WASHINGTON GEOLOGY

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Hercules No. 1 quarry in Tenino sandstone at Lemon Hill in Tenino (ca. 1908), operated by the Hercules Sandstone Co. A coal- or wood-fired, steam-driven, double channeler under 200 pounds of steam is cutting blocks. The channeler moved 40 feet each half hour and cut a groove 2 inches deep on each pass; it took many passes to cut the 52-inch depth of these blocks. A set of three tempered steel bits was located on each side of the channeler; two bits were arranged with blades perpendicular to the channel length, and the center bit was set at 45 degrees to the other bits. Bits used to make the first cut in the channels were 2.5 inches wide, but were progressively changed and were 1 inch wide for the deepest part of the groove. A man walked on each side of this machine, using a long-handled spoon to remove stone chips from the grooves. The machine ran 24 hours a day. A derrick moved the channeler to new positions. Water for the boiler was brought up in barrels. Hoses on the left are for steam drills run by power from the channeler. Men on the right in this photo are using wedges to split off parts of the outermost block. Blocks were also split off at the base with wedges. The corner of the "platform" has broken at a joint. Photo courtesy of Larry Scheel.

WASHINGTON GEOLOGY

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Victor F. Hollister Exploration Files

by Raymond Lasmanis

Victor F. Hollister, a well-known explorationist, lecturer, and writer has donated his Washington State files to the Division of Geology and Earth Resources. They span 43 years, from 1946 through 1989, and contain invaluable information on the state's copper, molybdenum, lead, zinc, and precious metal properties. The reports are bound in 31 volumes and are available for public inspection in the division's library. The files contain the following material:

- Chelan County prospects and mines
- Van Epps mine, Chelan County
- Republic district, Ferry County
- Middle Fork Snoqualmie, King County
- Mt. Si, King County
- North Fork Snoqualmie, King County
- Mineral Creek district, Kittitas County
- Okanogan County prospects and mines
- Loup Loup deposit, Okanogan County
- Mazama deposit, Okanogan County
- Margaret deposit, Skamania County
- McCoy Creek district, Skamania County
- Miners Queen deposit, Skamania County
- Wind River mine, Skamania County
- Snohomish County prospects and mines
- Silver Creek district, Snohomish County
- Stevens County prospects and mines
- North Columbia project, Stevens County
- Van Stone mine, Stevens County
- Excelsior deposit, Whatcom County
- American River (Mesatchee), Yakima Co.
- Georgia Pacific lands, western Washington

I want to thank Vic Hollister for his thoughtfulness and encourage other colleagues to donate their files to the division so that significant historical information can be preserved and made available for future generations. ■

Division Librarian Wins NWGS Service Award

Division of Geology and Earth Resources librarian Connie Manson received the Northwest Geological Society's "Tool of Geology" Award (a hammer and a case of wine) at the May 11, 1993, meeting. It was presented along with the statement: "We all agree that she has earned the highest honor we can give for her effective, energetic and unselfish service as DGER Librarian." Congratulations, Connie!

Lone Star Steilacoom Ranked First in U.S. Production

Despite the overall downward turn in production that most of 1992's Top 20 sand and gravel plants have taken in the past few years, Lone Star Northwest's Steilacoom facility managed to climb from fifth to first place since 1989, when *Rock Products* last ranked individual plant production. The plant did see production fall off since 1989, from 3.9 million tons to 3.5 million tons in 1992.

From "Top 20 Sand & Gravel Plants", by Steven Prokopy, in Rock Products, November 1993

Washington's Stone Industry—A History

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Washington has a rich history in its stone products. During the heyday of stone use (1876–1930), preparing finished stone became a major industry that employed hundreds of people and sent its products worldwide. Quarries at more than 250 locations (Moen, 1967) provided dimension stone that went into hundreds of historic buildings and structures in Washington state and many other localities in the U.S. and British Columbia. Many remain in public and private use. Other significant products were monuments, riprap, and paving stones. Figure 1 shows the Washington towns and cities cited in this article in which stone products were used.

Surveys by Gulick (1992), Moen (1967), Shedd (1903), Landes (1902), and Bethune (1891, 1892) provide much of the information about this industry. However, many aspects of early quarrying and developments before and between these studies are not well documented. No public surveys of the industry were kept before 1890 (Bethune, 1891), and no detailed history exists. Most private records have either not survived or have become widely scattered. This article reviews the evolution of the industry from examination of public and private records and interviews with people who were active in the industry.

EARLY USES

The earliest known use of stone in Washington was by ancient American hunters known as the Clovis people. Their chalcedony tools found near East Wenatchee are the oldest undisputed artifacts found in the New World and are believed to be about 11,250 years old (Mehringer, 1988; Mehringer and Foit, 1990). Later, Native Americans created specialized stone tools such as saddlestones (for grinding grain by hand), arrowheads, clubs, and axes. Some of these stones were quarried at distant locations—for example, obsidian for arrowheads may have come from either Oregon or British Columbia and indicates trade with distant tribes (Kirk and Daugherty, 1978).

European fur traders and settlers used local fieldstone for chimneys, kilns, and foundations in their early structures. Although few of these structures have survived, they were typically built with materials found on or near the construction site. Fieldstone or riverstone in the Spokane House fireplace (1810, razed) (Kingston, 1948) and Spokane Flour Mill foundation (1895) are examples (Garrett, 1977). The chimney of the Mattoon cabin near Sawyer (1864) was built of blocks that were probably split from local outcrops.

Washington pioneers relied heavily on imported goods for most finished products throughout the 19th century. Ships that served early settlements carried ballast stones that came from distant beaches or other sources. The tendency for rounded ballast rock to shift in rough water drove a change to squared quarried stones in about 1820 (Gurcke, 1988). Ships visiting Washington probably took on local rock for ballast. Stone from beaches also was also used in construction.

The abundance and widespread occurrence of basalt and other volcanic rocks in Washington undoubtedly encouraged their early and common use. An outcrop of the Eocene Cowlitz Formation on the Columbia River near Longview "was extensively quarried and leveled" in the early 1800s, although the use of the rock was not specified (Moulton, 1990). One of the largest stone structures in Washington, the Territorial Prison (now State Penitentiary) in Walla Walla (1887) has walls made of rock quarried from the Columbia River Basalt Group near Dixie (Mary Christianson, Administrative Assistant to the Superintendent, Washington State Penitentiary, Walla Walla, oral commun., Nov. 1993). Dimensional vesicular basalt also was used; an example is the Odd Fellows Building (1894) in Yakima.

BEGINNINGS OF AN INDUSTRY

The industry traditionally categorized coarse-grained felsic and mafic rocks (including some of their metamorphic counterparts, such as gneiss and amphibolite) as granite (Moen, 1967). The first finished stone in the Puget Sound area was probably "quarried" from large granitic erratics dug out of till. The foundation and walls of the original Presbyterian Church in Port Townsend (1876, razed 1889?) and the steps of the Crawford & Harrington Building in Seattle (1875, razed) are examples of stone from this source (McCurdy, 1937; Conover, [1958?]).

Obviously, these erratics yielded limited and scattered supplies; new buildings soon required transporting this material from distant sites, as local reserves were depleted. The foundation for the Territorial University in Seattle (1861, razed) was built with granite from Port Orchard (Binns, 1941).

Other buildings made use of stone salvaged from previous structures on their sites, because of the scarcity or expense of brick and stone. The present First Presbyterian Church in Port Townsend (1889) recycled stone from its original building (1876) for its new foundation (McCurdy, 1937).

The first recorded use of griststones for milling in Washington was by pioneers from the British Northwest Fur Company near Marcus (1816). This griststone was moved to Meyers Falls, 9 miles northwest of Colville on the Colville River, where a second griststone was added by the Hudson's Bay Company around 1843 (Sherfey, 1978). The origins of these stones, however, were not recorded and they may have been imported. The first griststone known to be from Washington was "ground out of a piece of granite" from an unspecified place on the Snake River in Whitman County during the 1840s and used near Alpowa (*The Washington Historian*, 1900). Numerous other griststones were brought to the state, many from France, which was reputed to produce the highest quality griststones during that era (F. E. Sherfey, oral commun., Aug. 1993).

Granitic bedrock also was quarried early in Washington. Howe (1857) reported quarrying activity in the San Juan Islands. Major granite quarrying, however, started in 1876. The U.S. Custom House in Portland, OR, used 50,000 cubic feet of rock from the Snake River granite quarry near Wawawai (Shedd, 1903; Moen, 1967). Other major sources of granitic building stone included quarries near Spokane and Medical Lake (Landes, 1902), Baring (Pickett photos, Special Collections and Preservation Div., Allen Library, Univ. of Washington Libraries), and the Western Granite Works

Figure 1. Buildings, quarries, and sites mentioned in this article that incorporate stone quarried in Washington can be seen in the cities and localities indicated on this map.

Figure 2. Western Granite Works (Soderberg quarry) at Index (date unknown). Wooden planks on two metal rods protruding from bedrock support three men who are drilling holes for blasting (center of rockface). Cobblestones were made in the tarpaulin "tents" and loaded on railroad cars for transport. The rectangular slabs behind the railroad car were split to size from irregular quarry rock and used for steps on buildings. The quarry site currently is a popular destination for technical rock climbers. Photo courtesy of Special Collections Division, Univ. of Washington Libraries, Pickett photo #1058.

quarry (1894?–1932) of John Soderberg (founder of Seattle's Swedish Hospital) near Index (Hanford, 1924). Index granite (actually granodiorite) is perhaps best known for its use in the steps of the current State Legislative Building in Olympia (Fig. 2). Information about most dates of operations for specific quarries can be found in the references listed at the end of this report.

Marble generally refers to rocks containing calcium carbonate, including limestones that can take a good polish and travertine, but also brucite and serpentine (Moen, 1967). Washington's first native marble tombstone came from near Fort Colville in 1862 (Western Historical Publishing Company, 1904). Later, marble was mined extensively in Stevens County for monuments and decorative stone. By the turn of the century, the Canyon Green quarry at Valley (1898–1900s?) had become the largest stone quarry in the state (Landes, 1902). Canyon Green marble (actually serpentine) from the U.S. Marble Co. was shipped to several eastern states, including New York, Pennsylvania, Illinois, and South Carolina (Spokane *Spokesman-Review*, April 8 and May 31, 1902; Mitchell, 1903). Chewelah marble quarried near Northport was shipped to Minnesota (Spokane *Spokesman-Review*, Sept. 3, 1905).

Beginning in 1916, however, many dolomite and brucite "marble" quarries in eastern Washington were mined solely for their magnesium content. World War I had halted shipments of magnesite from the nation's major supplier, Austria (*Pit and Quarry*, 1930; Chewelah Historical Museum displays and scrapbooks). This new and successful industry eventually exhausted some deposits of decorative marble.

Sandstone quarries were in operation along the Cowlitz River (Cowlitz or Lewis Counties) and on the San Juan Islands (probably Sucia Island) and Bellingham by the 1850s (Swan, 1857; Howe, 1857; Seattle *Post-Intelligencer*, Aug. 16, 1889; Burlingame, 1961). Opening in 1856, the Chuckanut quarry near Bellingham would become a major producer. It was owned by Henry Roeder, who was raised near the sandstone quarries of Ohio. Roeder recognized the need for construction stone in the state, and his quarry supplied material to build lighthouses at Victoria, BC, New Dungeness, and Smith Island and for the walkways at Fort Bellingham (1856–1858) (Koert and Biery, 1980; Seattle *Post-Intelligencer*, Aug. 16, 1889; Barton, 1889; Edson, 1968). The quarry's location on Chuckanut Bay (reportedly named by Roeder; Bolster, [1945?]) also facilitated shipping by boat (Fig. 3). Access to marine transport was a great advantage for quarries—

Figure 3. The Chuckanut quarry on Chuckanut Bay near Bellingham (photo taken before 1904). These irregular boulders were blasted from the steeply dipping rock face. Horse-drawn heavy-duty wagons move rock and debris in the quarry. The wooden brace on the right is a stiff-legged derrick (note size of wooden beams); this brace and guy wires (not visible here) stabilize the mast and boom on the left. The boom lifts a sandstone block encircled by a chain; steel links were typically 0.75 inches thick and chains were sectioned into 20-foot lengths. Two men on the left of the block are carrying another chain. To the right of (behind) the stiff-legged derrick, men on the rockfall are drilling holes by hand for later splitting with wedges. Typically, one person held the bit and rotated it while another person hammered; debris in the chiseled hole was removed with long-handled spoons. Photo courtesy of Galen Biery.

remote locations and transportation problems had made many early coal mines unprofitable (Melder, 1938).

Until 1876, the Chuckanut quarry produced small quantities of its dark gray and olive-green sandstone, which weathers buff with reddish highlights (probably from hematite). When an order for 6,000 tons was received for the U.S. Custom House at Portland, OR (Seattle *Post-Intelligencer*, Aug. 16, 1889), Bellingham's reputation as a center for building stone began (*Washington Standard*, Nov. 2, 1878). Dimension stone sold for "50 cents a foot" for blocks to 10 feet long, and stone that was less than 6 inches by 6 inches went for "33 cents a foot" (Roeder, April 5, 1876). With Roeder's influence as an eight-term Washington legislative representative, numerous early public buildings around Puget Sound were built with the trade-named Chuckanut sandstone (also called Chuckanut Bay sandstone) (Weaver, 1937; *Washington Standard*, Oct. 3, 1902). These include a former Washington state capitol building (1892).

The Chuckanut quarry, however, did not have a monopoly on building stone. A quarry on Newcastle Island (near Nanaimo, BC), leased to an American contractor, shipped stone for buildings as distant as the federal mint in San Francisco (Cracroft, 1870).

Despite Washington's abundant timber resources, a demand for stone gradually developed. Three major factors contributed to its popularity as a building material. First, in the 1880s and 1890s, Washington's population grew quickly from the influx of immigrants and the need to serve tens of thousands of prospectors on their way to strike gold in the Klondike (Petersen and Williams, 1991). Selection of locations for future railroad routes, governmental offices, and institutions (such as custom houses, universities, and prisons) caused early businesses and cities to compete fiercely for this new development and trade. Substantial buildings of stone and brick added an air of prosperity and permanence, setting them apart from the competition. Second, many Washington residents came from the East, where the scarcity of lumber made stone and brick standard building materials (Glover, 1936). This undoubtedly led many to favor such components for construction. Third, and most significantly, fire threatened the mostly wooden structures of that time. Multiple major fires occurred in numerous towns, and some destroyed entire business districts. Enormous demand for stone products began in 1889, after devastating fires in Seattle, Spokane, Ellensburg, Cheney, and Vancouver. Developers raced to rebuild, guided by new codes specifying construction with fireproof materials (Corley, 1970). This huge and immediate demand for stone and brick caused local shortages that continued for years.

