Chapter 2

Quaternary Geology of the Channeled Scabland and Adjacent Areas

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ABSTRACT

The Quaternary history of the Channeled Scabland is characterized by discrete episodes of catastrophic flooding and prolonged periods of loess accumulation and soil formation. The loess sequence is correlated with Richmond's Rocky Mountain glacial chronology. Two pre-Bull Lake (pre-Illinoian) loess units are characterized by siliceous petrocalcic horizons. The Bull Lake loess (Palouse Formation) apparently accumulated episodically be downwind accretion, followed by periods of relative stability and soil formation. The Palouse paleosols have platy calcic horizons but do not show petrocalcic horizons. Pinedale (= Fraser Glaciation) loess is paler in color than the older units; its paleosol calcic horizons lack the platy structure of the older loess paleosols.

At least five major catastrophic flood events occurred in the general vicinity of the Channeled Scabland. The earliest episode occurred prior to the extensive deposition of the Palouse Formation. Its surviving records are but fragmentary. Probable Missoula flood deposits in the Cheney-Palouse scabland tract are overlain by the younger pre-Palouse loess and a petrocalcic soil profile. Flood deposits in the Quincy Basin came from an unknown western source across Babcock Ridge. The Quincy Basin flood deposits are overlain by other flood deposits of probable Bull Lake age (Illinoian) also derived from a western source. Catastrophic flooding from Lake Bonne-ville affected the southern margin of the Channeled Scabland about 30,000 years B.P.

The last major episode of flooding occurred between about 18,000 and 13,000 years ago. It probably consisted of two outbursts from Glacial Lake Missoula. The earlier outburst predates the Vashon maximum (= Withrow Moraine of the Okanogan ice lobe). This flood affected Moses Coulee, the Grand Coulee (prior to its present configuration), and the eastern Channeled Scabland (Telford-Crab Creek and Cheney-Palouse scabland tracts). A second flood, probably involving less volume than the first, coincides with the deglacial phase of the Okanogan ice lobe. It mainly affected the Columbia River northwest of the Channeled Scabland downstream from a hydraulic constriction of the canyon at the site of Coulee Dam. The last phase of that flood probably also involved catastrophic flow down the Grand Coulee. Slackwater facies of this flood contain the Mount St. Helens set "S" ash erupted about 13,000 years B.P. according to D. R. Mullineaux and co-workers.

INTRODUCTION

The Channeled Scabland of eastern Washington (Fig. 2.1) consists of a spectacular complex of anastomosing channels, cataracts, loess "islands," and immense gravel bars created by the catastrophic fluvial erosion of the loess and basalt

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of the Columbia Plateau (Bretz and others, 1956). The erosion and deposition that produced the scabland topography resulted from the failure of the ice dam impounding glacial Lake Missoula. At its maximum outflow, near the end of the last major Pleistocene glaciation, the lake discharged as much as 21.3×10^6 m³/sec into the vicinity of Spokane, Washington (Baker, 1973a). Recently the origin and history of the Channeled Scabland has assumed new significance because of morphologic similarities to outflow channels of probable flood origin on Mars (Baker and Milton, 1974; Sharp and Malin, 1975; Masursky and others, 1977). Despite detailed study since the 1920's (Bretz, 1923a, 1928c, 1932b, 1959, 1969; Richmond and others 1965), the exact number and timing of major floods which resulted from the outpourings of Lake Missoula remains a major unresolved problem

in the Quaternary history of eastern Washington. This paper will summarize the general Quaternary geology of the Channeled Scabland and present some new data on the number of catastrophic floods.

