonly induced by man. Only exogenic subsidence will be discussed in this paper.

We investigated six types of exogenic subsidence that might occur in Washington:

- Hydrocompaction, or subsidence due to the wetting of soils
- Subsidence due to fluid withdrawal from both confined and unconfined aquifers
- Subsidence due to the degradation of organic matter
- Subsidence due to piping
- Subsidence into cavities created by dissolution
- Mining-induced subsidence

HYDROCOMPACTION

Hydrocompaction is a type of subsidence that typically occurs in loess or wind-blown silt and alongside irrigation canals or behind dams where the water table is artificially raised.

Although hydrocompaction (also called hydroconsolidation) is common in loess in most of the United States, no cases have been reported in loess in Washington (Olson, 1979). In fact, road cuts in the Palouse Formation commonly stand vertical for decades. Two principal reasons for this are: (1) the composition of the cementing agent in the loess and (2) the history of the loess since its deposition.

Montmorillonite is the primary cement in loesses of the mid-western states, whereas illite, with only trace amounts of montmorillonite, comprises the primary cement in the Palouse Formation of eastern Washington (Lobdell, 1981). The ability of montmorillonite to absorb water in its crystal lattice on wetting causes a loss of strength and results in collapse at any points of contact between grains in loess. Research shows that illite can absorb less than half the amount of water that montmorillonite can, making illite-cemented soils much less susceptible to hydrocompaction than montmorillonite-cemented soils.

Another reason why the Palouse loess is less sensitive to hydrocompaction than other loesses may be due to its environmental history. Olson (1979) attributes the stability of the Palouse Formation to the possibility that it has been subjected to previous wetting. Dry densities of 95-98 pcf (1,520-1,568 kg/cu m) at porosities of 42 to 44 percent were reported by Lobdell (1981) for Palouse loess; in contrast, mid-west loesses have dry densities of 70 to 90 pcf (1,120-1,440 kg/cu m). The relative difference in density may indicate prior compaction of Palouse loess, possibly due to wetting.

Loess in western Washington is also stable. Thorsen (1987) attributes the stability both to prior wetting and compaction by overriding glaciers.

The only hydrocompaction of any significance has occurred in coal mine spoils. A residence near Bellingham suffered foundation damage due to hydrocompaction of the mine dump from the Rocky Ridge mine. Another instance of hydrocompaction of mine spoils occurred in the town of Black Diamond, where a settlement of fill over a period of several months in 1987 caused a burn barrel to sink below the previous ground level.

FLUID WITHDRAWAL

Fluid withdrawal from confined and semiconfined aquifers can induce subsidence. Prokopovich (1975) defined two mechanisms: (1) active or quick-response subsidence which occurs in the coarser grained sediments due to a decrease in artesian head and a corresponding increase in effective load, causing a readjustment of pore pressures and rapid compaction and subsidence; and (2) residual subsidence, which occurs in the finer grained sediments due to a decrease in piezometric head; this increases the effective gravitational load and leads to dewatering into the adjacent aquifer, causing a decrease in pore pressures and gradual compaction subsidence, particularly in highly compressible sedimentary rocks. Dewatering of aquitards is accompanied by the additional stress of vertical seepage (Poland, 1981). Holzer (1984) suggests that extension due to horizontal capillary pressure and localized differential compaction also occur and lead to surface rupture. These types of subsidence can be widespread and can result in a large lowering of ground surface. Subsidence in California's San Joaquin Valley affects 13,500 sq km and reached a maximum of 28 ft (Poland, 1981).

Subsidence due to oil withdrawal at the Wilmington oil field in southern California caused noticeable effects over an area of 41 sq km, lowered Terminal Island completely below sea level, and reached a maximum of 29 ft (Kopper and Finlayson, 1981). Many instances of subsidence due to fluid withdrawal from confined aquifers have been reported throughout the United States (Poland, 1981), but none has been reported in the state of Washington. There are currently no producing oil or gas fields in the state, and the ones that produced in the past were small (McFarland, 1983). The principal areas of ground-water mining occur in the Columbia Basin where water is withdrawn from semiconfined aquifers in flowtop breccias of Columbia River basalt and in interbedded gravel. Because the porosity in these rocks is due largely to vesiculation, pores are rigid and do not adjust to the lowering of hydrostatic pressure. Also, because the overlying and underlying basalts are dense and have extremely low porosities, ground water does not seep into the aquifer as it does from shales. Therefore, the basalt aquifers are not subject to either active or residual subsidence.

DEGRADATION OF ORGANIC MATTER

Subsidence due to organic matter degradation commonly occurs by the draining and subsequent oxidation of peaty soils, by the overloading of peaty soils, or by the use of organic matter, usually logging slash, in construction site fills.

Peaty deposits are fairly common in Washington state and, although easily recognized, still have been the sites of local but costly subsidence-induced damage. For example, a small parking lot in western Washington was recently built on a scarified peat bed and immediately began to subside. Removal of the fill material was required, at a substantial cost.

Subsidence is also known to occur where logging slash is disposed of in fill for building pads for homes or in fills for log haul roads. Within a few years the slash begins to decay, and eventually subsidence occurs, causing structural damage to houses or failure of road fills. Because burial of slash in a construction fill is unlikely to be documented, the potential for this type of failure is difficult to predict and is often only hypothesized because no other mechanism seems likely. If rotting slash is not deeply buried, however, this failure mechanism can sometimes be observed; it was noted by geologists from the Washington Division of Geology and Earth Resources in a housing development near Olympia in 1982.

PIPING

Subsidence due to piping in natural materials is rare, whereas failures along sewer lines and water mains are fairly common.

Fredricksen (1936) reported 18 in. of subsidence over an area of 320 by 325 ft in Bellingham, Washington. Although a portion of the affected area is underlain by a coal mine, the mine is located at a depth of 496 ft below the surface in a well indurated Tertiary sandstone unit. No evidence could be found within the then-active mine to suggest that mine collapse was the cause of subsidence. Deposits of fine sand at the emergence of springs from the overlying glacial unit suggested winnowing of the sand from a gravel unit overlying a relatively impermeable clay. Fredricksen concluded that the subsidence was caused by the washout of the sand matrix, suggesting that natural piping within the sand and gravel and subsequent collapse of pipes were the cause of this subsidence.

A more frequent and more significant type of subsidence due to piping, particularly in urban areas, is the outwash of fills and natural unconsolidated sediments into ruptured pipes. Sewer mains rupture for many different reasons, such as deterioration brought on by age, by the buildup of caustic acids (most notably sulfuric acid) due to inadequate flushing of sewage, or by earthquake damage. Several recent examples illustrate the seriousness of the problem.

In March of 1986 a sinkhole 40 ft across appeared in Hudson Street in Longview, Washington. The subsidence was attributed to failure of a sewer line that subsequently acted as a vacuum and sucked the fill from under the street and into the sewer. Temporary repairs were made at a cost of more than $150,000, but the sewer failed again 9 months later. Eventually 1,000 sq ft of concrete street and 75 ft of sewer line had to be replaced (The Olympian, 1986).

In another incident, 20 to 25 cy of sand and gravel was washed down a sewer line from beneath a busy street in Lacey, Washington, nearly resulting in a collapse. The cave-in was first recognizable only as a manhole-size hole in the pavement (Figure 1); however, closer examination revealed that a cavity 19 ft deep and 10 ft across had formed beneath the street. The sewer line had deteriorated as a result of attack by sulfuric acid formed from hydrogen sulfide gas being emitted by slow moving or stagnant sewage. The failure was in a 21-in. reinforced concrete pipe at a depth of 19 ft. Repair was costly, as not only did the pipe need to be relined but downstream sewage lines also had to be purged of gravel deposits. Ventilation of the lines is recommended to prevent future damage from occurring.

Figure 1. Surface expression of piping-induced cavity beneath street in Lacey, Washington. The 3-ft-diameter hole opens to a 10-ft-diameter, 19-ft-deep hole beneath a heavily travelled street. Note base of road barriers at top for scale.