Demand for Stone

After the Seattle fire, the popularity of stone for both commercial and residential construction grew rapidly. Despite cost differences, "lumber, as a construction material, [was] fast giving way either completely or in major portion to stone" (Bethune, 1891). In 1891 alone, production of building stone tripled (Bethune, 1892).

With the aid of a stone saw installed in 1887, the Chuckanut quarry achieved a daily output of 200 tons and blasted rockfalls as large as 40,000 tons (Seattle *Post-Intelligencer*, Aug. 16, 1889; Roth, 1926). Later production was as high as 10,000 tons a month (Spokane *Spokesman-Review*, Jan. 21, 1895). The quarry was described as a bonanza (North Pacific History Company, 1889). The Tenino quarry also flourished at this time, daily shipping as many as 14 carloads, each containing 20–30 tons of sandstone (*Washington Standard*, Sept. 4, 1891). Although reports like these were often exaggerated, the prosperity of the industry was obvious.

The search for building material prompted many cities to try local stone, but most proved either inferior or too remote to ship competitively. Most sedimentary rock in Washington is too poorly consolidated for use as building stone. Basalt near Puget Sound was commonly of varied quality and low strength (Galster and Laprade, 1991). Additionally, the wet climate and freeze–thaw cycles weakened many stones that had initially appeared adequate. Scow Bay sandstone from Indian Island in Jefferson County was used for the structural components of many buildings in Port Townsend (1873?–1890s?) (McCurdy, 1937). The rain, however, literally eroded the walls of buildings made of these stones, and concrete was needed to patch and face the stone to protect it from the elements (Garred, 1970). Examples of similarly unstable stones in buildings also exist in Yakima, Selah, Roslyn and Cle Elum. The trolley barn in Yakima (1910) even included some diatomite in its mostly sandstone construction! Numerous other sandstone quarries opened in many locations but with varying successes.

From the many stones quarried, three Washington sandstones became widely used for construction: Chuckanut (1856–1917?, Chuckanut Formation), Tenino (1887?–1935, McIntosh Formation), and Wilkeson (1883–1982, Carbonado Formation of the Puget Group). The compact grain configuration, cementation (for example, silica), and(or) low porosity (about 10 percent for the Chuckanut and Wilkeson sandstones (Shedd, 1903)) of these stones resulted in high strength and integrity, and they needed no waterproofing. Demand for quality stone created markets for these products in Washington (Table 1), Oregon, California, British Columbia, Idaho, and Montana.

Washington's stone industry profited from its distance from other quality stone and brick sources. The high demand for and scarcity of good stone and brick boosted product value, and the high prices paid for stone created excellent wages at many quarries. Skilled workers at the sandstone quarry on Waldron Island (1890s?–1910s?) were paid as much as $1.50 an hour in the 1890s—an extremely high wage for the time (Ludwig, 1959). Stonecutters at the Tenino quarry received $2.50 a day in 1894, also an excellent wage (Fenton, 1935). High wages were the product of the Journeymen Stonecutters Union of North America, whose members staffed many of the larger quarries (L. F. Scheel, stonecutter at the Western quarry and son of an owner of the Hercules quarries, oral commun., Oct. 1993).

Early quarrying procedures typically began with filling rock joints, drill holes, or crawl-space-size "coyote holes" with black powder, blasting massive irregular boulders from the outcrop, and then splitting them into smaller blocks with black powder, plug and feather wedges, chisels, and mauls. Stonecutters and carvers, many of English, Scottish, and Scandinavian descent, worked in simple tents or structures nearby (Gatto, 1965; Ludwig, 1959). While many orders were filled from these shops, final cutting and carving normally occurred at the construction site (L. F. Scheel, oral commun., Oct. 1993). As production grew, several quarries built shops and purchased channelers, gang saws, planers, and other equipment (Fig. 4) (Landes, 1902).

Although demand for stone fluctuated with the economy and depressions or wars ruined many established quarries, local growth caused some quarries to reopen and prosper under new ownership when conditions recovered. Quarry managers often treated their workers as family and struggled to keep skilled employees through hard times.

Table 1. Selected examples of architectural uses of Washington stone in Washington, with dates of construction. The probable source formations or plutons, if known, are listed. In some buildings, only windowsills or steps are made of the stones listed. Over the years, many buildings have been renamed, remodeled or razed, making it difficult to locate some specific stone products.

Angeles sandstone (Lyre or Twin River Formation, Angeles and Tumwater quarries, south of Port Angeles)

Port Angeles: Olympic National Park Headquarters buildings (1940–1944), Aldwell Building (1906, razed 1966)

Seattle: Federal Building (1905)

Yakima: Courthouse (1905–1906?, razed)

Chuckanut sandstone (Chuckanut Formation; Chuckanut [including Chuckanut Bay, Roth, Pacific American Fisheries, Sidell and Burfiend], Fairhaven, Lysle and Huntoon, and Sehome Hill quarries in the Bellingham area)

Anacortes: Anacortes depot (1911)

Bellingham: B & B Building (Flatiron Building, 1907), DeMotto Block (Sunset Block, 1890), Fairhaven Public Library (1904), Hotel Laube (1900), Lottie Roth Block (1890), New Whatcom City Hall (1892–1893, Whatcom Museum of History and Art, foundation), Victor A. Roeder home (1903–1908), Squalicum breakwater (Pacific American Fisheries and Lummi Island quarries, 1934–1936), Western Washington University Campus (Old Main, 1896–1899, originally New Whatcom Normal School), Whatcom Falls Park bridge (1939–1940, stone from the razed Bellingham National Bank Building)

Bremerton: Bremerton Navy Yard (before 1907)

Olympia: Federal Building, west end of old Washington State Capitol Building (1891–1892, west end, Chuckanut sandstone; east end [annex], 1905, Tenino sandstone)

Port Townsend area: U.S. Custom House and Post Office (1893), Fort Worden (before 1907)

Puget Sound: Smith's Island Lighthouse (1858, abandoned 1957)

Seattle: Boston Block, Broadway High School, Fort Lawton (1899–1908), Fort Magnolia Bluffs (before 1907), Crawford & Harrington Building (1875, steps cut from a granitic erratic), Maynard Building, Noyes Building (1889), Public Library, U.S. Post Office (before 1907), Yesler Building

Spokane: Elks Club, First Presbyterian Church

Strait of Juan de Fuca: New Dungeness Lighthouse (1857, tower height reduced due to structural weakness, 1927)

Whidbey Island: Fort Casey (1896?–1899?)

Sandstone from Republic area (Klondike Mountain Formation)

Republic: Episcopal Church of the Redeemer (1908), Golden Age Club building

Roslyn sandstone (Roslyn Formation, two quarries near Roslyn)

Roslyn: Brewery, The Brick Saloon (1889), City Grocery, Roslyn Cafe (1896?), Russian Saloon, Schaw Garage, Mt. Pisgah Presbyterian Church (foundation)

Sandstone from Scow Bay area (informally named "Scow Bay Formation"?, southern Indian Island, Jefferson County)

Port Townsend: Enoch Fowler (or Leader) Building (1874), First Presbyterian Church (1889–1890, quoins; granite [from erratics] in foundation are stone from original church, 1876, razed 1889)

Sandstone from Sucia Island (Nanaimo or Chuckanut Formation, on Fossil Bay)

Orcas Island: lime kiln construction

Port Orchard: federal drydock (1892–1896)

Seattle: old Public Safety Building, paving blocks

Tenino sandstone (McIntosh Formation, from the Guinett quarry [formerly Hercules No. 1 quarry and Western quarry], Hercules No. 2 [formerly the Eureka quarry], Manville quarry, and Tenino quarry [formerly Russell quarry and Long quarry])

Aberdeen: Hayes and Hayes Bank Building (Tenino quarry)

Centralia: Union Depot (1912) and Union Loan and Trust Company Building (Tenino quarry)

Chehalis: Chehalis National Bank (Hercules No. 1 quarry); City Hall and State Training School (Tenino quarry)

Ellensburg: Farmers Bank Building (1910–1911)

Everett: Washington School (Tenino quarry)

Fort Lewis (near Tacoma): numerous window sills on barracks and hospital (Western quarry)

Fort Ward (south Bainbridge Island): Army post buildings (Tenino quarry)

Grays Harbor: jetty riprap (Hercules No. 2 quarry)

Hoquiam: Hoquiam's Castle (Robert Lytle Mansion, 1897)

Montesano: Chehalis (Grays Harbor) County Courthouse (Tenino quarry); bank building (1907, Hercules No. 1 quarry)

Olympia: Odd Fellows Building (1888) and Olympia Hotel (foundation stone, 1890, destroyed by fire, 1904) (Manville quarry); Temple of Justice Building (basement only), old Thurston County Courthouse (1901, razed 1931), and another old Thurston County Courthouse (1930) (Western quarry); U.S. Post Office, old Washington State Capitol Building, east wing [annex] only (1905), and Grace Baptist Church (Tenino quarry)

Port Orchard: Port Orchard drydock (1893–1896)

Pullman: United Presbyterian Church (Greystone Church, 1898–1899), Washington State College Science Hall (1899, foundation and trim, Tenino quarry)

Ritzville: Carnegie Library (Tenino quarry)

Seattle: Bailey Building (1889–1891, also known as the Harrisburg Building), old part of Bon Marché (Tenino quarry); Dexter Horton Building (1922–1924), municipal buildings, Swedish Mission Church, and Bon Marché Annex (Hercules No. 1 quarry); Seattle Public Auditorium (before 1915), Seattle Public Library (before 1941), U.S. Post Office

Sedro Woolley: Sedro Woolley High School (Tenino quarry)

Shelton: Mason County Courthouse (1929) (Western quarry)

Spokane: numerous business blocks, Carnegie Library (1904–1905) and Masonic Temple (Hercules No. 1 quarry); Elks Hall (1930, Tenino quarry); First Presbyterian Church

Tacoma: California Building, First Christian Church, and Catholic Church (Tenino quarry); First Congregational Church and Knights of Pythias Temple (1907), Taylor-Gardner Building, and Temple of Music Building (Hercules No. 1 quarry); Pierce County Courthouse (1890–1893, razed, Wilkeson sandstone from Burnett and Tenino sandstone from the Long quarry); Saint Patrick's Church (1906), Stone-Fisher Company building (1906, addition 1924)

Tenino: Campbell and Campbell Building and Columbia Building (1906, quarry not known), Hercules Sandstone Company Office (currently the Tenino City Hall, 1913, Hercules No. 1 quarry); Tenino Stone Company Quarry House (1900), Russell Building (1910) (Tenino quarry); State Bank of Tenino (1906), Tenino depot museum (1914), Tenino Independent Building (1914), Masonic Temple (1921), Miller Block (1906), Wolf Building (1908)

Vancouver: Fort Vancouver military buildings and State School for the Deaf and Dumb (1915, lintels and trim) (Tenino quarry)

Walla Walla: Central Christian Church, Masonic Temple, and City Hall (Tenino quarry)

Yakima: Methodist Episcopal Church (Tenino quarry)

Sandstone quarry on Waldron Island (Nanaimo Formation, on Point Disney)

Mouth of Columbia River: breakwater riprap

Table 1. Selected examples of architectural uses of Washington stone in Washington *(continued)*

Seattle: paving blocks on Yesler Way and other streets (now covered by asphalt)

Wenatchee Yellow sandstone (Wenatchee Formation?, Dry Gulch, Wenatchee area)

Leavenworth: unnamed bank

Seattle: various homes

Wenatchee: Wenatchee Junior College and First Methodist Church (1951)

Wilkeson sandstone (Carbonado Formation of the Puget Group; from seven area quarries: Mitchell quarry, Walker-Wilkeson quarries, which were previously known as the Northern Pacific and Wilkeson quarries, and unnamed quarries at Burnett and Pittsburg). Buildings constructed between 1907 and 1959 are of Walker-Wilkeson sandstone.

Aberdeen: U.S. Post Office

Bellevue: First Congregational Church, Puget Power and Light Building (last major commercial building built with Wilkeson sandstone); Saint Thomas Church (in Medina)

Bellingham: City Hall (1940)

Buckley: The National Bank of Washington, Walker residence

Everett: U.S. Post Office and Custom House (1915–1917)

Fort Lewis: The Ninety-First Division Memorial (before 1930)

Olympia: Capitol National Bank Building, Washington State Capitol Campus: Governor's Mansion (1908–1909), Insurance Building (1921), Institutions Building (1934), Legislative Building (1922–1928), Public Lands–Social Services Building (1937), State Library (1959–1961), Temple of Justice Building (1917–1920) (outside Wilkeson sandstone, basement is of Tenino sandstone), Transportation Building (1940)

Port Angeles: U.S. Post Office and Federal Building (1932), Clallam County Courthouse (1980, cornerstone)

Puyallup: Ezra Meeker Mansion (1890, foundation stone), bank building

Seattle: 1411 Fourth Avenue Building (1929), The Post-Intelligencer Building, Saint Andrews Church, Saint Stephens Episcopal Church, old Seattle Art Museum (1932), Skinner–Fifth Avenue Theatre Building (1926), Trinity Parish Church (1891, enlarged 1902), United Presbyterian Church

Spokane: Cathedral of Saint John the Evangelist (1926–1954, Wilkeson sandstone outside), Chamber of Commerce Building (1931, columns), Davenport Hotel (1914), Elks Temple (1930)

Steilacoom: Western Washington State Hospital (before 1948)

Tacoma: The Bank of California (1929), Central School (1922?), City–County Building (1959), Ferry Museum (1911, addition 1973, now Washington State Historical Society Museum), First Baptist Church (before 1925), First Congregational Church, The National Bank of Tacoma (1919, now the Tacoma Art Museum), Saint Luke's Memorial Episcopal Church (1883, oldest building of Wilkeson sandstone), Stadium High School (1891, remodeled 1906), Walker Apartments (1928), Walker residence (before 1925), University of Puget Sound campus buildings

White Center: Holy Family Parish Church (1959)

Wilkeson: Wilkeson City Archway (1927), Wilkeson School (1912, remodeled 1981), Wilkeson Town Hall and Library (1923)

Yakima: Christian Science church, Pacific Power and Light building

Quartzite from the Kifer quarry (metamorphic rocks of Tenas Mary Creek, about 4 miles northwest of Kettle Falls area)

Republic: Title Building

Cumberland sandstone quarry (Puget Group, at Cumberland, closed 1894)

Seattle: Trinity Church and other buildings

Sandstone from a quarry on Orcas Island (Nanaimo Formation, near North Beach)

Orcas Island: Mount Constitution lookout tower

Sandstone from three quarries in the Yakima–Selah area (Ellensburg Formation)

Cowiche: Saint Peter Church and Retreat Center

Selah: Central School (1910, destroyed by fire) and Selah State Bank Building (1910) (Bourdon's quarry); Dutch Meyer House (razed 1993)

Yakima: Trolley barn (1910), Lund Building (1885 or 1898–1899), Odd Fellows building (1894, quoins)