PHYSIOGRAPHY, CLIMATE, AND SOILS

Freeman and others (1945) have formalized the physiographic divisions of the regions covered in this report. The entire study area lies in the Columbia Basin Subprovince of the Columbia Intermontane Physiographic Province. The Columbia Basin is a regional lowland surrounded by the Blue Mountains to the south, Cascade Mountains to the west, the Okanogan Highlands to the north, and the mountains of northern Idaho in the east. The region is also informally called
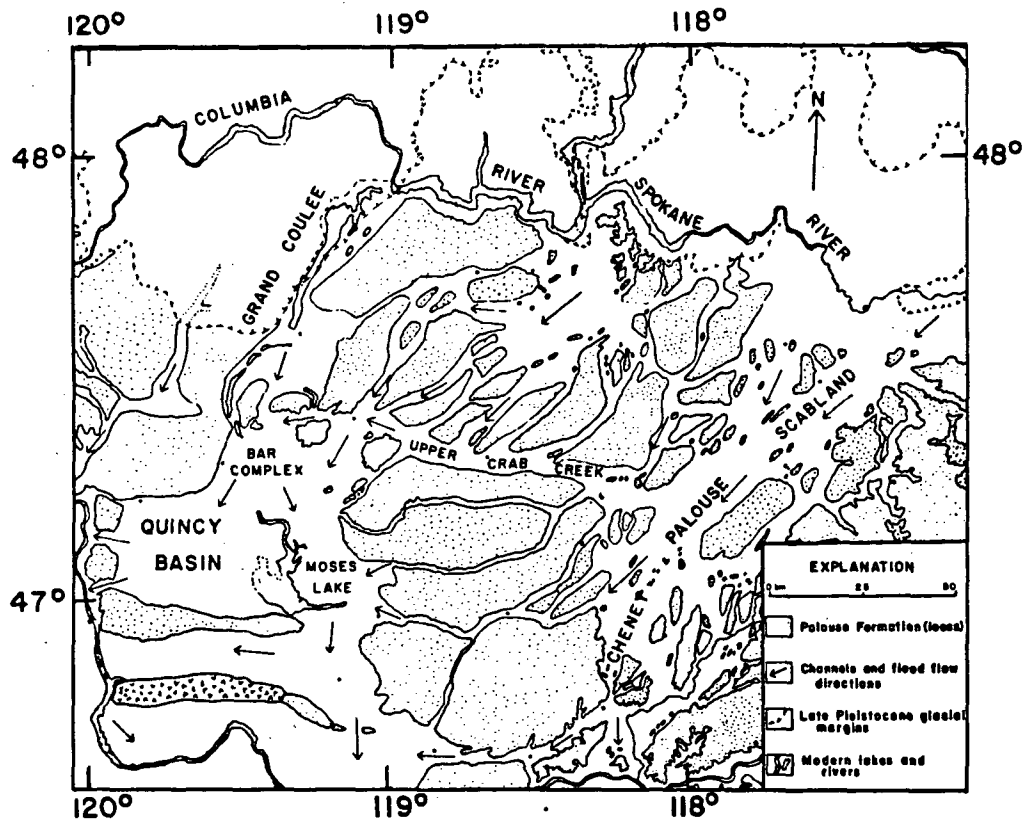

Figure 2.1. Map of the Channeled Scabland in eastern Washington showing the distribution of channels and the general extent of loess (Palouse Formation) that was not stripped away by the last major episode of flooding.

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the "Columbia Plateau," but intense folding in the western part produces a series of basins with intervening ridges. The basalt bedrock of the basin has the regional aspect of a structural basin.

The western part of the Columbia Basin, termed the "Yakima Folds," consists of a series of anticlinal ridges extending eastward from the Cascade Mountains. Several of these ridges are transected by the Columbia River. From north to south these are the Frenchman Hills, Saddle Mountains, and Horse Heaven Hills.

The northwest portion of the Columbia Basin, the Waterville Plateau, was not appreciably disturbed by the Neogene folding. A major canyon, Moses Coulee, is deeply excavated into the Waterville Plateau and extends southwestward from its center to the Columbia River Valley.

The far eastern part of the Columbia Basin is characterized by relatively undeformed basalt overlain by as much as 75 m of Pleistocene loess. The loess has been dissected to form a rolling topography known as the Palouse Hills. Elevation of the Palouse Hills declines from about 750 m on the northeastern margin to 100-120 m in the southwest. This gradient reflects the regional dip of the basalt toward the center of the basin.

Between the Palouse Hills and the Yakima Folds, extensive stripping occurred of the loess mantle by the catastrophic flooding of glacial Lake Missoula. The maturely dissected loess presents an abrupt contrast with the black cliffs and ragged appearance of the flood-eroded scabland tracts. Steep scarps on the eroded channel margins resemble wave-cut headlands rising above a desiccated sea. Bretz (1923b) named this region the Channeled Scabland.