One of the most spectacular incidents of sewer piping occurred in Seattle in November 1957 (Haldeman, 1986). Downwarping of a few feet of the median strip of Ravenna Boulevard was noted the first evening, but by the next morning a pit 100 ft long, 66 ft wide, and 40 ft deep occupied what had been a quiet neighborhood street. It was speculated that a 6-ft-wide sewer main located 145 ft below the street level had failed, possibly from cracking developed in the 1949 earthquake. The damaged main eventually provided a passageway for thousands of cubic yards of Quaternary glacial sediments to be flushed away. Trapped sediment and debris moved through the main, blowing manhole covers into the air, flooding homes and businesses in adjacent neighborhoods, and causing subsidence in other areas. Within 3 days the pit had grown to 200 ft in length, 175 ft in width, and 60 ft in depth. A slurry of sand and water occupied the pit floor and was eventually stabilized by using the Joosten Process of forcing a mixture of sodium silicate and calcium chloride into the slurry, causing it to harden. After a bypass was successfully completed, 17,000 cy of fill was used to plug the pit. More than $2 million was spent to rehabilitate the area.

Subsidence of this type can exact a high toll and necessitates increased maintenance on the part of municipalities. Spokane has recently launched a 7-yr program to line their entire sewer system at a cost of $2.8 million (Laughtland, 1987). Such costs pale next to the costs of damage and potential liability at a collapsed city intersection.

Broken water mains are also a common cause of subsidence, again in urban areas where repairs are usually very costly. One such failure occurred in downtown Seattle, Washington, in February 1987 (The Olympian, 1987). A hole about 50 ft wide and 8 ft deep forced closure of downtown streets and interruption of gas, power, water, and sewer service to nearby businesses. Damages were estimated to be well into six figures in one affected building alone.

DISSOLUTION

Subsidence due to dissolution occurs in rocks that are highly water soluble, such as halite or gypsum, or in rocks that are soluble in weak acids, such as limestone. Rocks of the highly water-soluble variety are rare in Washington, but limestones do occur. Many small areas of the state have developed karst topography (Figure 2), and a number of caves have formed by limestone dissolution, the largest of which, Gardner Cave, has a slope length of 1,050 ft (Halliday, 1963).

The limestone areas of Washington are mostly restricted to the sparsely populated northern part of the state, in a discontinuous belt from the San Juan Islands to the Okanogan Highlands. The other areas are either insignificantly small or are restricted to sparsely populated areas of high elevation in the Cascade Range. Because many of the limestone units consist of steeply dipping strata, their extent is usually restricted to long narrow areas. Because of the small area, pattern of exposure, and sparse population, subsidence due to limestone dissolution creates no damage to structures and generally goes unnoticed in Washington.

MINING-INDUCED SUBSIDENCE

Subsidence related to coal mining is a significant problem worldwide and constitutes the principal subsidence hazard in Washington, at least in terms of total affected acreage. Mine maps on file at the Washington Division of Geology and Earth Resources (Schasse et al., 1983) document that underground coal mine workings underlie at least 50,000 acres in western and central Washington, in both rural and urban areas. Additional acreage is affected by small mines and prospects for which there are no records. Outcrop and shallow subsurface geologic data are sufficient to estimate coal reserves for an area in Washington of approximately 250,000 acres (Figure 2). Although most of this area is not underlain by mines or prospects, it represents the maximum potential extent of mines and prospects.

The types of subsidence that occur depend on the method of mining and on the character of the coal deposit. Therefore, evaluation of subsidence requires an understanding of the historical development of the mines and mining methods in order to predict where areas of instability may lie.

Coal Mining Methods

Coal mining methods used in Washington are summarized by Evans (1912), Green (1943), and Magill and Associates (1979), from whom the following discussion is drawn. In the early days of mining, coal was usually

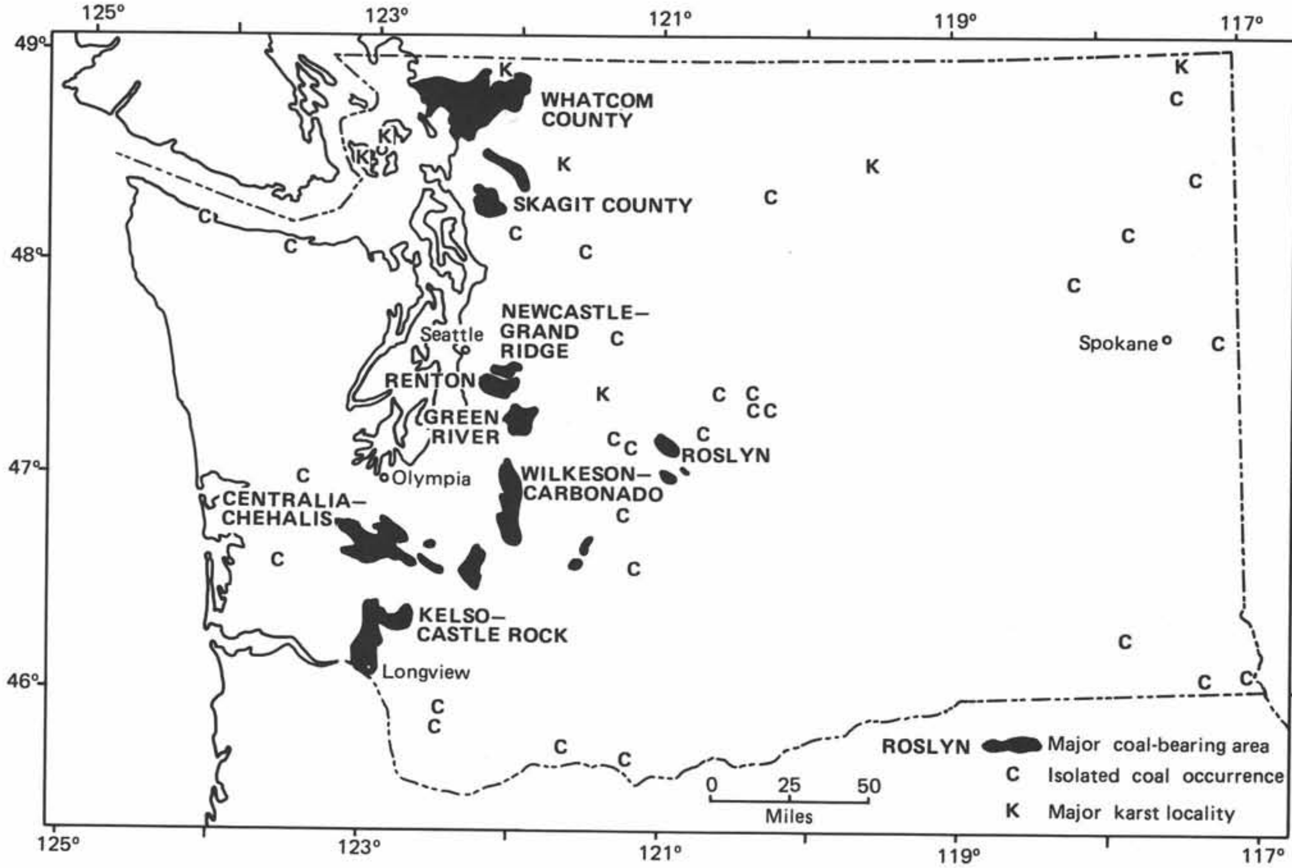

Figure 2. Coal-bearing areas of Washington and areas of karst topography. Modified from Beikman et al. (1961) and Halliday (1963).

accessed by a water-level drift driven into a hillside from a stream valley. The drift had a slope toward the stream of less than one degree to facilitate drainage and to allow loaded cars a downslope trip and empty cars the upslope trip. The drift was driven approximately at the top of the static water level and allowed the mine to be self-draining. Only coal topographically higher than the drift could be worked by this method, so drift mines, or water-level mines, were usually limited to one or two levels.

Once coal was worked out of the drift mine, the coal usually had to be mined from a slope. A slope was driven on the full dip of the coal seam unless the seam dipped more steeply than approximately 50 degrees, in which case an oblique slope was driven. In larger mines, a companion slope was also driven for air circulation. At some mines, in order to have the mine entry in an advantageous location to load the coal (such as on tidewater or at a railroad), the slope was reached through a rock tunnel. Rock tunnel entries were also used to reach the coal seam subcrop beneath glacial deposits and to access coal downdip of older mine workings.