Washington Green sandstone (Swauk Formation?, operated 1946–1955, about 2 miles east of Liberty)

Ellensburg: various homes and two churches

Moses Lake: at least one residence

Seattle–Tacoma area: various homes

Yakima: various homes, including the Floyd Packston residence (80 tons)

Medical Lake granite quarries (two quarries)

Medical Lake: Medical Lake Insane Asylum, various buildings and homes

Pullman: old Administration Building (now Thompson Hall, foundations and trim), Washington State College

Crystal Marble Company (quarry near Addy)

Seattle: U.S. Federal Building (ca. 1904; 50,000 cubic feet)

Index granite (Index batholith, Soderberg quarry at Index, 1894?–1960)

Bremerton: drydock

Carnation: Nan Fullerton Stuart Memorial Chapel

Ellensburg: Federal Building and U.S. Post Office (1916–1917)

Everett: U.S. Post Office and Custom House (1915–1917)

Olympia: Legislative Building steps, Capitol Campus

Seattle: Smith Tower (lower three stories), U.S. Post Office, Times Square Building (1916), Union Pacific depot (before 1907), American Bank Building (before 1907), New Washington Hotel (before 1907), Frederick and Nelson Building, Great Northern depot, as well as tombstones, paving blocks and street curbing, park benches, and picnic tables

Also Seattle and Portland Railway Company bridge across the Columbia River

Granite quarry on the Snake River (near Wawawai, Whitman County)

Spokane and Walla Walla: street curbing and gutters

Mouth of the Snake River: Northern Pacific bridge (piers and buttresses)

Granite from the Ellis quarry (Index batholith)

Seattle: piers of Arcade Building, monument bases

Baring granite quarry in Baring (Index batholith)

Seattle: Franklin High School (foundation)

Dorset granite quarry (9 miles north of Spokane)

Cascade locks on the Oregon side of the Columbia River (ca. 1889; 26,000 cubic feet)

Spokane: bank building at Howard and Sprague Streets

Hale and Kern basalt quarry (near Fisher)

Grays Harbor: jetty (before 1902)

Kirsch rhyolite quarry (volcanic rocks of Swauk or Teanaway Formation?, about 2 miles east of Liberty)

Cle Elum: U.S. Post Office

Figure 4. Western Granite Works mill at Index (Soderberg quarry, ca. 1927). Stonecutters finished Index granite and imported stone for buildings and monuments. An "endless chain" holds the suspended column with hooks inserted in holes cut into the ends of the stone (see the column on the right of this photo). Only metal hammers and pneumatic hand chisels were used here because of the hardness of granite. Planing machines with their wide horizontal belts can be seen in the rear of the shop. Stone products from this quarry were shipped as far away as Hawaii. Fire in the early 1930s destroyed this building and closed the quarry (Galvin Lord, oral commun., Oct. 1993). Photo courtesy of Special Collections Division, Univ. of Washington Libraries, Pickett photo #3882.

Stone cutting was essentially an all-male profession. Apprenticeships were common at major quarries through 1955 (R. G. Walker, Jr., former manager of the Walker Cut Stone Company and son of the owner, oral commun., Oct. 1993, and personal archives). Despite the dust and dirt associated with the job, there was a tradition among stonecutters of dressing well for work, in much the same manner as chimney sweeps. Work at the quarries commonly slowed during winter—cold, water-saturated stone was difficult to cut or carve and could shatter if frozen. While waiting for more work, Tenino area stonecutters often knitted to keep their fingers nimble (L. F. Scheel, oral commun., Oct. 1993). Dusty working conditions and rare use of protective masks (before the establishment of industrial regulations and insurance) made silicosis prevalent among early sandstone cutters (L. F. Scheel, oral commun., Oct. 1993). Accidents at the quarries were another significant danger (for example, Thomas, 1971).

By the time Tenino sandstone from the Tenino quarry was used to construct the east wing (annex) of the former Washington state capitol building in Olympia (1905), another outcrop of the sandstone unit being quarried at the Hercules No. 1 quarry (1891–1917?) in Tenino became a direct competitor (cover photo). The Tenino sandstone comes in two colors, trade-named Tenino Blue (a dark gray) and Tenino Buff. This stone represents Washington in the selection of state stones displayed at the Washington Monument (contributed 1914, Washington, DC) and the Philadelphia Freedom Memorial (1987) (Seattle *Post-Intelligencer*, Aug. 19, 1987; South Thurston County Historical Society scrapbooks). However, some Tenino Blue weathered to buff, which upset some architecturally designed color schemes. Operators at the Western quarry (1923–1935, formerly the Hercules No. 1 quarry) subsequently treated both types of Tenino sandstone with phosphoric acid to produce a long-lasting, uniform, gray color (L. F. Scheel, oral commun., Oct. 1993).

Riprap

Basalt, sandstone, and granite were also used widely, and still are, for riprap. To obtain Tenino sandstone for the Grays Harbor jetty, the "Big Blast" (Feb. 17, 1912) was set off at the Hercules No. 2 quarry near Tenino (1911–1917?). It received much publicity (Fig. 5). A single rockfall of 200,000 cubic yards (about 500,000 tons), produced from 43,100 pounds of black powder (1,724 kegs) and 1,200 pounds of

Figure 5. The day of the Big Blast at the Hercules No. 2 quarry in Tenino sandstone (Feb. 17, 1912). Stone went to the Grays Harbor jetty. People standing at the top of outcrop (upper left in this photo) suggest the scale. Projectiles from the blast put holes up to ten feet in diameter in the walls of the quarry buildings. Photo courtesy of Larry Scheel.

dynamite (Roberts, 1912), damaged some buildings and buried the railroad track, closing traffic at the quarry. Much unusable stone was produced in the blast, however—perhaps as much as 40 percent of the rockfall (Vandermeer, 1981a; Fergusson, 1912). Shipping 1,250 tons a day, the Hercules Sandstone Company employed 160 men (Reid, 1912). More than $1 million of sandstone products was eventually sold by the Hercules quarries (Dwelley, 1984).

Andesite "granite" from the Hercules No. 6 quarry also was used in the Grays Harbor jetty. To encourage support for developing the quarry, Walter Scheel led his father and representatives from a bank and the Army down a long, rough foot trail that crossed the Skookumchuck River four times on the way to the proposed quarry site. Scheel carried each man across the river on his back each time (Painter, 1983), but the loan was secured only when the family mortgaged all their possessions. After the company was awarded a contract by the Army Corps of Engineers, laborers constructed a rail spur to the quarry, which is now partially submerged by the Skookumchuck Reservoir (Thurston County). Shortly after first production, the Army exercised the escape clause in the contract—war—and the company went bankrupt. The only stone ever cut from this quarry went to the Washington Monument (Washington, DC) shortly before World War I (Fig. 6). The jetty was later finished as a WPA project and used basalt; the structure is still in use (L. F. Scheel, oral commun., Oct. 1993).

The Wilkeson Sandstone

Although outcrops of the Wilkeson sandstone were first used by the Northern Pacific Railway to supply ballast along its west coast rail lines (late 1870s), Saint Luke's Episcopal Church in Tacoma (1883) marked its first use in construction (*The Northwest*, 1968). Seeing this stone on a visit to Washington, Robert Walker quit his post at a quarry in Minnesota and in 1907 moved west to develop and eventually buy the quarry (Bonney, 1927). Perhaps best known for its use in the current State Legislative Building in Olympia (1922–1928), 15,400 tons of the trade-named Walker-Wilkeson sandstone went into the dome alone (*The Northwest*, 1968). The dome is said to be one of two structural (self-supporting) stone domes in the U.S. (*The Northwest*, 1968) and the fifth highest all-masonry dome in the world (Jan Johnson, docent, Washington State Capitol tour program, oral commun., Oct. 1993). An additional example of the engineering skill and craftsmanship at the Walker-Wilkeson quarry is the Cathedral of Saint John the Evangelist in Spokane (1926–1954) (Figs. 7 and 8).

Figure 6. Andesite (locally called granite) from the Hercules No. 6 quarry on the Skookumchuck River (ca. 1917). This was the only cut stone produced from the quarry and is now in the Washington Monument (Washington, DC). On the left is Hans Scheel, one owner of the quarry; to the left of the pillar is his son Karl. Photo courtesy of Larry Scheel.

Paving Material

Another early use of stone was for paving streets. Street grades in Seattle, Tacoma, and other cities were as steep as 49 percent. Yesler Way in Seattle (called Skid Road before the regrade activities of 1890–1910) was one of these steep streets (Corley, 1970). Wooden blocks and planking originally used for street paving in many cities proved inadequate because of their lack of durability, low density, slipperiness, and expansion and contraction during wet and dry weather.

Figure 7. An example of Walker-Wilkeson sandstone on the Cathedral of Saint John the Evangelist in Spokane (1926–1954). This carved detail is below the western rose window (covered by a mesh that prevents birds from nesting on the stone). The building's exterior is made of the sandstone, and the interior is made of Indiana limestone and Boise sandstone.

Figure 8. Eagle chimera carved in Walker-Wilkeson sandstone on the west side of the Spokane cathedral (Fig. 7). This is a medieval symbol representing a traditional protector of the cathedral. Photo courtesy of Robert Walker, Jr.

Until the 1920s, stone cobbles and street curbing were widely adopted. Granite was popular for cobbles and curbs, but sandstone became preferred for cobblestones because it was easier to work into blocks than granite (Ludwig, 1959) and because it appeared to offer better traction for the hooves of horses than other stones (Roberts, 1917). Most sandstone, such as that from Sucia and Stuart Islands (San Juan County), however, proved unequal to the combined long wear of rain, wagons, and livestock (McLellan, 1927; McDonald, 1988).

Basalt also was popular for paving. A quarry in columnar basalt near Klickitat employed 50 men in 1906 to produce cobbles for Front Street and other roads in Portland, OR. The stone was considered very valuable—an offer of $50,000 to purchase the quarry was refused! But by 1919, changing trends in the stone industry caused it to close (Neils, 1967).

Other Uses

Other products made of Washington stone have been shipped worldwide. Holystones (4 x 6 x 8 inches) from the Tenino quarry, Hercules No. 1 quarry, and later the Western quarry were used for polishing wooden decks of Navy ships (L. F. Scheel, oral commun., Oct. 1993). Workers at the Wilkeson quarry made pulpstones (53.5-inch diameter x 27 inches long, with a 9.5-inch diameter hole at the center, for grinding timber into pulp) that were shipped to South America, Australia, and New Zealand (R. G. Walker and L. F. Scheel, oral communs., Oct. 1993).

THE DECLINE BEGINS

In 1906, Washington's first major portland cement plant opened near Concrete. Shortly thereafter, several others followed (Dwelley, 1980). Industry advancements such as reinforced concrete and the development of the horizontal rotary kiln (to improve mixing) helped concrete gain wide acceptance as a structural material (Coney, 1991). Concrete could be made to form on site, and it was less expensive than stone, which had to be quarried, cut, carved, and shipped longer distances than most local gravel. The need to pay high union wages for Journeymen Stonecutters was bypassed by hiring other laborers for concrete work (L. F. Scheel, oral commun., Oct. 1993). Construction took less time with concrete, and concrete colors and textures could be made to resemble sandstone. Numerous buildings were soon constructed of "cast stone", concrete blocks mass-produced from molds to be a reasonable simulation of chiseled stone. An example of this use of concrete is the Immaculate Conception Church in Republic (1913).

Concurrently, improvements in local brick production, the advent of structural steel-frame construction, and the versatility and lower cost of terra cotta increased competition among building materials (Aldridge, 1986). The darker gray stones also lost favor with builders, which hurt sales of many sandstones, granites, and basalts. Competing quarries, which took advantage of outcrops of similar stone near major quarries, also forced division of sales among local stone companies (Vandermeer, 1981b).

One by one, the major quarries failed. After the Depression, mostly minor building stone operations continued throughout Washington. From the 1940s to the 1960s, the old Soderberg and Baring granite quarries reopened, chiefly making chicken grit that became popular in the poultry indus-

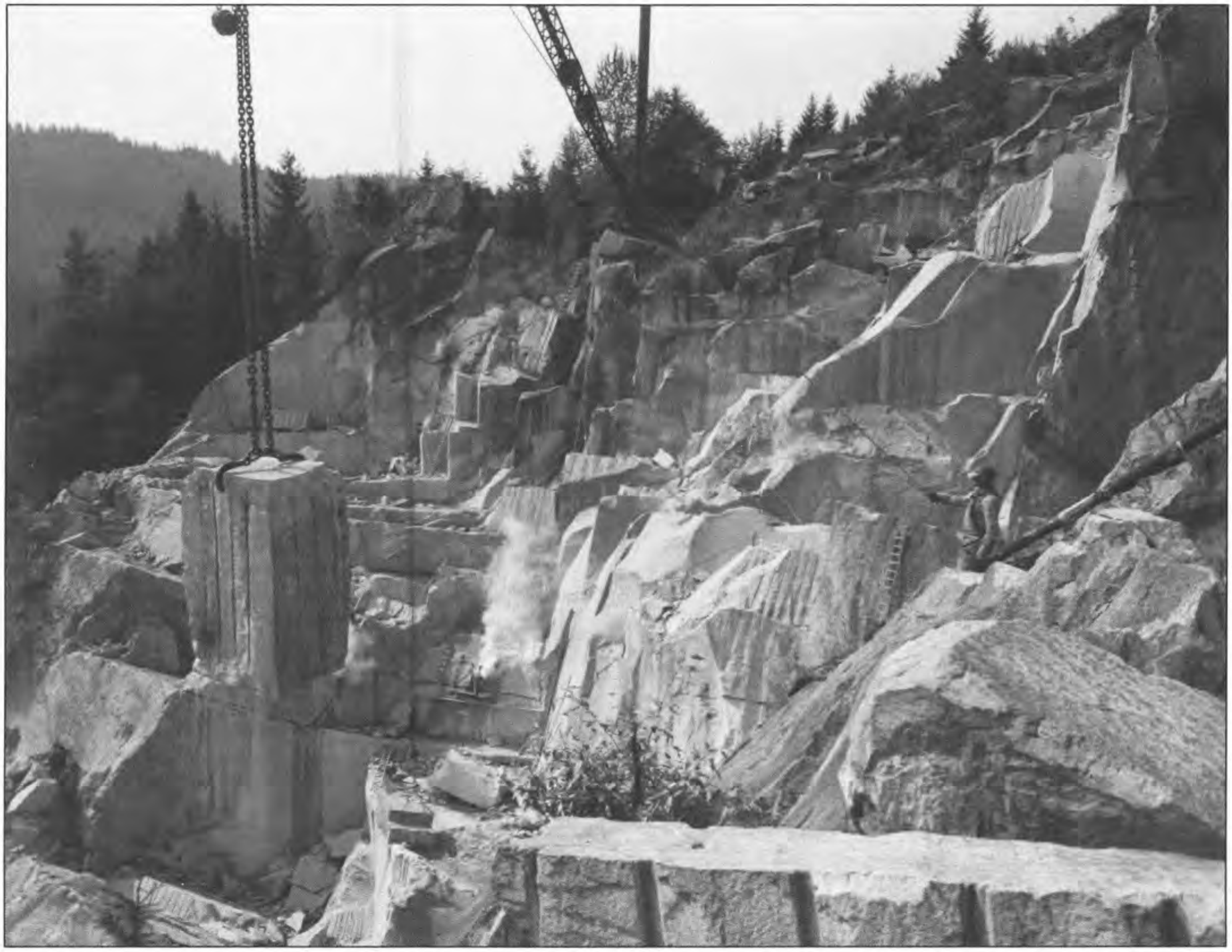

Figure 9. Lifting a 35-ton block (about 6 ft x 6 ft x 12 ft) of Walker-Wilkeson sandstone out of the quarry after dimensional blasting. Signaler on the right is steadying a line (above photo frame). Steam rises from a jackhammer drilling to prepare for blasting. Bedding in this quarry dips about 53 degrees, too steep for using channeling equipment. 1950s photo courtesy of Robert Walker, Jr.