The Columbia Plateau lies in the rain shadow of the Cascade Mountains. Precipitation in the western basins (elevation 180-300 m) is less than 20 cm per year, but increases with elevation northeastward, reaching nearly 50 cm per year on the updip margins of the plateau (elevation 850 m). The low precipitation results in a lack of perennial drainage through the huge ancient channels, called "coulees." The Columbia and Spokane Rivers, which are deeply entrenched along the northern and western margins of the plateau, intercept most of the drainage from the areas of higher precipitation in the bordering mountains.

The precipitation pattern is paralleled by a change in Great Soil Groups to the northeast. Sierozem soils form in the dry, southwestern portions of the plateau. Toward the northeast, Brown, Chestnut, and Chernozem soils appear in successively wetter portions of the plateau. These soils occur only on the loess and other fine-grained sediments. The eroded scabland channels are generally devoid of these parent materials for soil formation.

ANTEDILUVIAN EVENTS ON THE COLUMBIA PLATEAU

The Yakima Basalt comprises the bedrock in all but a few parts of the Channeled Scabland. This basalt unit is part of the extensive Neogene eruptions of plateau basalts that cover over 250,-000 km² in parts of Washington, Oregon, and Idaho. Most of the lava was erupted during the Miocene. The lava flows are exceptionally thick, and several can be traced over 150 km. Considerable structural and lithologic variation can be found in the basalt sequence, including jointing patterns, pillow-palagonite complexes, sedimentary interbeds (from lakes on the Miocene land surface) and geochemical variation. On the north and east margins of the plateau, the basalt is interbedded with extensive deposits of siltstone and shale of the Latah Formation, deposited as drainages were blocked by the basalt outpourings.

Deformation of the basalt sequence was most extensive during the Pliocene. The entire Columbia Plateau was regionally tilted from an elevation of about 760 m in the northeast to about 120 m in the southwest near Pasco, Washington. Superimposed on the regional structure are the east-west fold ridges described earlier. The upraised northern rim of the plateau is especially significant for the flood history of the Channeled Scabland. Only a truly phenomenal quantity of water could fill the great canyon of the Columbia River between Spokane and Coulee Dam. That filling would be necessary to have water spill over the northern rim of the plateau and flow southwestward, carving the great scabland channels.

During the Pliocene, the great structural basins of the western scablands accumulated a sequence

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of partly consolidated silt, gravel, and clay known as the Ringold Formation (Flint, 1938a; Newcomb, 1958). The age of this formation was poorly interpreted until Eric Gustafson studied the extensive upper Ringold vertebrate fauna from the White Bluffs area. Gustafson's White Bluffs fauna is early Blancan (Pliocene) in age. The faunal assemblage correlates best with the Hagerman fauna of Idaho, dated at about 3.5×10^0 years B.P.

Gustafson (1973) interprets the Ringold Formation as a sequence of stream-channel conglomerate, point-bar sandstone, and overbank deposits within a major fluvial depositional system. The predominance of browsing forms among the large mammals (interpreted from tooth form) including especially *Bretzia*, *Platygonus*, and *Megalonyx*, suggests that the Ringold flood plain supported considerable riparian forest. Circumstantial evidence suggests a strongly seasonal climate with yearly rainfall between 25 and 50 cm. Today the rainfall averages 20 cm, and the vegetation is xerophytic (sagebrush).

The Ringold Formation does not occur in the eastern Columbia Plateau, where late Pliocene and Pleistocene sedimentation was largely eolian, as expressed in a complex blanket of loess sheets (Fig. 2.2). The loess units provide a fairly complete Pleistocene chronology that was correlated by Richmond and others (1965) to Richmond's (1965) glacial chronology of the Rocky Mountains.