Coal in Washington has traditionally been mined by the methods of room and pillar (also known as breast and pillar), chute and pillar, and by booming. Longwall methods have been attempted in several mines but were not successful. Figure 3 shows the terms in use locally for various features of underground mines.

The room and pillar method is used in shallowly dipping coal seams. Nearly horizontal gangways are driven along the strike of the coal seam; a parallel tunnel updip is called the counter. The gangway is a haulage tunnel, and the counter is a return airway. Every 40 to 70 ft along strike, the two tunnels are connected by chutes from 4 to 10 ft wide. Updip of the counter, the chute is widened into a room (called a breast in more steeply dipping seams); coal is left between the rooms in blocks called pillars. In chute and pillar mining, chutes as much as 12 ft wide are driven up the dip, blocking out larger pillars. In both methods, pillars are eventually removed by cutting off slices or skips. If pillars can be completely removed (complete extraction), thereby eliminating all support, the roof can be collapsed, resulting in nearly immediate but even, controlled subsidence. If parts of the pillars must be left (partial extraction), the eventual subsidence may be postponed for decades, and the timing cannot be predicted (Kratzsch, 1986). A third method of mining used in Washington is a variant of either of the above, called booming. It is used where the coal seam is too thick for the roof to be securely tim-

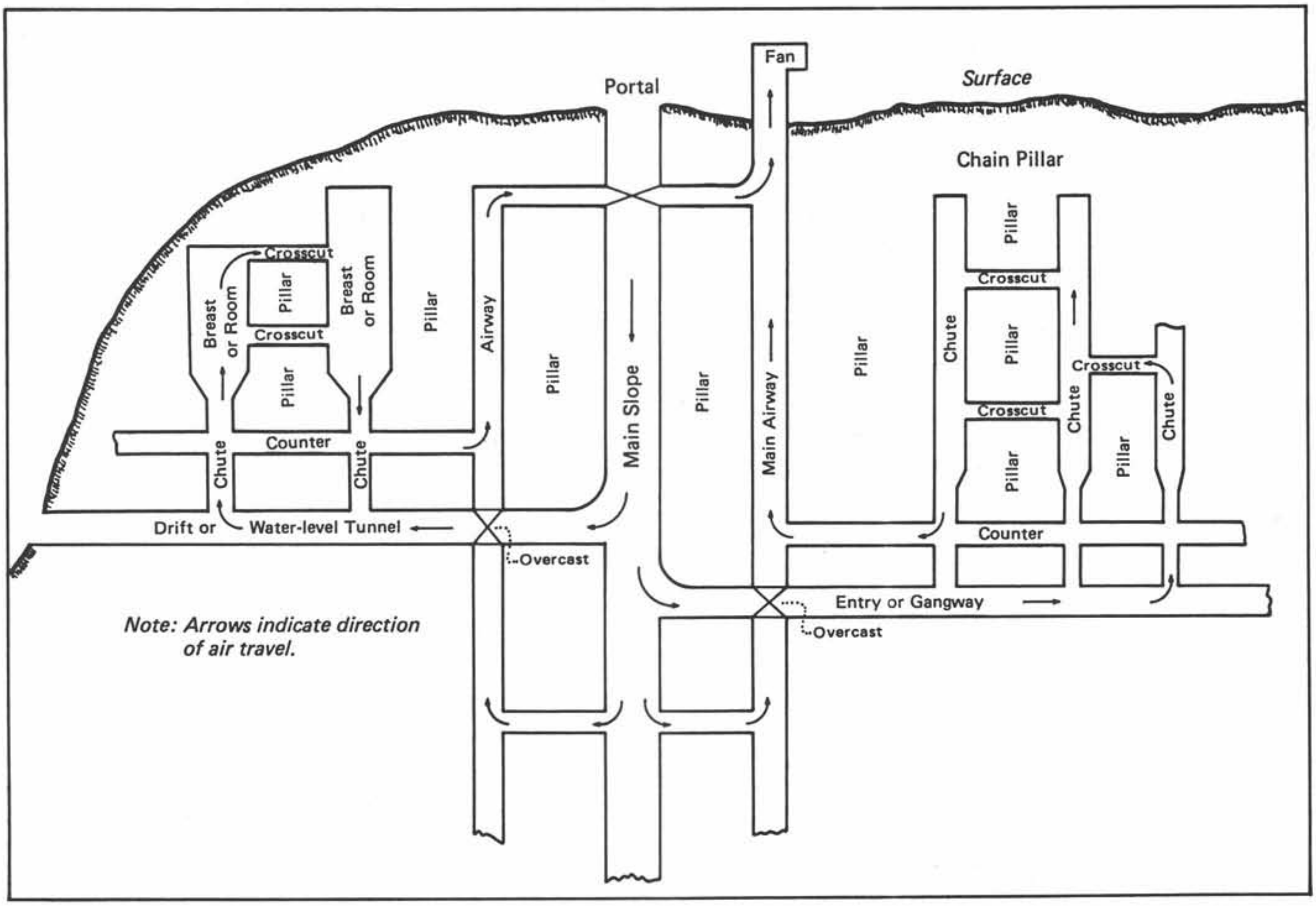

Figure 3. Diagram of features of underground coal mines and terminology in use in Washington. Modified from Green (1943).

bered (Green, 1943). In this method, the coal is shot from the pillar with explosives, and the roof is supported only by low wooden bulkheads to prevent complete collapse. This method frequently led to uncontrolled subsidence.

Coal was mined either while advancing or retreating. If mined on advance, pillars were blocked out, and skips were taken as the working face was extended. In retreat mining, the mine was developed to its maximum extent, and the pillars were blocked out and pulled from the outside in. This allowed for greater recovery, but if economic conditions forced the shutdown of a mine already blocked out for retreat mining, it would be abandoned with pillars remaining, which would leave only partial roof support that was not designed for permanent use.

Types of Coal Mine Subsidence

We include under coal mine subsidence both areal subsidence, or the general sagging of the ground surface, and cave-ins. Subsidence into a coal mine can occur in several ways. If the roof is weak, it will fall in blocks and leave a rubble on the floor. Successive roof falls occur until the void is filled. Because the rubble has a greater bulk than the undisturbed roof rock, the volume of roof fall necessary to fill the void is less than the volume of original void, and the maximum subsidence is less than the vertical extent of the mined horizon. Because the bulking factor depends on the shape, size, amount of rotation, and strength of overburden rock (Dunrud, 1984), prediction of subsidence depends on detailed information about the overburden. The maximum thickness of an individual roof fall is controlled by the vertical and horizontal dimensions of the void, and also by the shape, but is typically between 70 percent and 95 percent of the thickness of the coal seam for a single roof fall (Kratsch, 1983). If the roof fall remains on the floor, the void will be filled by a few roof falls, and the overburden will be partially supported. Above this, the overburden will sag but will break no further. In some mines, however, the roof fall occurs above a slope or above a steeply dipping floor. If the surface is steep enough, the rubble will continue to slough downslope, and the roof fall can stope to the surface, regardless of the thickness of overburden. Subsidence also can reach the surface from deeper voids if more than one seam is mined. Then the subsidence can be additive. If the void is very close to the surface, the entire overburden can collapse at once. This is called a crop fall.

Subsidence can occur by the plunging of a pillar into an incompetent underclay. This results in uplift of the floor adjacent to the pillar into the void space.

Pillars can also fail by crushing, since they bear the entire lithostatic load over a smaller area than was the case before mining, and they are laterally unsupported.

The surface expression of these types of subsidence depends on the physical properties of the overburden but is generally of two types, trenches and pits or sinkholes. Pits characteristically form above roof failure of a room or breast, and trenches form above failed pillars (Gray and Bruhn, 1984).

Another type of subsidence associated with underground coal mines is the failure of slope entries and airways or the fills with which they were plugged. Tree stumps and car bodies are commonly dumped into steeply dipping tunnels to anchor fills that are then merely bulldozed into the hole. Inevitably, the anchors will slip downslope or the tree stumps will rot, although the failure may be postponed for a generation.