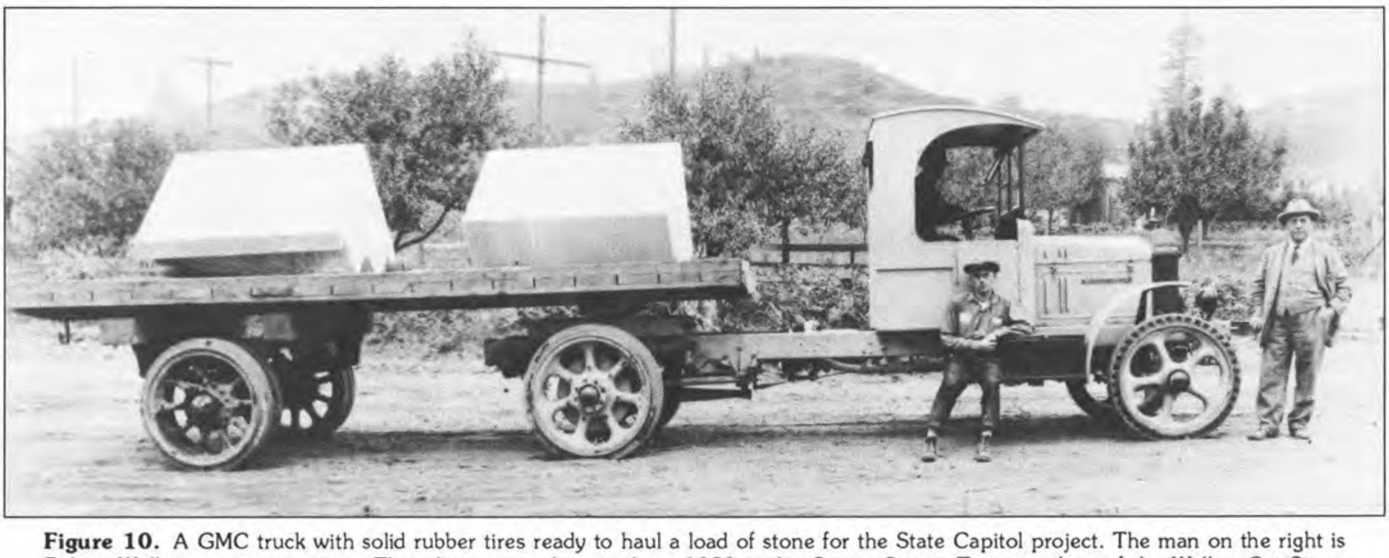

Figure 10. A GMC truck with solid rubber tires ready to haul a load of stone for the State Capitol project. The man on the right is Robert Walker, company owner. This photo was taken in about 1920 at the Center Street, Tacoma, shop of the Walker Cut Stone Company. Photo courtesy of the Tacoma Public Library.

Figure 11. Sandstone at the Walker-Wilkeson quarry rough-cut as columns for the state capitol building is lying near the mast and boom derrick. These segments were shipped to the Tacoma plant and finished on a lathe. Some stones are on railroad cars awaiting shipment. The blocks of rock were let down the tramway (rails, lower left) to the saw shed. Other buildings here housed a blacksmith shop, gang saws, steam donkeys, and equipment. Photo (ca. 1926) courtesy of the Tacoma Public Library.

try (Galvin Lord, former quarry foreman, oral commun., Oct. 1993; Moen, 1967). Changes in mining regulations that set minimum fees and mining tonnages closed more quarries in the 1950s, among them the sandstone and rhyolite quarries near Liberty (J. J. Kirsch, former quarry owner, oral commun., Oct. 1993).

The continuous production from the Walker-Wilkeson quarry, however, was unique. With its distinctive light-gray color and the help of major government projects such as the current Washington State Capitol campus, the quarry survived the rise of concrete construction, wars, and the Depression (Figs. 9–12). The development of its ashlar products in the 1940s also contributed to its success. The company opened the Wilkeson-Wenatchee quarry near Wenatchee and marketed its Wenatchee Yellow sandstone in the 1950s to satisfy demand for mixed contrasting stone colors in residential and commercial construction (R. G. Walker, Jr., oral commun., Oct. 1993; Strand, 1953). While tempered steel tools were used at Tenino, tungsten carbide tools were used here to work the sandstone, which was then cleaned with muriatic acid (HCl) before shipment. Production continued until 1982 when, after changes in ownership, bankruptcy closed what is probably the most famous quarry in the state. Orders totaling at least $250,000 were left unfilled (*The Olympian*, Dec. 27, 1982).

Before Washington's longest running cut stone operation at Wilkeson closed, many remarked at its antiquated operations (Hack, 1980), but modern technology had changed few quarrying procedures, and some drills and other equipment (most built before 1929) were still driven by steam (Thomas, 1976). With its closing, however, Washington state lost its last sophisticated operation. Remaining quarries function at a level typical of 100 years ago: large irregular boulders are again being blasted loose and then split to size. No dimensional blasting, channeling, or wire (cable) sawing from bedrock is currently being done in the state. Stones imported from other states dominate the market for commercial buildings and monuments in Washington; many come from the Cold Spring Granite Co., Inc., of Cold Spring, MN (Univ. of Puget Sound Geology Department, 1993), which owns quarries in several states and has a wider variety of finishing equipment than is locally available.

THE INDUSTRY REBOUNDS

Recently, however, Washington's stone industry has somewhat rebounded. More expensive buildings, higher lumber prices, and the desire for building longevity are increasing the use of stone in construction. Masonry stone for residences is largely ignored by distant importers, and demand has caused production and investments by local stone companies to increase. High Cascades granite (a diorite) from the Marenakos Rock Center (Issaquah) is being used in the Medina mansion of Microsoft's Bill Gates. A variety of equipment, including a computerized, convertible 6- to 9-foot-diameter circular saw (reportedly the largest west of South Dakota), has been installed by the company (Rod Hyde, an owner of the Marenakos quarry, oral commun., Oct. 1993).

This "stone boom" also has reopened some abandoned quarries (Rod Hyde, oral commun., Oct. 1993; see also Stewart, 1988). The Hercules No. 1 quarry (now Guinett quarry, owned by Northwest Stone, Inc., Tualatin, OR) has sold stone for building and artistic uses in Portland, OR. The Walker-Wilkeson quarry (now owned by Rockeries, Inc. of Federal Way, WA) sells stone chiefly for pilings and rockeries. Additionally, Wilkeson sandstone miniatures of classic stone architecture (most less than a foot tall) are sold in shops and art galleries in Europe and North America; these are produced by the Monumental Miniatures Corporation of Vergennes, VT, and Stoneage Wonders of Auburn, WA. Other abandoned quarries may be reopened, thanks to expanding markets.

Figure 12. A drill that was converted to steam being used at the Walker-Wilkeson quarry. Rods in the foreground are drill extensions; behind the driller are steam pipes and hoses. Steam cleared the holes of rock debris. Photo (ca. 1926) courtesy of the Tacoma Public Library.

Unlike the products of other mineral industries, those from various stone businesses are easily recognized in the numerous buildings in which they are used (Table 1). A stone can be distinguished by color and weathering characteristics; its source commonly can be determined from construction dates and the architectural detailing attributable to individual stone companies and their carvers. Many of these buildings are on the National Historical Register, and they testify to the work of talented artists, craftspeople, and engineers who used quarrying, carving, and construction techniques now largely forgotten. These people proudly created Washington's legacy of stone by making enduring masterpieces of art, structure, and form.

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Editor's note: The author would appreciate hearing from anyone who has information about old quarries or historical photos of the stone industry. The author has applied for copyright of this material. ■

National Natural Landmarks Get Attention

Activities involving Washington's National Natural Landmarks (NNLs) are proceeding on several fronts. The National Park Service's (NPS) Pacific Northwest Office in Seattle recently released the fall issue of *Landmark News* detailing both ongoing and new start-up projects.

In 1992, the NPS established a Challenge Cost-Share Program (CCSP) to broaden opportunities for non-federal involvement in the agency's activities. The CCSP encourages contributions from non-federal sources by providing a maximum federal cost share of 50 percent for projects on park land or projects off park lands but that support NPS programs. Types of projects on Park Service lands can include historic and archaeological site restoration, scientific research, trail maintenance, interpretive exhibit enhancement, and management, inventory, and monitoring of resources. Projects off Park Service lands that support NNL and National Historic Trails programs can include (but are not limited to) those that deal with the Rivers, Trails and Conservation Assistance Program, National Scenic Trails, National Historic Trails, and Wild and Scenic Rivers which are managed by the states, as well as resource-specific projects designated by Congress or the Secretary of the Interior and for which the NPS has a cooperative and oversight role.

Two CCSP projects were funded in 1993, one in Oregon with The Nature Conservancy and the other involving the Washington State Parks and Recreation Commission at Ginkgo Petrified Forest State Park just north of Interstate Highway 90 at Vantage on the Columbia River. The NPS plans to give the commission $6,000 to update and expand the interpretive displays at the state park and to provide a small stipend for volunteers operating the Interpretive Center. In contrast to 1992, when fiscal constraints closed the center during the summer, a stipend ensured public access to the center throughout the summer of 1993.

Currently, projects at three Washington NNLs are being considered for CCSP funding for 1994: (1) ecological restoration at Mima Mounds south of Olympia that involves the Department of Natural Resources and will attempt to reduce the dominance of Scotch broom and remove Douglas fir from the former prairie; (2) the Drumheller Information Center, involving a private landowner, which will provide visitors with information about the flood-scoured scabland topography south of Potholes Reservoir in southeastern Grant County, and (3) the Ginkgo Interpretive Center, which will provide brochures about the state park. Selection of projects to be funded will be made before January 1994.

As mentioned previously, the Department of Natural Resources is one year into a 10-year project at the Mima Mounds. The initial goals of the program are to restore plant communities in the formerly open areas. An integrated approach including controlled burns will be used to manage the Scotch broom in conjunction with replanting cleared areas with native plant species. The burns will mimic the Native American use of fire in this vegetative community. This project was the result of the involvement of neighboring landowners, academic and special interest groups, as well as other state and local agencies.

An Ice Age Flood Task Force, comprising state, federal, and private entities, was formed in the spring of 1993 to develop a comprehensive framework for interpreting the flood story. Eight NNLs in Washington are in areas affected by the glacial outburst floods. (See *Washington Geology*, v. 21, no. 1.) The task force schedule calls for completing a report by April 1994; recommendations for implementation will be made shortly thereafter.

More information about these and other NNL activities is available from Steve Gibbons at the National Park Service, Pacific Northwest Region, 909 First Ave., Seattle, WA 98104-1060. ■

Landslide Inventory and Analysis of the Tilton River–Mineral Creek Area, Lewis County, Washington*

Part 2: Soils, Harvest Age, and Conclusions

by Joe D. Dragovich, Matthew J. Brunengo, and Wendy J. Gerstel

INTRODUCTION

In the previous issue of *Washington Geology* (vol. 21, no. 3), we introduced our pilot slope-stability study and described the methods that allowed us to evaluate relations among landslides, terrain characteristics (such as elevation, aspect, and slope gradient), and geologic materials in the study area. We suggested further that slope-stability is influenced by both bedding attitude and jointing.

In Part 1, we showed that slope gradients measured using topographic maps were consistently less than those measured in the field. This is significant because landslide incidence and slope gradient show a strong correlation: slopes steeper than 25 degrees, and especially 35 degrees, are sites of numerous shallow road and hillslope landslides.

Forty-four percent of the shallow landslides we mapped occurred on deep-seated landslides, which cover approximately 20 percent of the focus study area (half of this is total surface of ruptures and about half is the total deposit area on and below the ruptures). These shallow landslides typically originate on the scarps, flanks, or toes of deep-seated failures; fewer shallow landslides were found on the feet or main bodies.

We also observed that undercutting of slopes is an important cause of failure in the study area, particularly in narrow gorges where streamflow is constrained by steep slopes. Removal of slope buttresses and the resultant landsliding by undercutting contributed to 37 percent of the deep-seated landslides, 18 percent of the shallow landslides, and 12 percent of the road-related landslides in the focus area, which constitutes about half of the 190.6-square-mile general study area.

Landslide occurrence appears to be less directly dependent upon parent material (that is, rock type and surficial material) than, for example, on slope gradient. But parent material indirectly controls several important landslide variables. We documented a very high incidence of landslides on the Hayden Creek till and on some of the intrusive igneous units, particularly those with relatively high quartz and low ferromagnesian mineral contents.

Furthermore, we showed that shallow road and hillslope landslides are somewhat more common between elevations of 1,500 and 3,000 feet and on slopes that face south than in other settings. This may be due to climatic effects: storm-driven rain and warm winds that can preferentially melt snow in this elevation range, saturate the soil column, and destabilize some hillslopes, particularly southerly slopes that face the storms.

In Part 1 of this article, we described how we reached these conclusions. In this follow-up article, we examine relations of soils and timber harvesting history to landsliding in the study area, and we compare and contrast a soils-based slope-stability hazard scheme with our analyses of the landslide inventory. It is important to investigate the effects of stand age as a factor in landslide incidence and to demonstrate how this may affect landslide distribution and hazard zonation efforts. The intent of comparing the landslide inventory and soils hazard zonation scheme is to highlight some limitations of that zonation method. (Also see Thorsen and Othberg, 1979). While the soil-based hazard zonation scheme has been useful for ranking relative slope stability, recent progress toward improved information sources, such as complete geologic map coverage and computer-generated slope gradient maps, allows more accurate depiction of slope stability.

METHODS

We estimated tree canopy ages on and(or) around each landslide using information obtained in the field and from the study of aerial photos. The resulting map of canopy age was digitized into a Geographic Information System (GIS), which allowed easy calculation of planimetric areas of various harvest age classes. These areas, together with our landslide inventory information, were used to determine the density of landslides for each harvest age class—that is, number of landslides/160 acres (quarter section) by 10-year increments since harvest.