The oldest loess units are considered to be pre-Bull Lake in age. By the revised glacial chronology of Pierce and others (1976), Bull Lake time correlates to Illinoian, about 125,000 to 200,000 years ago. Two pre-Bull Lake loess units can be recognized in the field by the well-indurated, siliceous petrocalcic horizons that formed on them. The older of the two petrocalcic horizons is colored pinkish by an associated oxidized tuff. These petrocalcic horizons consist of as much as 0.6 m of roughly horizontal carbonate laminae over a calcic horizon of carbonate-plugged loess. This profile is an extremely strong soil horizon that qualifies for the designation "K horizon" (Gile and others, 1966), defined by the presence of 50% or more $CaCO_3$. Fryxell and Cook (1964) describe as much as 3 m of B horizon associated with the pre-Bull Lake loess units.

Most of the loess on the Columbia Plateau is correlated to Bull Lake Glaciation (Richmond and others, 1965). This loess, which has a thickness of up to 75 m (Ringe, 1970), is formally designated the Palouse Formation (Newcomb, 1961). Richmond and others (1965) recognize three cycles of soil formation in the Palouse Formation, but unpublished observations by the author indicate that more cycles may have occurred. Each soil shows a mature profile with a well-developed textural B horizon. The underlying Cca horizon is strongly calcareous and has a well-developed platy structure. Unlike soils on older loess units, however, this calcic horizon is less thoroughly cemented and does not qualify as a K horizon. Boulders derived from the Cca or B horizons of Palouse Formation soils are commonly found in deposits of the late Wisconsin flooding on the Columbia Plateau.

The Bull Lake age of the Palouse Formation was established by its relationship to glacial deposits in the vicinity of Spokane. It is obvious, however, that the detailed stratigraphic information in this loess sequence is a better record of mid-Pleistocene events than is the glacial sequence to the north. The Palouse Formation should be given detailed study, employing modern techniques as described by Kukla (1975) for the loess of Czechoslovakia. Paleomagnetic and tephrachronologic studies would probably yield an important new stratigraphic interpretation for the Palouse Formation and older loess units on the Columbia Plateau.

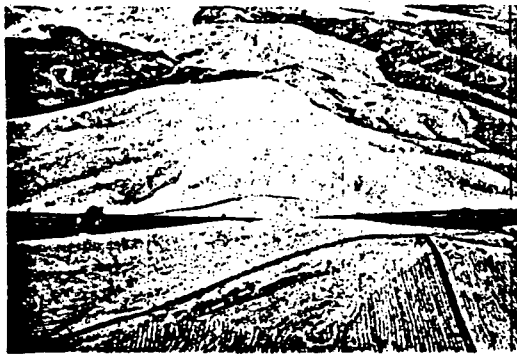A major unconformity separates the Palouse

Figure 2.2. Oblique aerial photograph of a road cut through "Palouse Hills" topography about 5 km west of Washtucna, Washington. The white layers are calcic paleosols in the loess sequence.

Formation from younger loess, correlated to the Pinedale Glaciation by Richmond and others (1965). The Pinedale loess is much paler in color than the Palouse Formation. Associated soil profiles have only weakly developed textural B horizons and lack the structural Cca or K horizons of older soils. $CaCO_3$ occurs in veins or nodules but not in continuous plates. In contrast, soils of Holocene age show A-C profiles of minimal development.

The soils within a typical loess hill show periods of stability during the progressive northwesterly accumulation of loess. A section through a loess hill near La Crosse (SE ¼, Sec. 1, T. 15N., R. 39E.) is shown in Figure 2.3. The three Bull Lake loess units have been truncated by a loess unit of a younger age (Pinedale?) which mantles the surface of the whole hill. The entire body of Bull Lake loess has a dull brown color (7.5YR 6/3). Color or textural B horizons were not apparent in this section. The younger loess units are dull yellow orange (10YR 7/3).

PRE-WISCONSIN FLOODING IN THE CHANNELED SCABLAND

The eastern portion of the Channeled Scabland (Fig. 2.4) contains several exposures of pre-Wisconsin flood gravel. The most complete section is exposed in a railroad cut through a gravel bar on the downstream end of a residual loess island about one kilometer west of Marengo, Washington (location 1, Fig. 2.4). The cut exposes a succession of two flood gravel units separated by three layers of loess (Fig. 2.5). These

three loess units are each capped by a pedogenic calcic horizon. The lower flood deposit is a poorly sorted mixture of basalt and loess pebbles and cobbles in a matrix of granule-sized basalt grains. The texture is similar to that of the extensive deposits of the last major episode of scabland flooding. Typical of many scabland gravel deposits is the presence of loess cobbles, implying fluvial transport in suspension which prevented destruction of the loess. Cobbles in this deposit are dull orange (7.5 YR 7/4) in color and have black manganese dioxide staining on their surfaces.