Coal Mining in Washington

Although it was discovered much earlier, coal was first mined near Bellingham in 1853 (Beikman et al., 1961). In 1854, mines were opened near Renton and Issaquah, and by 1887 coal mining was a major industry in Washington Territory, with mines also operating in the Skagit River valley, near the towns of Roslyn and Cle Elum in central Washington, in the vicinity of Black Diamond in King County, and near Wilkeson and Carbonado in Pierce County (Figure 2). In 1887, the first report was published by the newly established office of the Territorial Mine Inspector. Initially, the powers of the office were limited, and it was not until the turn of the century that detailed mine maps began to be filed with the mine inspector. Eventually, all mine operators filed annual progress maps at a scale of 1 in. = 100 ft. This map collection, numbering more than 900 maps, is housed at the office of the Washington Division of Geology and Earth Resources (Schasse et al., 1983). These maps constitute an invaluable source of geological and engineering data on the coal resources of Washington, but they do not cover the first half-century of the coal mining industry, when more than 20 million tons of coal were taken from underground mines.

The coal fields of the state that are most important in a discussion of urban mine subsidence are Whatcom County, Newcastle-Grand Ridge, and Renton (Figure 2). Other coal fields, such as Wilkeson-Carbonado, Roslyn, and Centralia-Chehalis (Figure 2) are responsible for considerable subsidence but are largely located in rural areas. There also are numerous smaller coal areas that can cause localized subsidence hazards.

Whatcom County Area

The Whatcom County area consists of scattered coalfields of varyied sizes, isolated from each other by cover of glacial drift. The largest and most important of these is the Bellingham field. There have been two mines and several prospects in this field, dating to the discovery of these coal measures in 1852 by a Captain Pattle. Pattle and two partners located and later sold claims in the south part of Bellingham, but their work never resulted in a commercial mine (Jenkins, 1923). In 1853, two loggers named Brown and Hewitt discovered a seam of coal in the roots of an uprooted tree at what was then called Sehome, and it was this discovery that led to the first mine (Landes, 1902). The Bellingham Bay Coal Company was created to mine the seam, which was named the Bellingham #1. The entry to the mine was located at what is now the corner of Myrtle Street and Railroad Avenue (Jenkins, 1923). No map of the mine is available, but the narrative descriptions of Goodyear (1877) and Watson (1887) permit reconstruction (Figure 4). Because this reconstruction is only approximately located, areas of potential subsidence are poorly known. It is also not known how near the surface the mine was worked. Jenkins (1923) reported that the barrier pillars left to support the surface were only 20 ft thick, but the thickness of glacial deposits overlying the coal measures is unknown. Because recessional glacial outwash will have less strength than the Eocene sandstones overlying the coal, the thickness of these deposits is important for delineating areas of subsidence risk.

Jenkins (1923) reported that there was considerable trouble with subsidence that required concrete arches to support buildings, particularly near the intersection of Holly Street and Railroad Avenue. Subsidence-induced structural damage has been noted in a number of older buildings above the mine, but newer construction is unaffected (Tetra Tech, Inc., 1984). Whether this implies that there is no remaining void space associated with the mine is not known.

In 1918, a new mine was opened on the Bellingham #1. It operated almost continuously until 1955, with a total production of about 5-1/4 million tons of coal (LaSalata et al., 1985). Figure 4 shows the locations and elevations of the main passageways of the mine. Subsidence has been reported at several sites over the mine, although the workings are deeper than would normally be thought of as capable of producing surface effects. These subsidences have not been investigated in detail, and there is some question as to whether they are truly mine-related (Batchelor, 1982; Tetra Tech, Inc., 1984). Nonetheless, there are significant areas overlying the mine which are probably unstable and capable of producing surface effects.

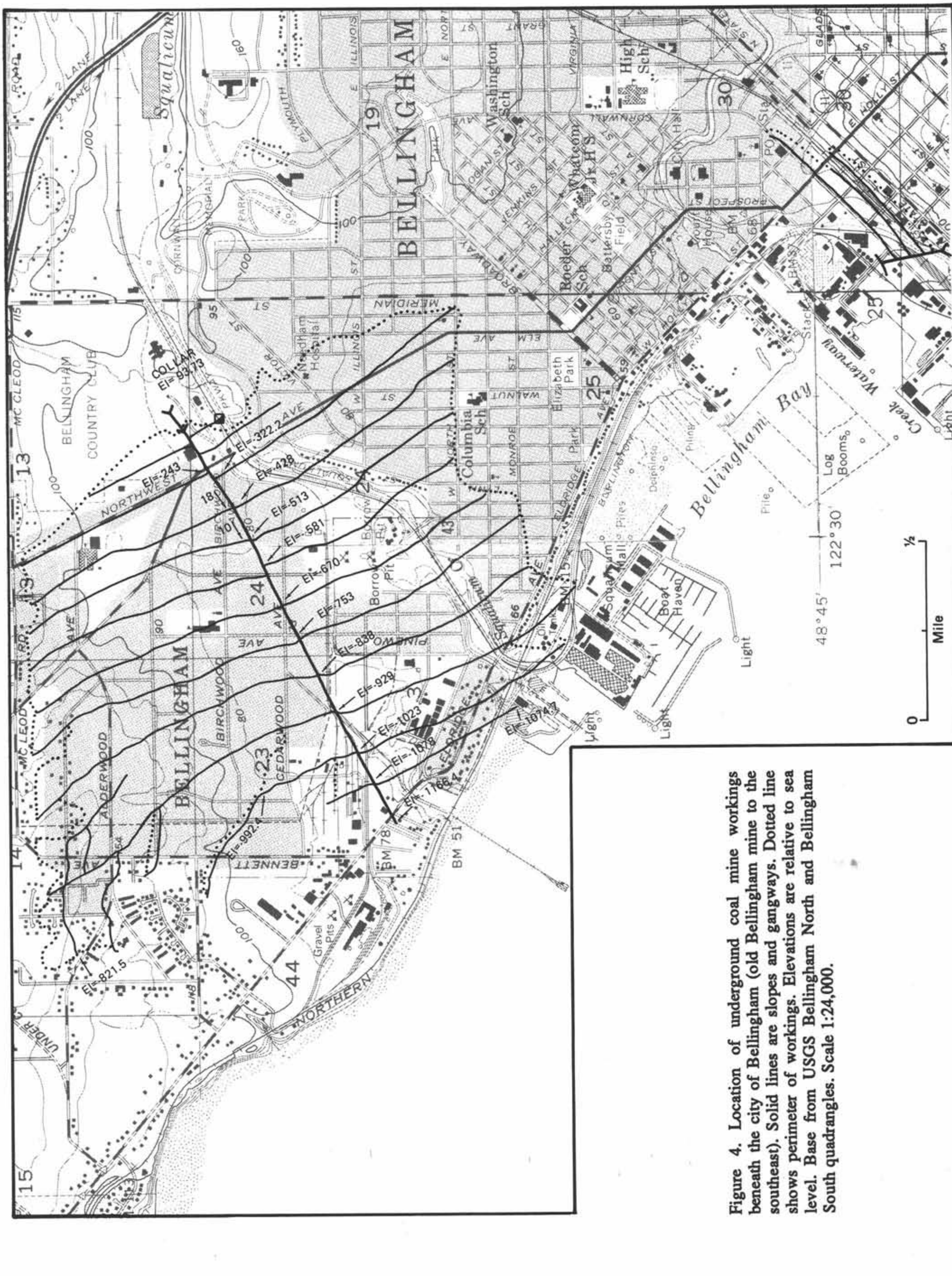

Figure 4. Location of underground coal mine workings beneath the city of Bellingham (old Bellingham mine to the southeast). Solid lines are slopes and gangways. Dotted line shows perimeter of workings. Elevations are relative to sea level. Base from USGS Bellingham North and Bellingham South quadrangles. Scale 1:24,000.