Our study relied heavily on two sources of information about soils in the study area: the Soil Conservation Service soil survey of Lewis County (SSLC) (Evans and others, 1987) and the Department of Natural Resources (DNR) soil survey report for the Central Region (undated, ca. 1983?). The areas occupied by individual soil units in the study area were calculated using the DNR soil information available in GIS. We used SSLC soil maps to identify the soil unit(s) above the rupture surface of each landslide.

A *soil series* comprises soils that have similar profiles but in which textures differ in the surface layer or underlying material. All the soils of a series have horizons that are similar in composition, thickness, and arrangement (Evans and others, 1987). The more general soil series are subdivided into smaller soil map units, chiefly on the basis of slope gradient (expressed in percent) but also on features that affect land use and management. These units are called *soil phases* and are the principal units of comparison of soils in this study. Examples of soil phases in the study area are the Baumgard silty loam 15–30%, 30–65%, and 65–90% phases (where the numerals represent range of slope gradient for each soil phase). The 47 soil series in the general study area are divided into 135 soil phases.

We indirectly tested the utility of the soils as hazard rating units by determining the landslide densities for the distributions of two soil properties determined from soil surveys: slope gradient and basal soil type. Soils are divided into one or more horizons partly on the basis of the Unified Soil Classification System (USCS). The SSLC indexed several engineering properties for each horizon, including the classifica-

* The title of Part 1 was incorrectly given as "Landslide inventory and analysis of the Tilton Creek–Mineral River area, Lewis County, Washington". It should be as given in this part of the article.

tion by the USCS (American Society of Testing and Materials designation D-2487-85 and D-2488-84) and Atterberg limits, some of which describe the consistency of a soil on the basis of its water content.

We directly tested the utility of soil phases as hazard rating units by determining landslide densities for the soil phases and comparing and contrasting these values with the soil hazard ratings assigned to these phases. These ratings are not a formal component of any current state slope-stability hazard zonation scheme. However, the ratings have been considered during some forest practice application inquiries and were one of several factors used to prioritize Washington watersheds for further analyses (Green and others, 1993). They thus warrant consideration.

FINDINGS

Landslides and Soils

Soil mantle stability is also influenced by soil properties such as morphology (that is, thickness and layering), texture, depth, organic content, and drainage characteristics.

Many hillslope and road-related shallow landslides have failure surfaces that parallel, and commonly coincide with, the soil–rock interface. Consequently, basal soil-horizon properties, as compiled by the SSLC, should be relatable to soil mantle stability. Deep-seated landslides are less directly relatable to soil type because these are initiated *in* bedrock or thick accumulations of surficial materials. However, soil properties reflect parent material, and therefore soil behavior may be indirectly related to the stability of the parent material. Cliff failures are initiated along bedding or joint planes in rock.

Our comparative analysis for the focus study area shows a degree of correlation among USCS soil types (Table 1), landslide types (Fig. 1), and a slope-stability principle: fine-grained parent materials tend to fail by a deep-seated processes, whereas coarse-grained materials fail by shallow processes. We found that, generally, cohesive fine-grained soils have a high incidence of deep-seated failure (for example, CH-MH and CL-CH), whereas non-cohesive coarse-grained soils (such as GM, GM-SM, SP-GP-SM-GM) have a high incidence of shallow failure. In our study area, as elsewhere, deep-seated landslides appear to be more common in parent materials that weather to fine-grained (more cohesive) soils. Shallow failures such as debris slides, avalanches, and flows can be expected in non-cohesive, dominantly coarse-grained soils. We found that cliff failures (rockfalls, topples, and slides) correlate strongly with gravelly soils (GM, GM-GP), as would be expected for talus deposits directly below cliffs (Fig. 1). Basal soil types for which no landslides are recorded, particularly the CL and GM-ML-SM soils, are found in small areas and thus may be under-represented in our analyses.

In Part 1 of this article, we showed the relation between slope gradient and landslide density (Fig. 2). Because of the importance of this relation, we also looked at the correlation between slope-gradient range (termed slope class) of each soil phase and the occurrence of landslides on these soil phases. Using the area of each soil phase in the general and focus study areas (taken from DNR's GIS soils coverage), we normalized the landslide data using the planimetric area of the soil phases and derived a landslide density for each soil phase.

The relation between landslide density and slope classes for the various soil phases is illustrated in Figure 3. The density of shallow hillslope landslides and, to a lesser degree, of road-related and deep-seated landslides generally increases with slope gradient on all soil types. Shallow landslides show a distinct concentration of failures in the 45–90 and 65–90 percent slope classes. However, comparison of our field-measured landslide slope gradients (Table 2; Fig. 2) and the density of landslides for each soil slope class (Fig. 3) suggests that the landslide densities on slopes having low gradients (0–30%, 5–30%, and 8–30%) are anomalously high. The vast majority of the landslides in the study area, regardless of type, occur on slopes steeper than 30 percent (16.7°; Table 2, Fig. 3). The lack of correspondence between the slope-gradient estimates for the soil phases and our field slope measurements suggests that (1) the soil-phase slope-gradient estimates are low and(or) (2) steep areas are not accurately portrayed by the soil-phase slope-gradient classes. These errors are probably related to determining slope ranges from topographic maps and(or) to natural factors, such as the presence of a forest canopy that may hinder adequate cartographic representation of (1) critical steep slope segments (discussed in Part 1) and (2) soil-phase map boundaries (delineated largely on the basis of slope gradient class).

Landslides and Timber Harvest Age

Timber harvesting and construction of logging roads in the mountainous regions of the Pacific Northwest have been shown by many investigators to influence erosion processes. (For a partial listing of relevant literature, see references

Table 1. Unified Soil Classification System (USCS)

Major divisions			Group symbols	Typical names
Coarse-grained soils (50% or more retained on No. 200 sieve)	Gravels (50% or more of coarse fraction retained on No. 4 sieve)	Clean gravels	GW	Well-graded gravels and gravel–sand mixtures, little or no fines
			GP	Poorly graded gravels and gravel–sand mixtures, little or no fines
		Gravels with fines	GM	Silty gravels, gravel–sand–silt mixtures
			GC	Clayey gravels and gravel–sand–clay mixtures
	Sands (50% or more of coarse fraction passes No. 4 sieve)	Clean sands	SW	Well-graded sands and gravelly sands, little or no fines
			SP	Poorly graded sands and gravelly sands, little or no fines
		Sands with fines	SM	Silty sands and sand–silt mixtures
			SC	Clayey sands and sand-clay mixtures
Fine-grained soils (50% or more passes No. 200 sieve)	Silts and clays (liquid limit 50% or less)		ML	Inorganic silts, very fine sands, rock flour, silty or clayey fine sands
			CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays
			OL	Organic silts and organic silty clays of low plasticity
	Silts and clays (liquid limit greater than 50%)		MH	Inorganic silts, micaceous or diatomaceous fine sands or silts, elastic silts
			CH	Inorganic clays of high plasticity, fat clays
			OH	Organic clays of medium to high plasticity
Highly organic soils			Pt	Peat, muck, and other highly organic soils

Graph designation	USCS soil type	Graph designation	USCS soil type
CH	CH	MH	MH
1	CH-MH	12	ML-MH
CL	CL	13	ML-SM
2	CL-CH	Pt	Pt
GM	GM	SM	SM
6	GM-GP	16	SM-ML-MH
7	GM-ML-SM	17	SM-SP
8	GM-SM-ML-MH	SP	SP
9	GM-SM	19	SP-GP-SM-GM
GP	GP		

marked by asterisks in the "References Cited" section.) Some operations accelerate mass-wasting processes on marginally stable slopes. In the study area, previous clearcuts provide plantation and second growth areas of various ages for comparison of landslide incidence using our landslide inventory data.

We calculated landslide densities by 10-year stand-age classes for hillslope and road-related failures (Figs. 4A,B). For these types of landslides, our findings demonstrate that active and recent slides are substantially more common on the 0–10- and 11–20-year-old stands than on stands more than 20 years old.

Plants stabilize slopes chiefly because their roots enhance soil cohesion and because plants remove some water via evapotranspiration and(or) interception (Pierson, 1980; Megahan, 1983, 1984; Peck and Williamson, 1987; Borg and others, 1988; Reid and others, 1988; Troendle, 1987; Troendle and King, 1987) (Table 3). Forest canopy intercepts some water and temporarily stores it or allows it to evaporate. Because of these buffering mechanisms (including transpiration by vegetation), less water is available to saturate the ground. This interception of water by vegetation is particularly important to slope stability during and after periods of heavy precipitation): annual interception "losses" have been estimated at between 14 percent in the winter and 24 percent in the summer (Krygier, 1971; Rothacher, 1963).

Previous studies indicate that the period of minimum root strength ranges from about 3 to 15 years after harvest, depending on the species cut and replanted, how long after clear-cutting replanting occurs, and climate (O'Loughlin, 1968, 1974; Burroughs and Thomas, 1977; Ziemer, 1981; O'Loughlin and Ziemer, 1982). During this period, which Sidle and others (1985) refer to as "the window of vulnerability", root strength is reduced and major water input during storms can result in soil failure. Root strength will *largely* recover to pre-harvest levels in about 10 to 20 years if significant tree regrowth has occurred; recovery rate depends somewhat on species and climate, and full recovery may take more than 60 years.

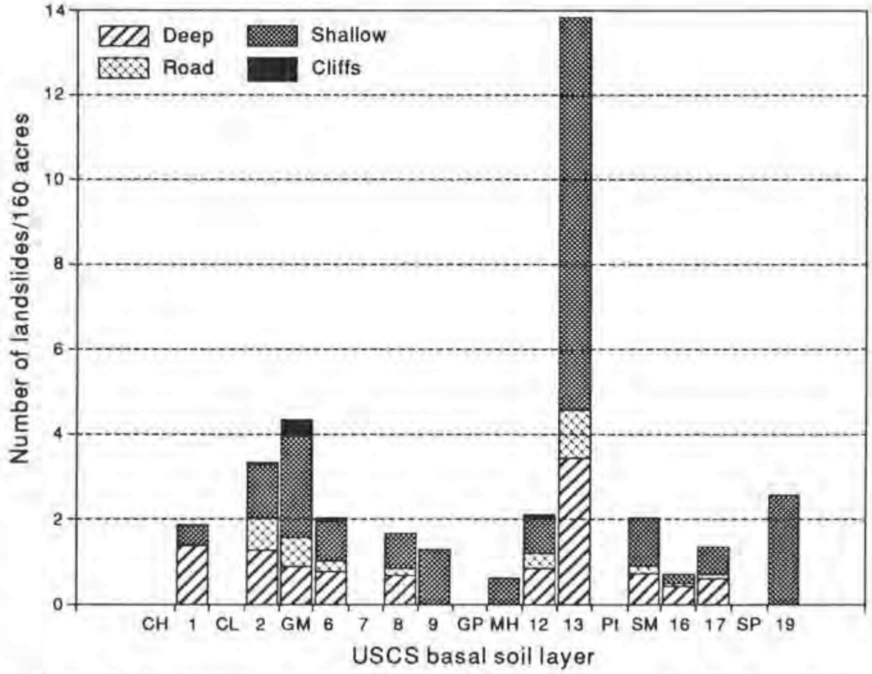


Figure 1. Landslide density (number of landslides/160 acres) by basal soil type for the focus study area. Basal soil types are defined by the Unified Soil Classification System (Table 1) as used in the soil survey of Lewis County (Evans and others, 1987). Soil designations (X-axis) are explained in the adjacent table. There is some correlation between basal soil type and landslide type: dominantly fine-grained soils (such as CH, CH-MH, CL, CL-CH, MH, ML-MH) have a generally higher incidence of deep-seated landsliding, whereas the dominantly coarse-grained soils (GM, GM-GP, GM-SM, SM, SM-SP, and SP-GP-SM-GM), which have low cohesion, have a generally higher incidence of shallow failure.

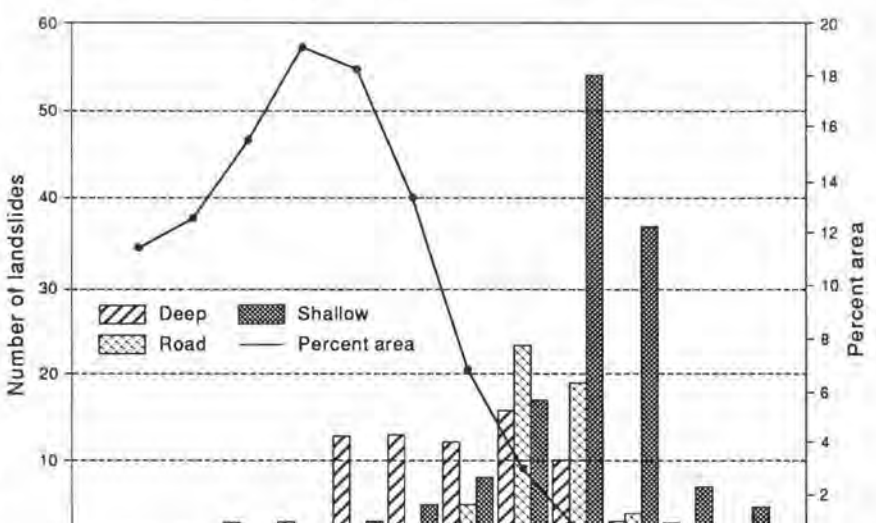


Figure 2. Number of landslides by type per category of field measured slope (in 5-degree classes, left axis) compared with percentage of the general study area (right axis) for each slope category. The number of landslides can be approximately normalized by noting the percent area (black line) for each slope class obtained by use of a GIS and DEM data for the general study area. For the GIS-generated slope ranges, the areas of slope classes decrease significantly at slopes steeper than 25 degrees. Hillslope and road-related shallow landslides are typically initiated at slopes steeper than 26 degrees (50 percent) and are very common on slopes steeper than 35 degrees. Deep-seated landslides are observed on slopes as gentle as 11 degrees and are generally initiated on gentler slopes than are shallow failures. The lack of slope-class percent area for slopes steeper than 50 degrees is a side effect of the way GIS measures slopes—the areas occupied by these slopes are so small that they are not accurately recorded by GIS at this scale.

The strong correlation between the densities of active and recent road landslides and the age of timber stands adjacent to roads (Fig. 4B) indicates that vegetation plays an important role in the stability of road fills, sidecasts, landings, and cut-slopes. Steep landing slopes and cut-slopes (particularly partial-bench road grades made of sidecast material) commonly have only marginal stability in steep terrain. Trees introduced by planting or natural revegetation along road margins provide added stability through root cohesion and evapotranspiration–interception of water (Table 3).