The lower flood gravel is overlain by 1 m of dark yellowish brown (10 YR 6/6) loess which is capped by a petrocalcic horizon 60 cm thick. There is also a well-developed argillic horizon on this loess characterized by a pronounced prismatic structure. Grain-size analysis indicates that the prismatic structure is associated with a relatively strong illuvial textural B horizon. Root casts infilled with caliche from the overlying petrocalcic horizon also occur in this argillic zone. The overlying petrocalcic horizon has a platy structure and completely plugs the uppermost part of this loess unit. Although no carbonate analysis was made on this horizon, its morphology is nearly pure carbonate (caliche) with little loess matrix. The horizon therefore qualifies for designation as a K horizon (> 50% carbonate) as described by Gile and others (1966). This pedocal soil appears to have been superimposed on the older, pedalfer soil (textural B horizon) and then eroded to its resistant carbonate layer prior to new loess deposition.
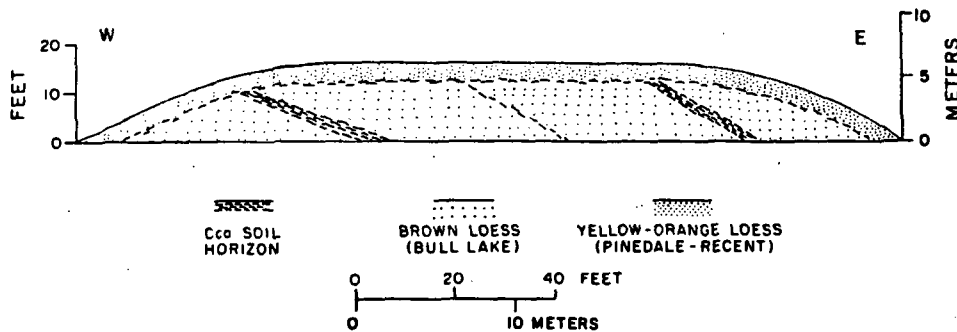

Figure 2.3. Loess stratigraphy exposed by a road cut 2.5 km east of La Crosse, Washington.

The K horizon is overlain by two pale yellowish brown (10 YR 7/3) loess units, each 50-60 cm thick and each capped by calcic soil horizons 10-20 cm thick. These loess layers lack the prismatic structure of the earlier loess and have moderately developed textural B horizons. The thin calcic horizons have a platy structure. Unlike the lower caliche, they do not qualify as petrocalcic horizons because the loess is not continuously cemented and indurated.