Renton Area

Mining began in the Renton area in 1853 (Phillips and Walsh, 1981), but most of the early mining was at a small scale. In 1874, the only large mine in the area was opened; the Renton mine, which underlies a large portion of the city (Figure 5), operated until 1922. The earliest workings were reached by a slope on the side of Renton Hill. The bulk of the coal was removed via a rock tunnel which bypassed the earlier slope. This mine was developed on a seam called the Renton #3. Two other seams, #2 and #1, overlie the #3 at stratigraphic intervals of approximately 85 and 195 ft respectively (Evans, 1912). Only small mines were developed on these seams, but the workings overlie those of the main Renton mine and pose the problem both of additive subsidence and additional area underlain by shallow mine workings. Mine maps for this area show the workings through 1922 but are badly damaged, making location of subsurface features suspect. Additionally, third mining or pillar robbing was done in this area at least through 1948 (LaSalata et al., 1985), but we have no maps of this.

Subsidence has been noted in Renton at least since 1965 (Mullineaux, 1965) and continues through the present (Table 1). Morrison-Knudsen Co., Inc. (1985) found six areas in Renton where subsidence had occurred. These included crop falls and fill failures, and one was a composite failure probably caused by ground water piping into a mine void, causing a loss of fill material into the mine.

Newcastle-Grand Ridge Area

The first mine in this area was located in the hillside just west of Issaquah in 1854 but was soon closed due to an Indian uprising (Phillips and Walsh, 1981). Later workings were opened to the west at Newcastle (Figure 6) and to the north along Grand Ridge, as well as at Issaquah (Figure 7). The only urban development in this area occurs over the Issaquah mines, and many of the original entries to the mines have been covered. A recent survey, however, reported 25 sites where subsidence was visible (Goodson and Associates, 1984). At least eight of these subsidences occurred since 1966. Most of these are in the Wildwood subdivision and are probably caused by crop fall into a water level entry that was abandoned in the 1950s. Although the damage from these subsidences has been slight, there is the potential for serious injury, and at least one cave-in was nearly disastrous. In 1967, a water-level tunnel collapsed in a newly terraced lot. Two children playing in the hole were overcome by lack of oxygen; their father and two policeman were also overcome in attempting to rescue the children. All were finally saved by firemen with oxygen equipment (Gilley and Collaizi, 1970). Although the main problem was dead air (lack of oxygen), physicians who treated the victims reported traces of methane in their lungs (Thorsen, 1987).

Many of the mine openings were filled and drainages were altered during the development of housing in this area and the quality of closures is not known (Goodson and Associates, 1984). It is likely that failure of these closures will lead to future subsidences in Issaquah.

Table 1. Mine-subsidence reclamation projects performed by OSMRE since enactment of SMCRA, 1977-1988. Failure types: 1, failure of fill in a shaft, slope, or rock tunnel; 2, cave-in due to roof fall; 3, sag due to roof fall; 4, hydrocompaction of spoil.

Project name	Mine name	Location	Date	Failure type
Engel	Wonder	SW/4 28(22-7)	2-79	2
Bevan	Burnett	S/2 16(19-6)	6-79	2
Campbell	Burnett	S/2 16(19-6)	5-81	1
Burdic	Wonder	SW/4 28(22-7)	9-81	1 or 2
Lake Whatcom	Rocky Ridge	SW/4 31(38-4)	11-82	2
Noorani	Denny-Renton	SW/4 17(23-5)	11-82	1
Gatto	Burnett	S/2 16(19-6)	2-82	1
May Creek	May Valley	SE/4 2(23-6)	6-82	2?
Beacon Hill	Beacon Hill	NE/4 14(23-4)	1-84	2
New # 12	New # 12	S/2 12(21-6)	1-84	1
Diamond	Diamond	SW/4 13(23-4)	7-84	1?
Davis	Davis	NW/4 14(21-7)	6-85	1
Denny-Renton	Renton	NW/4 20(23-5)	3-86	3?
Scott	unknown	NW/4 28(19-6)	5-87	1
Grgurich	#2	NE/4 14(21-6)	5-87	4
Koch	Rocky Ridge	SW/4 31(38-4)	9-87	4
Waterhouse	Waterhouse	NE/4 28(24-5)	2-88	1

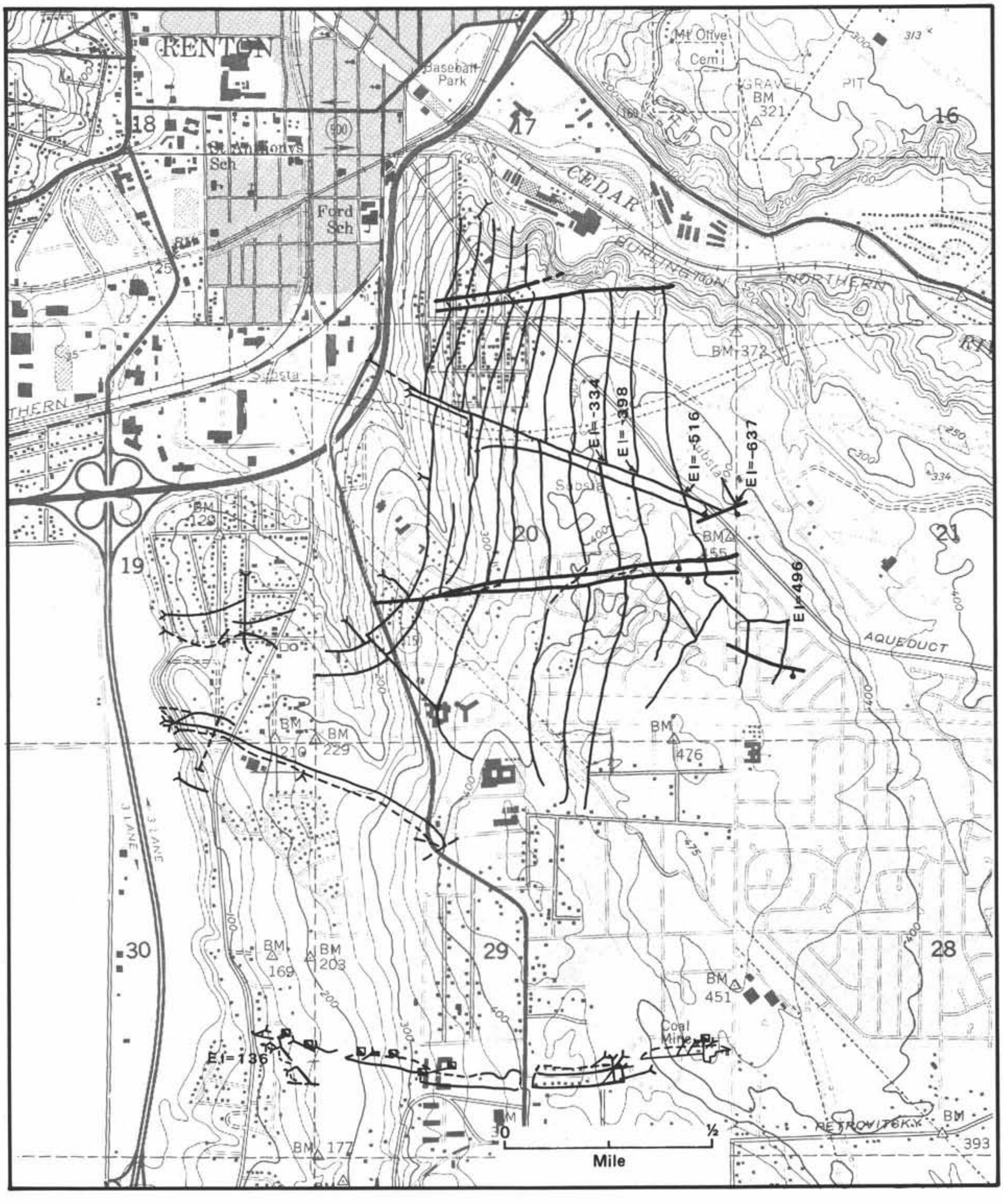

Figure 5. Location of underground coal mine workings in the vicinity of the City of Renton. Solid lines are slopes and gangways; dashed lines are rock tunnels; dotted lines are the perimeter of mine workings. Faults are shown as bolder line. In the main Renton mine, workings on upper coal seams are left off for clarity. Base from USGS Renton quadrangle. Scale 1:24,000.