Dormant shallow-hillslope and road-related landslides are largely in older timber stands, and their densities display a weaker correlation with stand age (Figs. 4A,B). These shallow landslides may have been initiated by root decay following earlier clear-cuts or forest fires. However, some active and recent shallow landslides occur in older stands, an observation that reinforces the fact that (1) mass wasting is natural at some sites and (2) root decay can be a secondary factor or non-factor in soil and fill stability. Failures in older stands commonly remove swaths of timber several trees wide, which makes these features visible on aerial photographs. In addition, our rigorous field verification in the focus areas gives us confidence in the low landslide density values for stands more than 20 or 30 years old.

In our study, forest practices (for example, tree removal) show a strong correlation with an increased landslide incidence on sites of marginal natural stability (for example, slopes steeper than 35°; see Part 1 or Fig. 2).

The effects forest practices have on deep-seated failures are less well understood than their effects on shallow soil-mantle failures. Because deep-seated landslides commonly fail below rooting depth, root cohesion and reinforcement normally do not play an important role in slope stabilization. Indeed, in the study area, we observed a weak correlation between both active and recent deep-seated landsliding and stand age. However, without detailed information about movement histories (for example, using displacement arrays to document slow motions) of deep-seated slides, precise statements cannot be made concerning the effect of tree removal on slow-moving deep-seated landslides.

The significantly increased water input to the ground in clear-cut areas as a result of vegetation removal and reduced evapotranspiration–interception may be important on some

Table 2. Landslide statistics for soil-phase slope classes (Fig. 3) having slopes of 30 percent (16.7°) or less for the focus study area. In the field (Fig. 2), we measured slope gradients on numerous random landslides and adjacent slopes in the 0–30 percent soil-phase slope classes (B and C). Of 49 measurements made on shallow landslides, none had a gradient of less than 30 percent. Compare these values with those for other landslide types. Our data suggest that soil-phase slope classes understate the actual gradient for these areas and do not precisely represent surface configurations

Query	Deep	Road	Shallow	Cliff
(A) Total number of inventoried landslides	512	249	838	43
(B) Number of inventoried landslides in soil-phase slope classes <30%	62	15	49	1
(C) Percent of inventoried landslides in soil-phase slope classes <30%	12	6	6	2
(D) Number of inventoried landslides in soil-phase slope classes <30% measured in the field	36	10	26	0
(E) Number of inventoried landslides in the <30% soil-phase slope classes actually having slopes <30% as measured in the field	1	0	0	0

Slope Gradient Conversion Table

Degrees	Percent	Degrees	Percent
5	8.7	2.7	5
10	17.6	4.6	8
15	26.8	5.7	10
20	36.4	8.5	15
25	46.6	11.3	20
30	57.7	14	25
35	70.0	16.7	30
40	83.9	19.3	35
45	100.0	21.8	40
50	119.2	24.2	45
55	142.8	26.6	50
60	173.2	28.8	55
65	214.5	31	60
70	274.7	33	65
75	373.2	35	70
80	567.1	36.9	75
85	1143.0	38.7	80
90	–	42	90

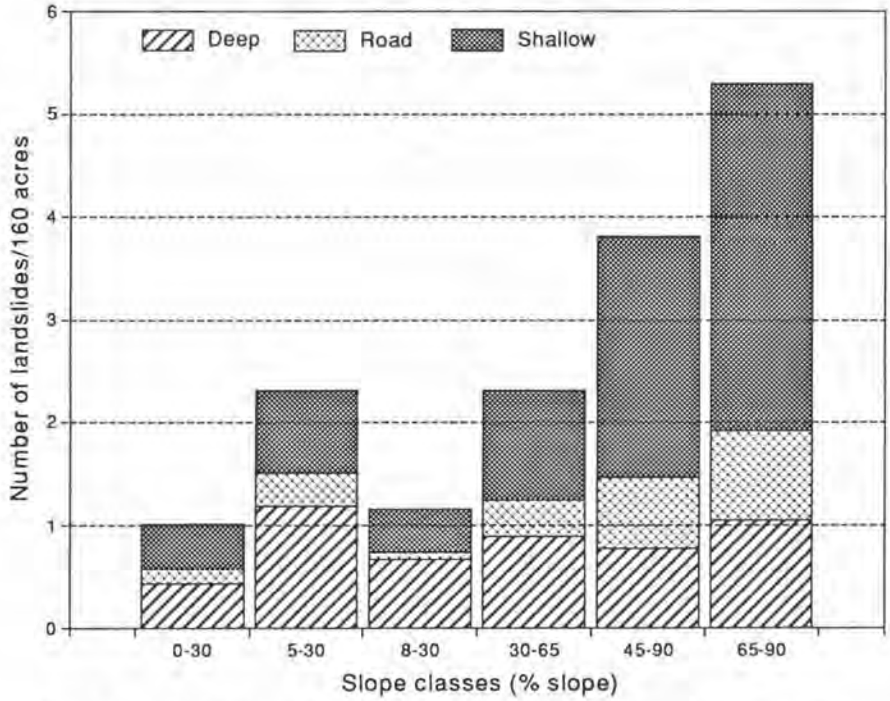
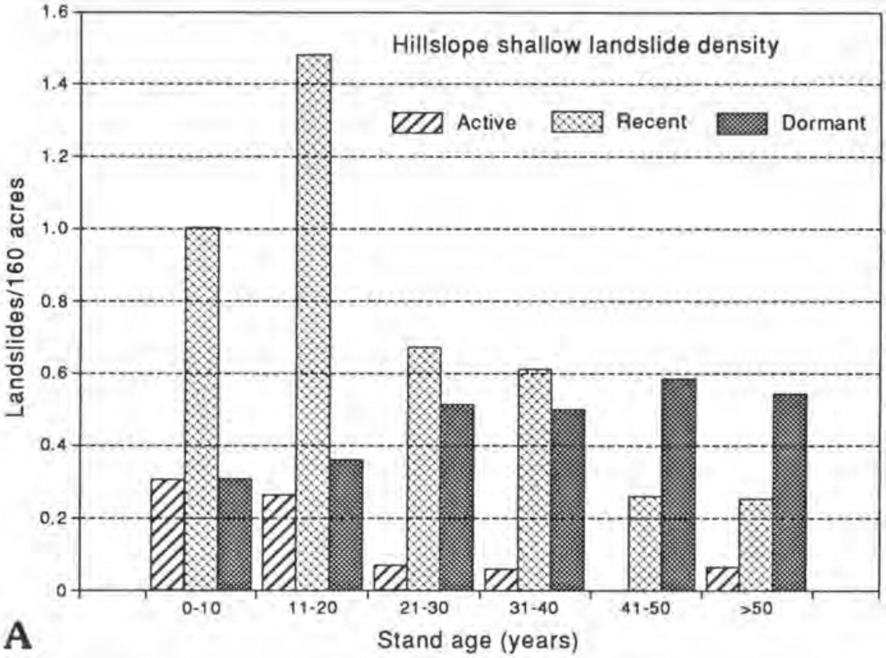


Figure 3. Landslide density (number of landslides/160 acres) versus slope range for soil phases in the focus study area. The slope ranges (termed classes) are derived from the Lewis County and DNR soil-phase slope designations. Slope-gradient conversions are shown in the adjacent table. On the basis of field measurements of slopes, the area of the slope classes in the study area (Fig. 2; Table 2), and the landslide densities observed for these slope classes suggest that the SSLC soil-map slope measurements are inaccurate. This is supported by the fact that we did not observe any hillslope or road-related shallow failures on slopes less than 30 percent (16.7°) (Table 2).



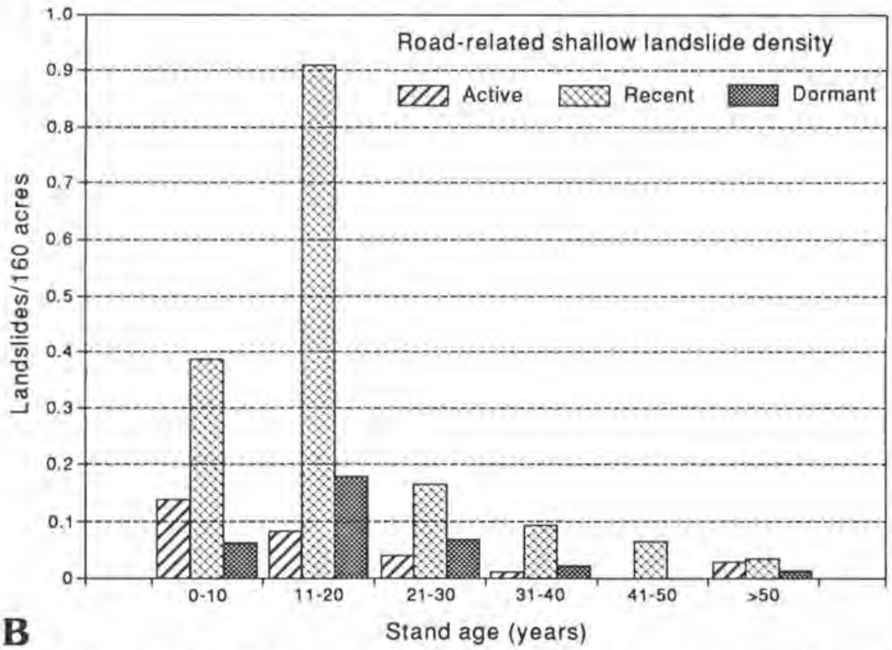


Figure 4. Hillslope (**A**) and road-related (**B**) shallow landslide density (number of landslides/160 acres) and landslide activity by stand age for the general study area. (Note Y-axis scale differences.) Most active and recent landslides here occur on the 0–20-year-old stands. Shallow and road-related landslides have failure planes within the soil mantle and thus are more sensitive to soil strength changes brought on by disturbance. Our finding supports those of several studies that show (1) that root reinforcement of soil is diminished from about 3 to 20 years after harvesting and (2) that roots approach pre-harvest strength after about 20 years, but it may take much longer for complete recovery. Note the reduction in active and recent landslide densities after about 20 years.

deep-seated landslides. Substantially increased peak flows were documented after logging in watersheds of the Oregon Cascades (Rothacher, 1971; Harr and others, 1975, 1979; Harr and McCorison, 1979). Where vegetation does not remove it, water can travel along bedding or failure surfaces and may initiate, rejuvenate, or accelerate deep-seated failures on these surfaces (Swanston, 1981; Swanston and others, 1988).

Even though large deep-seated failures cannot convincingly be tied to canopy removal, our data (provided in Part 1 of this article) show that shallow failures are more common on deep-seated failures in the study area. A high incidence of shallow slides on deep-seated slides may set up a feedback mechanism whereby shallow failures (especially those resulting from timber removal) may remove enough of the slide mass to reactivate slumping (particularly on toe areas that are susceptible to stream undercutting). Furthermore, aggradation of streams after forest removal reflects at least some sediment input resulting from shallow landslides. This aggradation could cause lateral channel migration that may further undercut toes of deep-seated landslides and thereby increase the possibility of deep-seated slide reactivation.

Landslides and Soil Hazard Ratings

The Department of Natural Resources soil survey report (DNR, 1983?), initiated by the Washington State Private Forest Land Grading Program (see, for example, Forest Land Grading Staff, 1978), rates hazards associated with slope stability and road construction on the basis of soil characteristics. The soil hazard ratings are divided into three general categories: (1) natural slope stability, (2) disturbed slope stability, and (3) stability of cuts, fills, and sidecasts (Tables 4 and 5). The natural slope-stability rating refers to a soil and its underlying material in an undisturbed state and under normal climatic circumstances. The hazard ratings for natural conditions are based on: (1) the physical characteristics and behavior of the soil; (2) the behavior of the underlying material; (3) drainage, seeps, and depth to a water table or perched water; and (4) observations of natural slope failures.

In contrast, the disturbed slope-stability rating covers conditions of soil and parent material after construction of roads and landings and(or) timber harvesting. The hazard ratings for disturbed management conditions consider the items that are listed above, as well as the incidence of slope failures on disturbed forest lands.

The roadcut, fill, and sidecast, or CFS, hazard rating refers to the hazard presented by erosion, slough or collapse of cut slopes and fills, as well as erosion, sliding, or down-slope flow of sidecast. These ratings are based on: (1) the physical characteristics and behavior of the soil; (2) the behavior of the underlying material; (3) slope steepness; (4) soil drainage (for example, presence of water table or seeps); and (5) seasonal wetness.

As we noted previously, landslide densities on soil phases were determined by combining the areas of soil phases (obtained from the DNR GIS soils coverage) and the numbers and types of landslides on each soil phase, using our inven-

Table 3. Relations between engineering activities and slope stability factors in the Pacific Northwest (modified from Swanston and Swanson, 1976); + and –, commonly increases or decreases stability, respectively

Factors	Deforestation	Roading	References
I. Hydrologic			
A. Movement of water by vegetation	Reduce evapotranspiration (–)	Eliminate evapotranspiration (–)	Gray (1970) Brown and Sheu (1975)
B. Surface and subsurface water movement	Alter snowmelt hydrology (– or +)	Alter snowmelt hydrology (– or +) and drainage network (–)	Anderson (1969) Harr and others (1975)
		Intercept subsurface water at roadcuts (–)	Megahan (1972)
	Alter concentration of unstable debris in channels (–)	Alter concentration of unstable debris in channels (–)	Rothacher (1959) Froehlich (1973)
	Reduce infiltration by ground surface disturbance (–)	Reduce infiltration by roadbed (–)	
II. Physical			
A1. Vegetation—roots	Reduce rooting strength (–)	Eliminate rooting strength (–)	Swanston (1970) Nakano (1971)
A2. Vegetation—bole and crown	Reduce medium for transfer of wind stress to soil mantle (+)	Eliminate medium for transfer of wind stress to soil mantle (+)	Swanston (1969)
B1. Slope angle		Increase slope angle at cut and fill slopes (–)	Parizek (1971) O'Loughlin (1972)
B2. Mass additions or subtractions to slope	Reduce mass of vegetation on slope (+)	Eliminate mass of vegetation on slope (+)	Bishop and Stevens (1964)
		Cut and fill redistributes mass of soil and rock on slope (– or +)	O'Loughlin (1972)
C. Soil properties		Reduce compaction and apparent cohesion of soil used as road fill (–)	

tory database. We sorted these densities by landslide type (deep, road, shallow, cliff) and by study area (focus and general). Data were secondarily sorted by land management history: landslides in areas where the stand ages are less than 60 years old were included in the disturbed category, and slides in stands more than 60 years old were included in the undisturbed or natural category. This division by age is based on extrapolated estimates for time required for complete root regrowth after disturbance (McMinn, 1963).