The two calcified loess units are overlain by approximately 1 m of granule-to-cobble sized gravel that was deposited by the latest flood to cross the Cheney-Palouse scabland. The loess gravel present in this deposit is predominantly composed of the brownish loess from the Palouse Formation, although a few of the reddish loess cobbles are also present. The gravels are covered by 1.5 m of late Pinedale loess on which a relatively weak A-B-C soil profile has formed. This
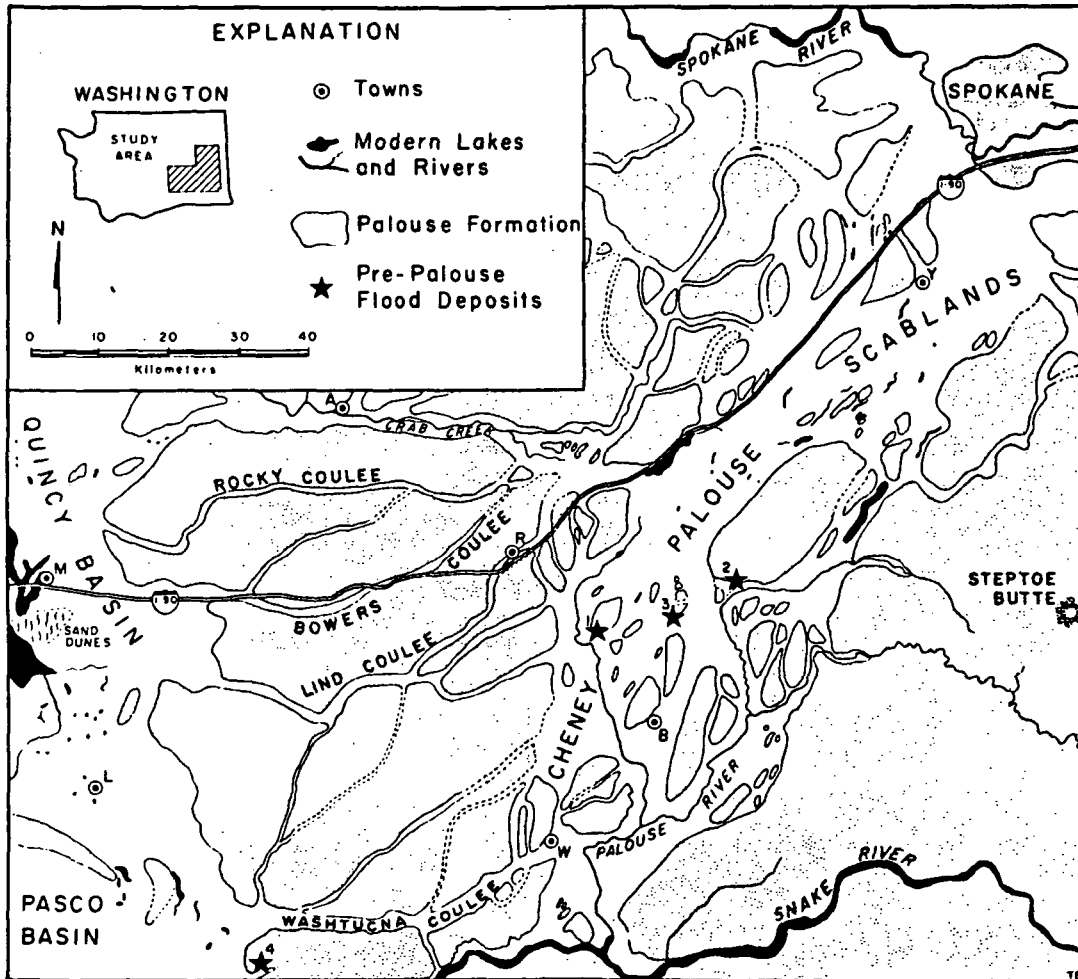