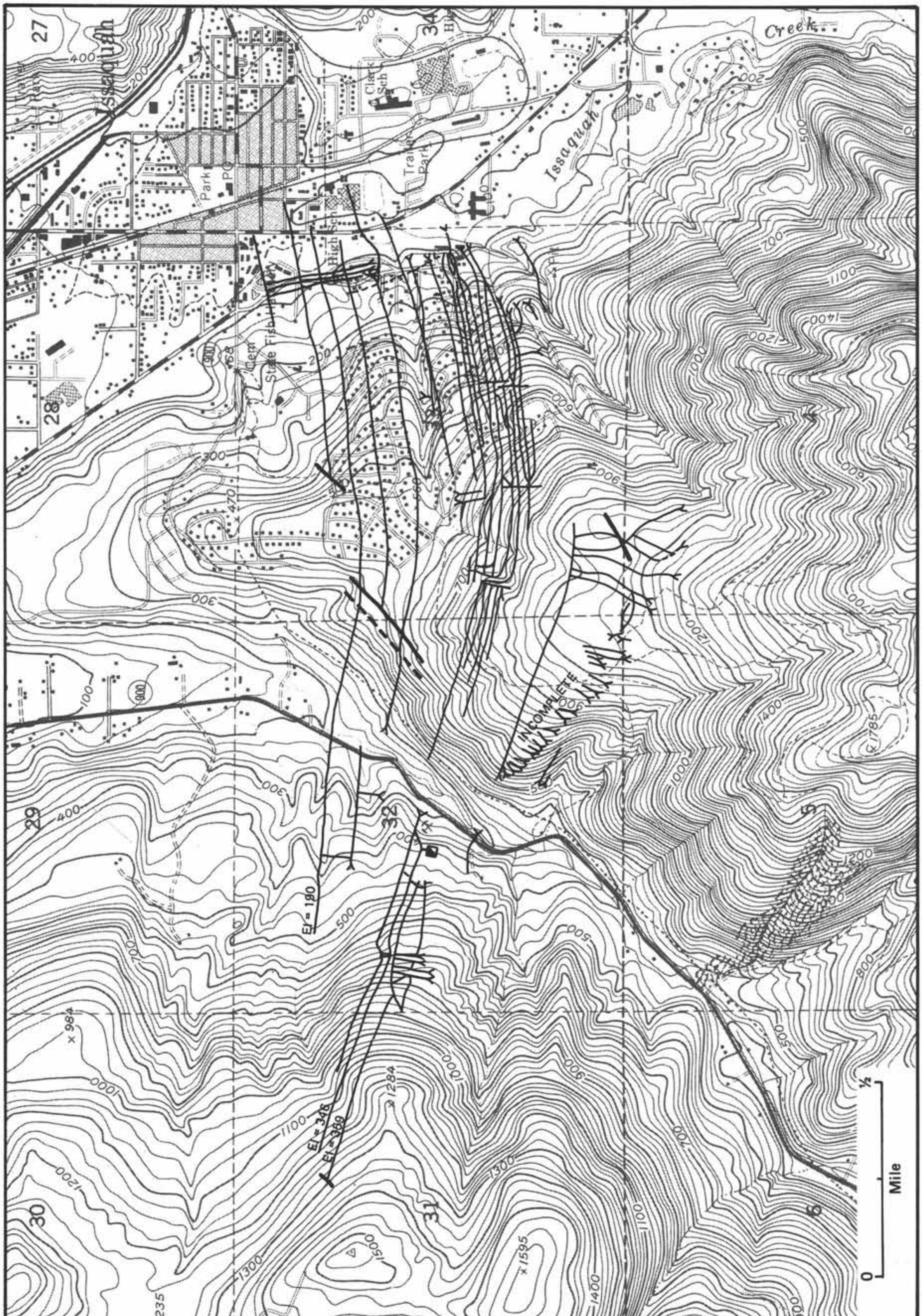

Figure 6. Location of underground coal mine workings in the Newcastle coalfield, located between the cities of Bellevue and Issaquah. Solid lines are slopes and gangways; dashed lines are rock tunnels; bolder lines are faults. Base from USGS Issaquah and Mercer Island quadrangles. Scale 1:24,000.

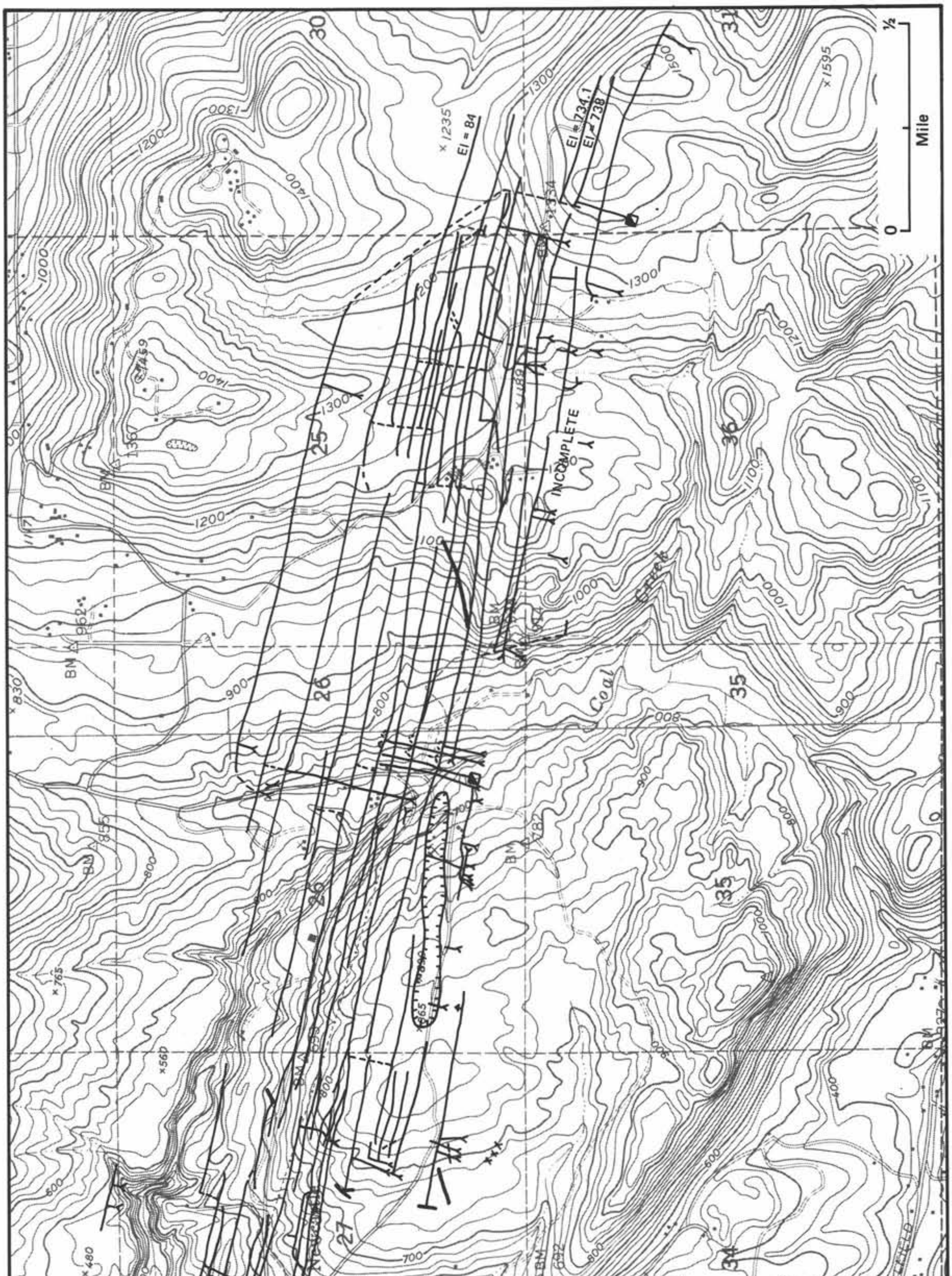

Figure 7. Location of underground coal mine workings near the city of Issaquah. Solid lines are slopes and gangways. Bolder lines are faults. Elevations are relative to sea level. Base from USGS Issaquah quadrangle. Scale 1:24,000.