The utility of the soils rating system can be tested by comparing the distribution of the soil hazard ratings and the densities of deep, shallow, road, and cliff landslides. We compared hillslope landslide densities to hillslope stability ratings in both natural and disturbed conditions. Road-related landslide densities were compared to the CFS hazard ratings in the "total" management condition (disturbed + undisturbed conditions). The average density (explained in Fig. 5A) of deep-seated, shallow (Figs. 5B,C), road (Fig. 5D), and cliff landslides increases with increasingly hazardous soil ratings in both the general and focus study areas and for disturbed and natural management histories.

We found that the DNR rating system predicts landsliding on very unstable soils in a disturbed setting, but it does not predict the landslides we documented on many "stable" soil units. Unrecognized deep-seated landslides are rated as stable on several hillslopes. Furthermore, on many of the soil units rated as "unstable" we found no landslides.

Several of the DNR "stable" units have high densities of shallow landslides in both natural and disturbed settings and in both the general and focus study areas (Tables 6 and 7). Shallow failures in natural settings tend to occur on steep slopes (>30% slope gradient) (Fig. 2). Some high landslide densities are associated with "stable" flood plain soil phases (such as Ledow sand and Reed silty clay loam). For example, the poorly drained Reed silty clay loam soil phase (0–3% slope) had 0.48 shallow landslides/160 acres in a disturbed setting.

In disturbed settings, failures of all types extend into areas of moderate to low slope gradients on flood plains, terraces, or general lowlands. In these "stable" areas, stream undercutting and(or) local over-steepening are important causes of failure, particularly where trees have been removed.

It is worthwhile noting that several rock-outcrop complexes have a high density of landslides. These mapped complexes may be prone to failure either because they contain significant pockets of thin soils between steep rocky exposures and(or) because of intrinsic weaknesses of jointed or fragmental rock masses, neither of which is indicated in the soil hazards designations of several of the soil units. Note the increased density of landslides on rock outcrop complexes (Table 6) in the disturbed state compared to natural conditions. This implies that these thin rocky soils are sensitive to disturbance and may be more prone to failure than is suggested by the soil hazard rating system.

The soil hazard rating system uses a determinative flow chart that incorporates several slope-stability criteria (Fig. 6). These include water-perching potential, presence of volcanic ash or cinders in the soil profile, slope gradient, management history (natural or disturbed), and presence of slumps, landslides, or other special slope problems. If responses to flowchart queries are based on erroneous or incomplete information, the result will probably be inaccurate hazard zonations.

We compared the soil hazard ratings determinative flow chart with the availability of information and our landslide inventory and observations. Our observations derived from these comparisons pertain directly to our study area. However, many of these observations are applicable beyond this area. The following points should be considered if the flowchart approach (Fig. 6) to hazard rating is followed:

- The query "Are there natural slumps or landslides [or] other natural slope problems?" presupposes some prior

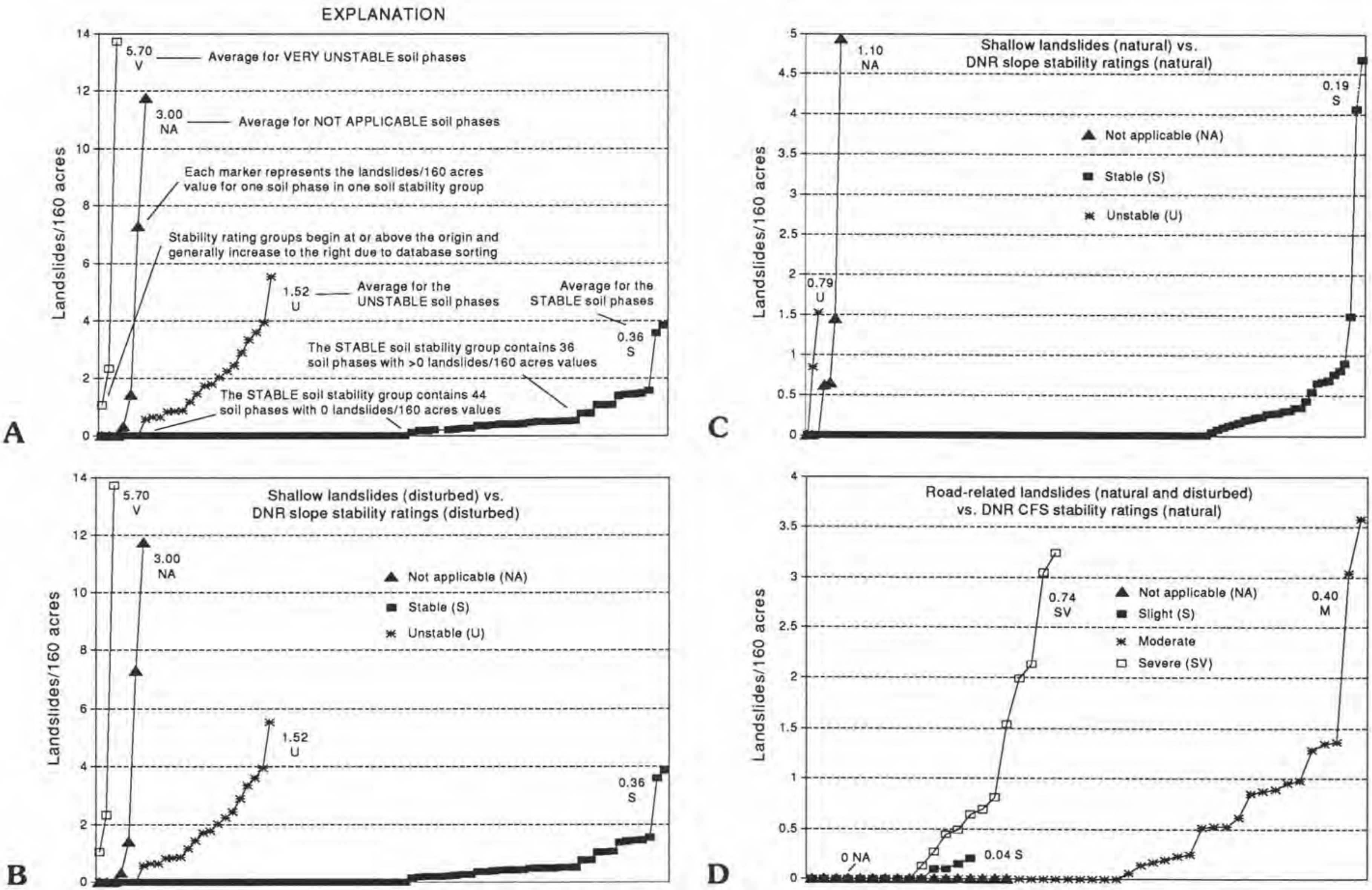


Figure 5. Comparison of landslide density by soil phase and soil hazard ratings (from Washington Department of Natural Resources, 1983?). Features of these line graphs are explained in **A**. Shallow landslide density by soil phase is compared to the soil hazard rating for natural (**B**) and disturbed (**C**) management conditions in the general study area. **D** shows the road-related landslide density by soil phase versus the cut-fill-sidecast (CFS) hazard rating in the focus study area. Note the Y-axis scale differences. Tables 6 and 7 list densities (greater than zero) for soil phases and shallow and road-related (focus study area) landslides, respectively. Generally, average landslide densities (numbers next to curves) increase with increasing hazard rating. However, some "stable" soil units display significant landslide densities (for example, Ledow sand, 0–3%, Table 6), and some unstable units have zero landslide densities. These apparent contradictions can be explained in terms of inadequate geologic, landslide inventory, or slope information used in determining the soil hazard ratings.

Table 4. Slope-stability hazard rating definitions and management considerations for slopes in natural and disturbed management conditions (DNR, 1983?). Definitions and considerations are for terms found in Figures 5B,C, and 6

Condition	Rating	Definition/management considerations
Natural	Stable	No significant stability problems occur under normal circumstances
Natural	Unstable	Significant stability problems occur under normal circumstances. Slope-stability should be a major consideration when selecting road locations, designing roads, and developing harvest plans
Disturbed	Stable	No significant stability problems related to soil or underlying material occur when careful road construction and timber harvesting techniques are applied
Disturbed	Unstable	Stability problems related to soil and underlying material can occur, but they can be overcome or minimized by applying current road construction technology, practicing good road maintenance and logging carefully, or by accepting practical alternatives that would avoid problems
Disturbed	Very unstable	Stability problems related to soil and underlying material can occur, and they cannot be entirely overcome by using current road construction and logging technology. Alternative road locations and logging methods should be considered

knowledge and should be based on thorough inventories. This query leads to "stable" and "unstable" ratings and may also explain the presence of landslides observed on soil phases rated as stable in the study area.

- The query "Is [the map unit identified] as "slumped" or "eroded" phase?" is used to differentiate "unstable" from "very unstable" hazard ratings. An accurate answer also requires detailed landslide mapping. Delineation of deep-seated landslides is important because these failures are sites of numerous shallow failures. (See Part 1.) The *very weak* correspondence between mapped soil-unit boundaries and our mapped scarp, main-body, and deposit boundaries for deep-seated failures indicates that the soil mapping in the study area does not accurately reflect areas affected by deep-seated failures. A few shallow and road-related landslides are demarcated by the SSLC, but they greatly under-represent the state and degree of landsliding in the study area.
- Slope gradient is commonly the dominant factor in stability of a slope. (See Part 1.) In the soil hazard rating system, a gradient of 65 percent (33°) divides stable from unstable or unstable from very unstable soil phases on natural or disturbed hillslopes, respectively. Our slope-gradient data and that of others (such as Sidle and others, 1985; Jones and Howard, 1992) suggest that a slope gradient of 50 percent (26.6°) or better delimits the onset of significant shallow landsliding on slopes prone to failure. A lower minimum slope gradient is also warranted by our observation that slope gradient is commonly underestimated. It should be noted that deep-seated failures are initiated at lower slope gradients than are shallow failures and are therefore more difficult to predict on the basis of slope gradient alone.
- Soil-phase slope estimates probably do not incorporate important local steep areas (such as inner gorges or small escarpments) in otherwise moderately rugged to gentle terrain. We mapped many landslides on soil phases rated as stable that are on steep segments in terrain classified as gently to moderately sloping.

Table 5. Cut, fill, and sidecast (CFS) hazard rating definitions and considerations for roads (DNR, 1983?). Definitions and considerations are for terms found in Figure 5D

Rating	Definition and considerations
N.A.	A rating is not applicable on this nearly level unit [which also includes a few units not found or not rated by the hazard rating system]
Slight	The hazard can be overcome by standard road construction methods, including careful cutting and filling
Moderate	The impacts of the hazard can be reduced or minimized by standard road construction methods, including carefully planned cutting and filling
Severe	The impacts of the hazard can be reduced only by special road construction methods, including carefully planned excavating and end-hauling

- Soils are typically weathering products of the underlying parent material, and thus their composition depends on the parent material. Previous geologic maps (for example, Fisher, 1957) covered only parts of the study area. A geologic compilation of the whole study area was not available until 1987 (Schasse, 1987). We re-examined this compilation during our field investigations and found that, in general, it accurately portrayed distribution of the geologic units. However, a map at a scale of 1:100,000 may not show lithologies prone to failure (such as breccias in volcanic units and shales sedimentary units). Also, the landslide-prone Hayden Creek till unit (see Part 1) along the lower slopes of the East Fork Tilton River was not mapped by previous workers.
- Figure 6 suggests that "(1) lacustrine, river, or ocean sediments; (2) residuum from siltstone or fine-grained sandstone; (3) sandy outwash" containing "slumped" or "eroded" phases or "natural slumps or landslides [or] other 'special' natural slope problems" are inherently less stable than "residuum from volcanics, medial ash, etc.". However, numerous landslides were observed on several of the latter geologic units (for example, residuum from volcanics). (See Part 1.) We believe that this query also disregards many important geologic units that are susceptible to mass wasting (for example, some intrusive or most ultramafic rocks).
- The flow chart states that if the "whole [soil] profile consists of (1) loose, coarse [volcanic] ash or cinders; (2) layers of ash and cinders", then it is unstable. However, boundaries are imprecisely known even for the most extensive deposits of this type. Most of these deposits have been redistributed by surface erosion, resulting in complex map patterns. Mapping these deposits, particularly older deposits, in the densely vegetated areas of western Washington requires intensive field investigation that may not be practical. To our knowledge, it has not been established that ash or tephra layers in soil profiles predispose soil mantles to landsliding. These typically thin deposits (1) constitute only a fraction of any randomly selected soil profile in the more distal parts of volcaniclastic deposits or in volcanic provinces; (2) generally have a low specific gravity, reducing the down-slope forces on these layers; and (3) in the case of pumice, are commonly porous and act as soil drains that can reduce pore pressures. Siliceous

Table 6. Shallow landslide densities (landslides/160 acres) for the focus study area. Hillslope stability ratings are: S, stable; U, unstable; V, very unstable