Subsidence over the Newcastle mines is more readily apparent than at Issaquah; a recent survey of this area revealed 166 mine entries, airways, and subsidences (Skelly and Loy Engineers-Consultants, 1985). Mine features are more visible in part because the area has not yet been developed, in part because the coal measures have an average dip of 47 degrees and are above water level through much of the area. Because the slopes are steeper than the angle of repose, roof fall above slopes sloughs into the mines, particularly when wetted. The principal hazards at these mines are the many slopes and air shafts that remain open (Skelly and Loy Engineers-Consultants, 1985) but considerable void space remains and future development must be carefully planned not only to avoid unstable ground but also to avoid raising the water level. In steeply dipping coal measures, friction across joint surfaces normal to bedding is increased, providing a measure of stability (Dunrud, 1987). Saturating these joints may provide enough lubrication to destabilize the roof rock and cause subsidence. Urbanization is encroaching on the Newcastle field, however, resulting in increased subsidence hazard. Recently, an abandoned prospect (Waterhouse prospect, Table 1) collapsed catastrophically beneath a house at the westernmost end of the field, damaging the house and its plumbing (Walsh, 1988).

Subsidence at the Grand Ridge mines is readily apparent in the vicinity of the entries but does not threaten any structures. There are housing developments in the vicinity, but much of the subsidence area lies beneath a main power line and development is unlikely in the near future. The northernmost part of the Grand Ridge area does contain a few homes, but these are stratigraphically below the mines. Planning for future development needs to take the mines into consideration because there are visible voids in the area (LaSalata et al., 1985) and further subsidence is possible.

Wilkeson-Carbonado Area

Subsidence in the Wilkeson coal field was first reported in 1923 (Knuppe and Sisson, 1923) and continues today. As recently as May 1987, shallow, undocumented mine workings collapsed in the back yard of a home to the west of Wilkeson and were fenced off prior to permanent reclamation (Table 1, Scott project). Most of the mine workings in this area are located in forested land and do not threaten any structures. The greatest hazards in the Wilkeson-Carbonado area are the open slopes, airways, and cave-ins into slopes and airways into which unwary hikers could fall.

Centralia-Chehalis Area

Coal was first mined in the Centralia-Chehalis area in the 1870s (Snavely et al., 1958), and workings were usually very shallow, due to gentle structure, poor roof conditions, and the economic limitation imposed by the low quality of the coal. Most of this coal field lies outside of the cities of Centralia and Chehalis, and older and current surface mines have removed the barrier pillars above some mines, leaving no subsurface voids.

There are some areas of mining within the city limits that have resulted in subsidence, most notably in Chehalis (LaSalata et al., 1985), but these are not well documented.

Roslyn-Cle Elum Area

Mining in the Roslyn area commenced in 1887 and continued through 1963. Extraction efficiency was considerably higher than in the western Washington coal fields, averaging 80 percent (Beikman et al., 1961). This results in much less roof support and earlier and more complete collapse. Voids can still be found in this coal field, and subsidence features are abundant, particularly near mine entries (Walker and Shideler, 1984; LaSalata et al., 1985). Most of the subsidence features are in forest or farmland and do not threaten any structures, although the towns of Ronald, Roslyn, and Cle Elum overlie old mine workings.

Miscellaneous Occurrences

Many small, isolated occurrences of coal exist in Washington (Figure 2). Some were mined commercially, but most were abandoned after limited shallow prospecting. These can be very troublesome because they were not likely to have been well shored; however, because of the small load carried above the void, they may not collapse for decades and usually not until a house is built on site (Figure 8). Nine of the 17 subsidences investigated since 1978 (Table 1) have been of this type.

Remediation

In 1977, Congress enacted Public Law 95-87, the Surface Mining Control and Reclamation Act (SMCRA), which provided, among other things, for the closure of abandoned underground mine openings, reclamation of coal mine-induced subsidence, and the amelioration of mine-related hazards. Funds for this work are provided by a tax on active coal mines at a rate ranging from 10 to 35 cents/ton, depending on coal rank. The act established an agency, the Office of Surface Mining Reclamation and Enforcement (OSMRE), to administer the provisions of SMCRA.

In Washington, mine reclamation is achieved by OSMRE in two ways:

(1) Emergencies, which are defined as recent, sudden events, are reclaimed on a first priority basis. These are most commonly subsidences but have included gas flows caused by a drop in hydrostatic pressure in a mine void during dry weather.

(2) Existing mine hazards were inventoried, and priorities for reclamation were established on a nationwide basis. These include sudden subsidences that have been fenced and thus are not in need of rapid reclamation.

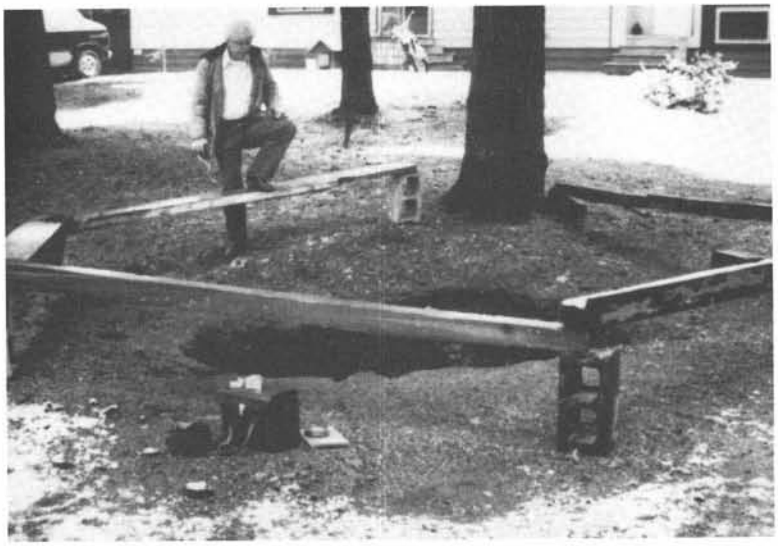

Figure 8. Cave-in over shallow mine workings. This subsidence into the Wonder mine, a small, poorly documented drift mine near Ravensdale, occurred in 1979 at the Engel home (Table 1). In 1981, a similar cave-in occurred about 1,000 ft to the north.

Funds for reclamation are allocated to those states with a federally approved surface mine regulatory program. States without such programs, such as Washington, receive funding at the discretion of the Secretary of the Interior to be expended directly by OSMRE. At present, OSMRE's reclamation expenditures in Washington are on the order of $750,000 annually. Reclamation of existing priority sites has been accomplished principally in the Roslyn-Cle Elum area, in the Newcastle coalfield, and the Wilkeson-Carbonado area. Emergency reclamation has been necessary about twice a year, chiefly for subsidence. Subsidence reclamation is summarized in Table 1.

Emergency reclamation typically is accomplished within a few weeks, but funding is available only for actual subsidence, not for repairing structural damage caused by subsidence. For this reason, prompt attention must be given to suspected coal mine subsidence before it causes damage, and contractors should consider the likelihood of future subsidence when building in areas of historic coal mining.

Local planning can help ease the potential impact of subsidence; planners are aware of mine-related hazards and can recommend construction techniques for areas affected by coal mines. King County, which has large areas underlain by abandoned coal mines, requires developers of lands designated as Coal Mine Hazard Areas to perform geotechnical studies in order to obtain building permits. King County Code 21.54.190 specifies that these studies must identify and quantify:

"1. existing underground voids resulting from previous mining activity;

"2. location and definition of all surface openings resulting from previous mining activity;

"3. location of all concentrations of lethal or noxious gases and groundwater within abandoned mine workings; and

"4. location, depth, and characteristics of all mine tailings on the surface of the site."

Any building permit issued requires, among other things, that all openings be sealed and all voids beneath building sites that present significant risk to human health, safety, and welfare be filled or otherwise remedied.

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REFERENCES

Batchelor, C. F., 1982, *Subsidence Over Abandoned Coal Mines–Bellingham, Washington* [M.S. thesis]: Western Washington University, Bellingham, WA, 122 p.

Beikman, H. M.; Gower, H. D.; and Dana, T. A. M., 1961, *Coal Reserves of Washington*: Washington Division of Mines and Geology Bulletin 47, Olympia, WA, 115 p.

Dunrud, C. R., 1984, Coal Mine Subsidence–Western United States. In Holzer, T. L. (editor), *Man-Induced Land Subsidence*: Geological Society of America Reviews in Engineering Geology, Vol. 6, pp. 151-194.

Dunrud, C. R., 1987, Personal communication, U.S. Geological Survey, Denver, CO.

Evans, G. W., 1912, *The Coal Fields of King County*: Washington Geological Survey Bulletin 3, Olympia, WA, 247 p.

Fredricksen, C. S., 1936, Ground Subsidence at Bellingham Coal Mine: *Northwest Science*, Vol. 10, No. 4, pp. 6-7.

Gilley, J. E. and Collaizi, G. J., 1970, *Investigation of Coal Mine Subsidence Problem at Issaquah, Washington*: U.S. Bureau of Mines unpublished report, Washington, DC, 22 p.

Goodson and Associates, Inc., 1984, *Abandoned Coal Mine Survey in the Area of Issaquah, King County, Washington*: Prepared for the U.S. Office of Surface Mining, Denver, CO, 77 p.

Goodyear, W. A., 1877, *The Coal Mines of the Western Coast of the United States*: A. L. Bancroft and Company, San Francisco, CA, 153 p.

Gray, R. E. and Bruhn, R. W., 1984, Coal mine subsidence–Eastern United States. In Holzer, T. L. (editor), *Man-Induced Land Subsidence*: Geological Society of America Reviews in Engineering Geology, Vol. 6, pp. 123-149.

Green, S. H., 1943, *Coal and Coal Mining in Washington*: Washington Division of Mines and Mining Report of Investigations 4, Olympia, WA, 41 p.

Haldeman, P., 1986, The great Ravenna cave-in: *Washington–The Evergreen State Magazine*, Vol. 3, No. 1, pp. 150-151.

Halliday, W. R., 1963, *Caves of Washington*: Washington Division of Mines and Geology Information Circular 40, Olympia, WA, 132 p.

Holzer, T. L., 1984, Ground failure induced by ground-water withdrawal from unconsolidated sediment. In Holzer, T. L. (editor), *Man-Induced Land Subsidence*: Geological Society of America Reviews in Engineering Geology, Vol. 6, pp. 67-105.

Jenkins, O. P., 1923, *Geological Investigation of the Coal Fields of Western Whatcom County, Washington*: Washington Division of Geology Bulletin 28, Olympia, WA, 135 p.

Knuppe, L. M. and Sisson, H. A., 1923, *Subsidence Resulting From Coal Mining Operations in the State of Washington* [B.S. thesis]: University of Washington, Seattle, WA, 72 p.

Kopper, W. and Finlayson, D., 1981 Legal aspects of subsidence due to well pumping: *Journal of the Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers*, Vol. 107, No. IR2, pp. 137-149.

Kratzsch, H., 1983, *Mining Subsidence Engineering*: Springer-Verlag, New York, NY, 543 p.

Kratzsch, H., 1986, Mining subsidence engineering: *Environmental Geology and Water Sciences*, Vol. 8, No. 3, pp. 133-136.

LaSalata, F. V.; Menard, M. C.; Walsh, T. J.; and Schasse, H. W., 1985, *Inventory of Abandoned Coal Mines in the State of Washington*: Washington Division of Geology and Earth Resources Open File Report 84-6, Olympia, WA, 42 p.

Landes, H., 1902, *The Coal Deposits of Washington*: Washington Geological Survey Annual Report for 1901, Vol. 1, Pt. 4, Olympia, WA, pp. 41-65.

Laughtland, J. G., 1987, Personal communication, Spokane Public Works Department, Spokane, WA.

Lobdell, G. T., 1981, Hydroconsolidation potential of Palouse Loess: *Journal of the Geotechnical Engineering Division, Proceedings of the American Society of Civil Engineers*, Vol. 107, No. GT6, Proc. Paper 16309, pp. 733-742.

McFarland, C. R., 1983, *Oil and Gas Exploration in Washington, 1900-1982*: Washington Division of Geology and Earth Resources Information Circular 75, Olympia, WA, 119 p.

Magill and Associates, 1979, *Annotated Bibliography of Source Materials in Locating Abandoned Coal Mine Problems in the State of Washington*: Prepared for U.S. Office of Surface Mining, Denver, CO, and Washington Division of Geology and Earth Resources, Olympia, WA, 84 p.

Morrison-Knudsen Company, Inc., 1985, *Engineering Investigation for the Renton Area, Washington*: Prepared for the U.S. Office of Surface Mining, Denver, CO, 64 p.

Mullineaux, D. R., 1965, *Geologic Map of the Renton Quadrangle, King County, Washington*: U.S. Geological Survey Geologic Quadrangle Map GQ-405, 1 sheet, scale 1:24,000.

Olson, B. E., 1979, Loess soils in Southeastern Washington: *Journal of the Geotechnical Engineering Division Proceedings of the American Society of Civil Engineers*, Vol. 105, No. GT6, pp. 786-791.

Phillips, W. M. and Walsh, T. J., 1981, Coal Geology of King County, Washington: *Washington Geologic Newsletter*, Vol. 9, No. 2, pp. 1-11.

Poland, J. F., 1981, Subsidence in United States due to ground-water withdrawal: *Journal of the Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers*, Vol. 107, No. IR2, pp. 115-135.

Prokopovich, N. P., 1975, Past and Future subsidence along San Luis Drain, San Joaquin Valley, California: *Bulletin of the Association of Engineering Geologists*, Vol. 12, No. 1, pp. 1-22.

Prokopovich, N. P., 1979, Genetic classification of land subsidence. In Saxena, S. K. (ed.), *Evaluation and Prediction of Subsidence*: American Society of Civil Engineers, New York, NY, pp. 389-399.

Schasse, H. W.; Koler, M. L.; and Herman, N. E., 1983, *Directory and User's Guide to the Washington State Coal Mine Map Collection*: Washington Division of Geology and Earth Resources Open File Report 83-8, Olympia, WA, 110 p.

Skelly and Loy Engineers-Consultants, 1985, *Abandoned Coal Mine Survey Coal Creek, King County, Washington*: Prepared for the U.S. Office of Surface Mining, Denver, CO, 66 p.

Snavely, P. D., Jr.; Brown, R. D., Jr.; Roberts, A. E.; and Rau, W. W., 1958, *Geology and Coal Resources of the Centralia-Chehalis District, Washington*: U.S. Geological Survey Bulletin 1053, 159 p.

Tetra Tech, Inc., 1984, *Final Report–Bellingham Abandoned Mine Land Survey*: Prepared for U.S. Office of Surface Mining, Denver, CO, 36 p.

The Olympian, 1986, Sinkhole back at same old stand: *The Olympian*, Olympia, WA, December 4, 1986, p. 4B.

The Olympian, 1987, Sinkhole closes Seattle streets: *The Olympian*, Olympia, WA, February 16, 1987, p. 2B.

Thorsen, G. W., 1987, Personal communication, Washington Division of Geology and Earth Resources, Olympia, WA.

Walker, C. W. and Shideler, J. C., 1984, *Final Report–Abandoned Coal Mine Hazards in the Roslyn Coal Field, Kittitas County, Washington*: Prepared for the U.S. Office of Surface Mining, Denver, CO, 46 p.

Walsh, T. J., 1988, Coal Mine Subsidence in Washington: *Washington Geologic Newsletter*, Vol. 16, No. 3, pp. 3-5.

Watson, J. H., 1887, *Report of the Inspector of Coal Mines and Ventilation of Washington Territory*: By Authority [of the Territorial Printer], Olympia, WA, 27 p.