Soil phase, % slope gradient	Stability rating	Landslide density
A. DISTURBED MANAGEMENT CONDITIONS		
Nesika loam, 2-5%	S	0.153
Zynbar gravelly silt loam, 30-65%	S	0.179
Stahl-Rock outcrop complex, 30-65%	S	0.195
Jonas gravelly silt loam, 8-30%	S	0.207
Cinebar silt loam, 8-15%	S	0.298
Cotteral very cindery sandy loam, 8-30%	S	0.363
Bellicum very cindery loamy sand, 30-65%	S	0.388
Newaukum gravelly silt loam, 15-30%	S	0.401
Pheeney-Jonas complex, 8-30%	S	0.415
Zynbar gravelly silt loam, 8-30%	S	0.453
Reed silty clay loam, 0-3%	S	0.476
Cispus cindery sandy loam, 15-30%	S	0.527
Pheeney-Rock outcrop complex, 30-65%	S	0.531
Galvin silt loam, 0-8%	S	0.606
Pheeney-Jonas complex, 30-65%	S	0.618
Newaukum gravelly silt loam, 30-65%	U	0.684
Bromo very cindery sandy loam, 8-30%	S	0.687
Andic Xerumbrepts, steep	U	0.693
Cattcreek very cindery loamy sand, 65-90%	U	0.718
Schneider-Baumgard complex, 30-65%	S	0.761
Stahl very gravelly silt loam, 65-90%	U	0.767
Bromo very cindery sandy loam, 30-65%	S	0.816
Cispus cindery sandy loam, 30-65%	U	0.840
Bellicum very cindery loamy sand, 65-90%	U	0.880
Jonas gravelly silt loam, 30-65%	S	0.889
Nevat-Rock outcrop complex, 65-90%	U	0.902
Rock outcrop-Pheeney complex, 65-90%	U	0.922
Cinebar silt loam, 30-65%	S	0.950
Cattcreek very cindery loamy sand, 30-65%	S	0.972
Mal clay loam, 8-30%	S	1.451
Stahl very gravelly silt loam, 30-65%	S	1.495
Cattcreek-Rock outcrop complex, 65-90%	U	1.543
Bellicum-Rock outcrop complex, 30-65%	S	1.622
Dobbs loam, 30-65%	U	1.849
Vailton silt loam, 30-65%	U	1.852
Pheeney gravelly loam, 30-65%	S	1.910
Vailton silt loam, 65-90%	V	2.136
Nevat-Rock outcrop complex, 30-65%	S	2.206
Rock outcrop-Stahl complex, 65-90%	U	2.388
Aquic Xerofluvents, overflow	S	2.561
Stahl-Rock outcrop complex, 65-90%	U	2.641
Pheeney gravelly loam, 65-90%	U	3.031
Vailton-Rock outcrop complex, 65-90%	V	3.243
Reichel loam, 30-65%	S	3.581
Rubbleland	NA	3.616
Bellicum-Rock outcrop complex, 65-90%	U	3.651
Schneider very gravelly silt loam, 65-90%	U	3.988
Pheeney-Rock outcrop complex, 65-90%	U	4.115
Vailton Variant loam, 30-65%	U	5.574
Rock outcrop	NA	6.743
Schneider-Rock outcrop complex, 65-90%	NA	9.987
Ledow sand, 0-3%	S	10.972
Vailton Variant-Rock outcrop, 65-90%	V	13.712
B. NATURAL MANAGEMENT CONDITIONS		
Zynbar gravelly silt loam, 8-30%	S	0.050
Pheeney gravelly loam, 65-90%	S	0.087
Cattcreek very cindery loamy sand, 30-65%	S	0.108
Pheeney-Jonas complex, 30-65%	S	0.137
Stahl very gravelly silt loam, 65-90%	S	0.192
Bellicum-Rock outcrop complex, 65-90%	S	0.215
Pheeney-Rock outcrop complex, 30-65%	S	0.266
Stahl-Reichel complex, 30-65%	S	0.268
Newaukum gravelly silt loam, 15-30%	S	0.301
Pheeney gravelly loam, 30-65%	S	0.332
Newaukum gravelly silt loam, 30-65%	S	0.342
Zynbar gravelly silt loam, 30-65%	S	0.359
Vailton silt loam, 30-65%	S	0.441
Vailton-Rock outcrop complex, 65-90%	U	0.541
Pheeney-Rock outcrop complex, 65-90%	S	0.787
Jonas gravelly silt loam, 8-30%	S	0.828
Stahl-Rock outcrop complex, 65-90%	S	0.880
Rock outcrop-Stahl complex, 65-90%	S	1.061
Vailton Variant-Rock outcrop, 65-90%	U	1.524
Andic Xerumbrepts, steep	S	1.645
Pheeney gravelly loam, 8-30%	S	2.672
Cinebar Variant silty clay loam, 30-65%	S	4.681
Rubbleland	NA	5.424
Rock outcrop-Pheeney complex, 65-90%	S	5.532

Table 7. Road-related landslide densities (landslides/160 acres) for the focus study area. Road stability ratings are: S, slight; M, moderate; SV, severe

Soil phase, % slope gradient	Stability rating	Landslide density
Zynbar gravelly silt loam, 30-65%	M	0.060
Cinebar silt loam, 8-15%	S	0.099
Zynbar gravelly silt loam, 8-30%	S	0.101
Bellicum very cindery loamy sand, 30-65%	SV	0.129
Pheeney-Jonas complex, 30-65%	M	0.137
Nesika loam, 2-5%	S	0.153
Pheeney gravelly loam, 30-65%	M	0.166
Newaukum gravelly silt loam, 30-65%	M	0.190
Jonas gravelly silt loam, 8-30%	S	0.207
Bromo very cindery sandy loam, 8-30%	M	0.229
Newaukum gravelly silt loam, 15-30%	M	0.251
Cattcreek very cindery loamy sand, 30-65%	SV	0.270
Nevat-Rock outcrop complex, 65-90%	SV	0.451
Cattcreek-Rock outcrop complex, 30-65%	SV	0.491
Pheeney gravelly loam, 65-90%	M	0.520
Cispus cindery sandy loam, 15-30%	M	0.527
Pheeney-Rock outcrop complex, 30-65%	M	0.531
Vailton silt loam, 30-65%	M	0.617
Bellicum-Rock outcrop complex, 65-90%	SV	0.644
Andic Xerumbrepts, steep	SV	0.693
Bellicum-Rock outcrop complex, 30-65%	SV	0.811
Pheeney-Rock outcrop complex, 65-90%	M	0.847
Mal clay loam, 8-30%	M	0.870
Jonas gravelly silt loam, 30-65%	M	0.889
Cinebar silt loam, 30-65%	M	0.950
Stahl-Rock outcrop complex, 30-65%	M	0.974
Stahl very gravelly silt loam, 30-65%	M	1.281
Stahl very gravelly silt loam, 65-90%	M	1.342
Stahl-Rock outcrop complex, 65-90%	M	1.361
Cattcreek-Rock outcrop complex, 65-90%	SV	1.543
Schneider very gravelly silt loam, 65-90%	SV	1.994
Vailton silt loam, 65-90%	SV	2.136
Schneider-Baumgard complex, 30-65%	M	3.044
Vailton Variant-Rock outcrop, 65-90%	SV	3.047
Vailton-Rock outcrop complex, 65-90%	SV	3.243
Reichel loam, 30-65%	M	3.581

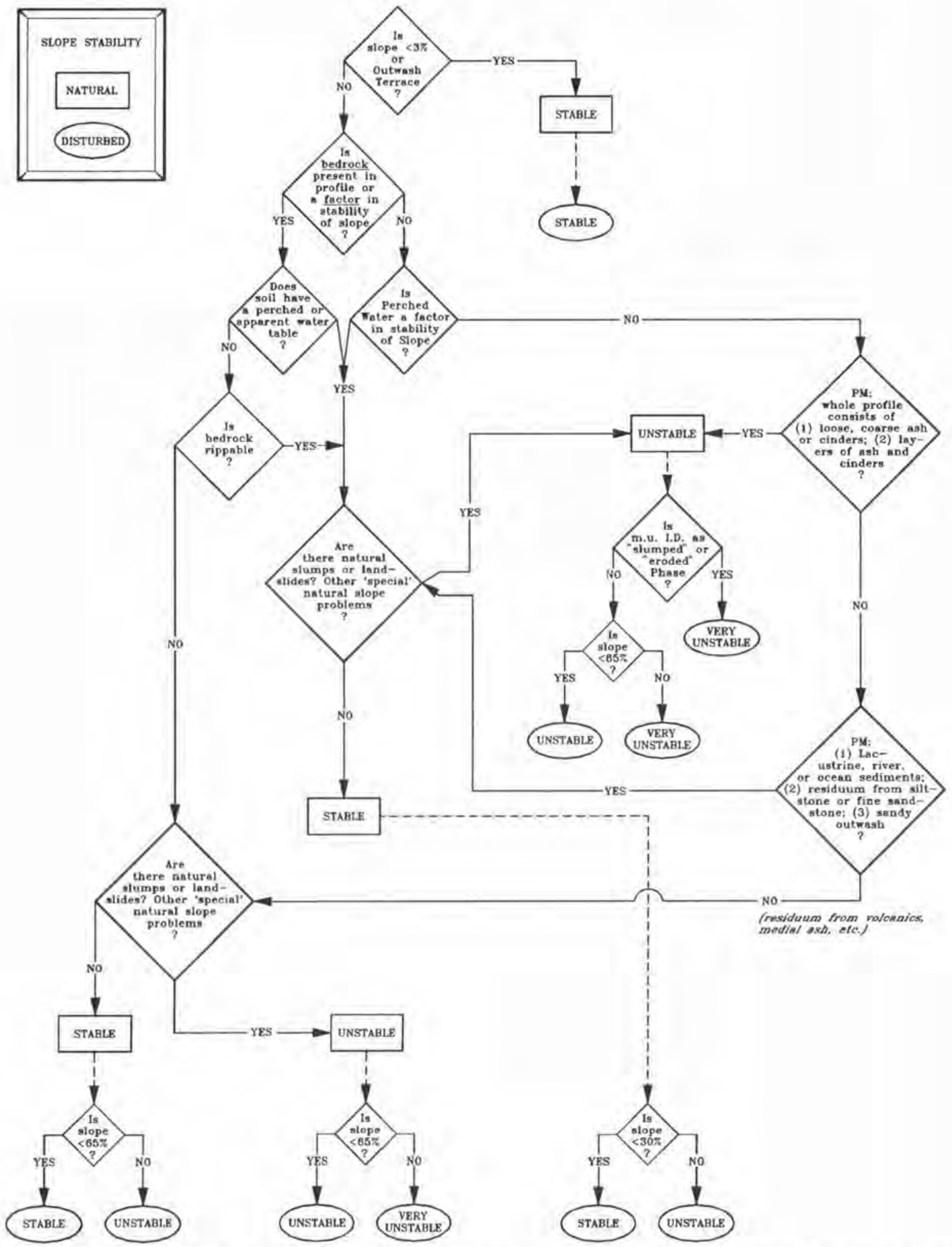


Figure 6. Department of Natural Resources flow model for determining slope-stability hazard. Determinations in rectangles and ellipses are for natural and disturbed management conditions, respectively (Table 4, definitions). PM, parent material; m.u. I.D., map unit identification (the soil phase). This hazard zonation method can predict overall relative stability (indicated by the averages in Fig. 5). Limitations of this method are reviewed in the text.

tephras contain low percentages of ferromagnesian minerals and probably produce less clay during alteration; they thus may be less cohesive. Older tephra deposits will be more thoroughly weathered, devitrified, and likely more cohesive. Re- examination of the significance of tephra of different ages, size ranges, and compositions seems warranted.

- The length of time that separates natural and disturbed management histories is not described by the DNR soil hazard rating system. On the basis of comparing results of both previous root-strength studies and our harvest-history/landslide-density data analysis, we conclude that a site should be classified as disturbed for at least 20 years and perhaps as long as 60 years after harvesting.

CONCLUSIONS

Assessments of slope-stability (including the soil hazards rating scheme) can be improved by using new data-gathering and analytical techniques such as GIS or incorporating recent studies (for example, landslide inventories). But the limitations of each data-gathering method must be recognized, and the data should be combined with the results of site-specific work to develop a more realistic evaluation of slope stability. For example, detailed slope-stability assessments should be supported by geologic mapping at 1:24,000 scale or larger. While the soil hazards ratings are useful as a preliminary tool, our pilot study has shown that a landslide inventory compiled using air-photo and field methods and more exacting slope-gradient class determinations can dramatically improve the precision and accuracy of hazard zonation.

We found that deep-seated landslides are common mass-wasting features on which there is typically a high incidence of shallow and road-related landslides. Slopes undercut by streams are particularly vulnerable to mass wasting.

Slope gradient is the dominant control of stability: shallow failures are common on slopes steeper than 25 degrees and can be abundant on slopes steeper than 35 degrees, especially if the slopes have been disturbed. We confirm results of several other studies that have shown that shallow sliding is increased from 3 to 20 years following timber harvesting, apparently as a result of decreased tree-root strength and reduced evapotranspiration and water interception.

GIS provides an efficient and cost-effective method of producing slope maps derived from digital elevation model (DEM) data. However, we have found that the resolution of DEM and GIS data may not accurately portray small steep areas. The wide spacing of spatial data (30-meter grid for U.S. Geological Survey 7.5-minute DEM data) tends to smooth out those important steep areas prone to failure. Nevertheless, the speed of GIS and its lower susceptibility to human error compared to methods of slope determination from topographic maps can compensate for this deficiency in some applications (for example, developing a slope gradient map for a large area).

On the basis of our findings, we believe that any method of slope-stability hazard zonation should include:

(1) a landslide map that emphasizes deep-seated landslides as features that generally have a higher incidence of shallow landsliding than non-slumped areas,

(2) a geologic map at 24,000-scale or larger (in Washington 1:100,000-scale geologic map coverage is generally available; larger scale maps are not commonly available),

(3) a slope-gradient map prepared using GIS or equivalent computer methods (as long as limitations of the method are evaluated); USGS 1:24,000-scale DEM data are now available for most of the state, and

(4) additional map information that may include the rain-on-snow zones, soil character (but acknowledging the limitations of the soil hazard ratings discussed previously), and(or) precipitation.

Stability of individual hillslopes could be zoned in considerable detail using field observations and other data, such as landslide aspect or elevation.

The authors are preparing an open-file report about this pilot project. The report will provide more detailed information about the investigation as well as the landslide inventory data.

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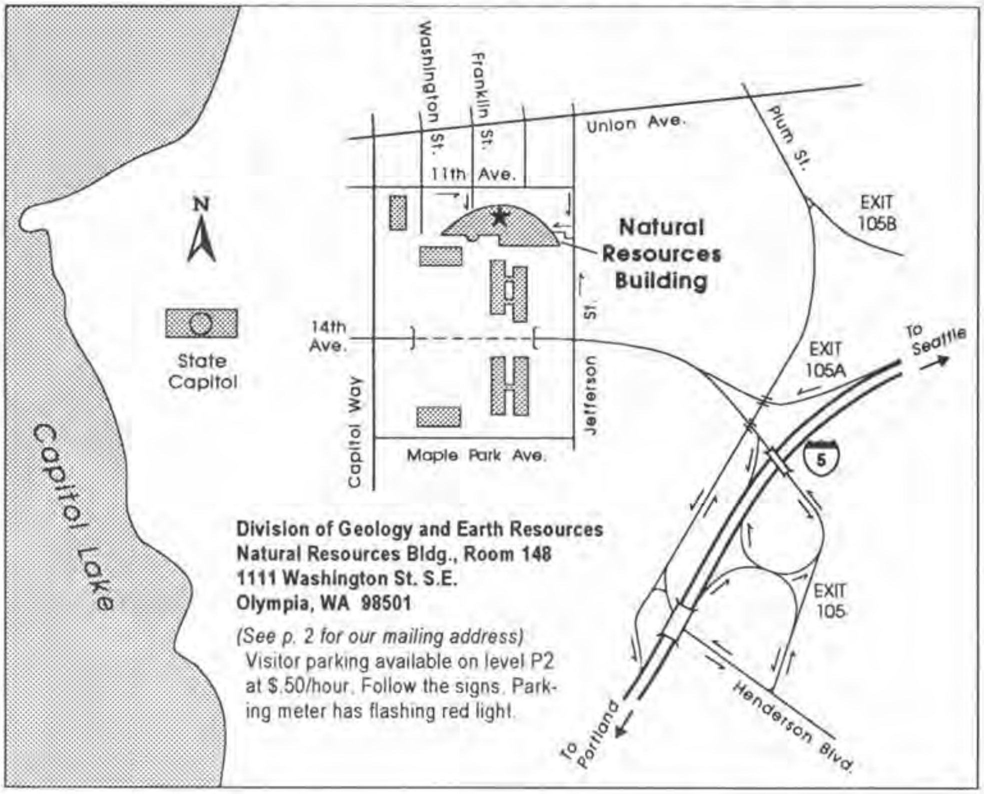

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