Figure 2.4 Location map showing the generalized distribution of the Palouse Formation in eastern Washington. Areas not covered by Palouse Formation were scoured by the early Pinedale catastrophic breakout flood of Lake Missoula. Pre-Palouse flood deposits have been found at the numbered localities: (1) Marengo, (2) Revere, (3) Macall, (4) Old Maid Coulee. Towns are indicated by letters: (A) Odessa, (B) Benge, (L) Othello, (M) Moses Lake, (R) Ritzville, (W) Washtucna, (Y) Cheney.
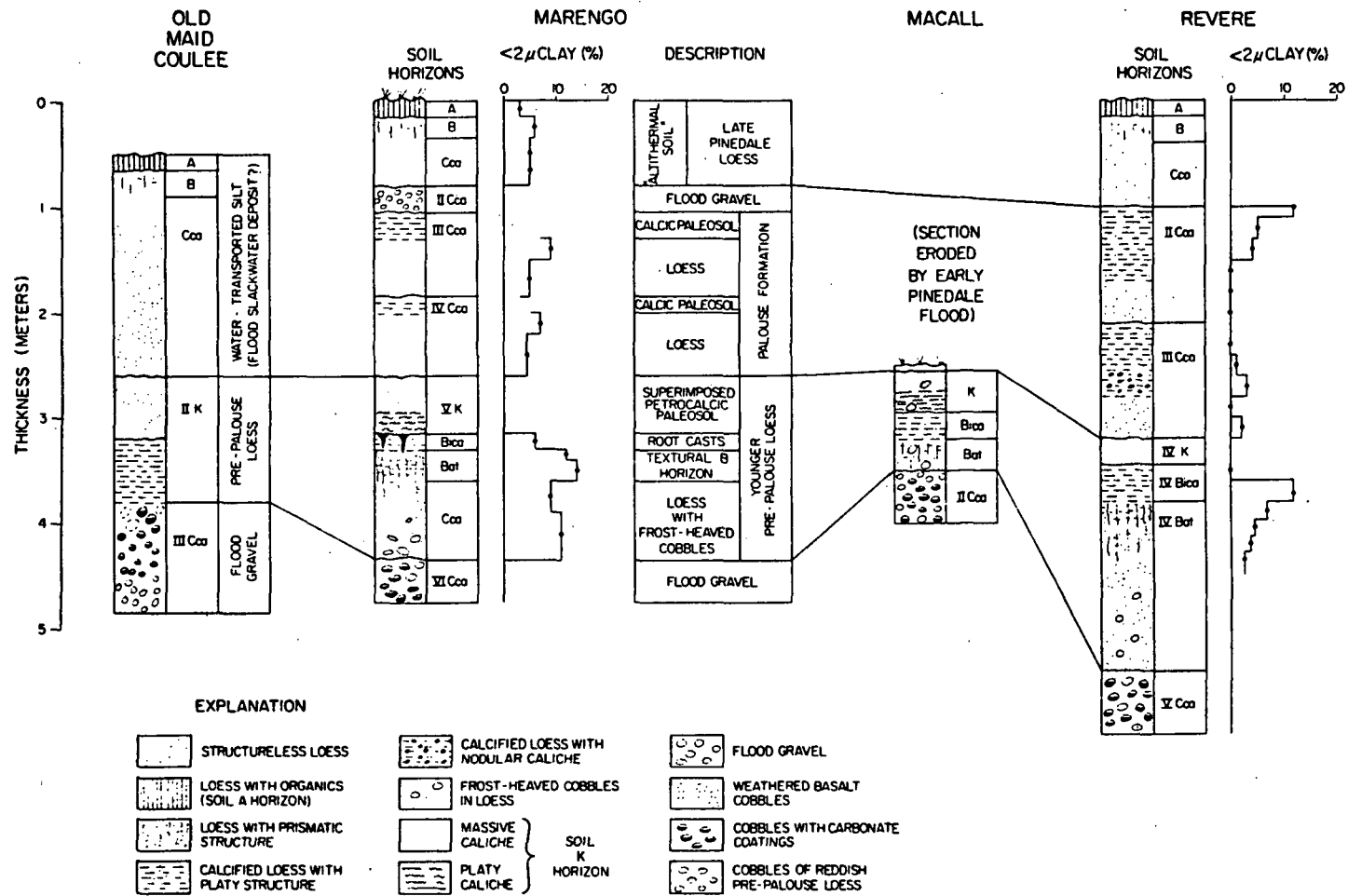
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Figure 2.5. Stratigraphic section at Marengo, Washington and its probable correlation to other sections in the Channeled Scabland.

latter profile corresponds to the late Wisconsin-early Holocene soil that is common throughout the region on post-scabland loess deposits (Fryxell, 1965; Baker, 1973a). The uppermost gravel unit threfore correlates with the extensive deposits of the last major episode of scabland flooding.

The lower flood gravel at Marengo has also been located at Revere (Locality 2, Fig. 2.4) and Macall (Locality 3, Fig. 2.4). These three new sections probably also correlate with a flood gravel exposed on a divide near the upper reaches of Old Maid Coulee (Locality 4, Fig. 2.4), a section previously interpreted by Bryan (1927, p. 27), by Flint (1938b, p. 518), and by Bretz and others (1956, p. 1006). It consists of foreset-bedded gravel overlain by calcified loess, which is, in turn, overlain by pale, water-transported silt (Fig. 2.6). About 20% of the basalt cobbles in the upper parts of the gravel are completely rotten, indicating prolonged weathering. The loess unit is capped by 60 cm of platy calcium carbonate, a soil petrocalcic or K horizon. The erosion surface at the top of the caliche is overlain by silt that is dull yellow orange color (10 YR 6/3). It lacks the darker coloration and well-developed buried soils of the Palouse Formation. Moreover, its position on a divide and its uniform texture suggest that it may be suspended load from the last major flood that was deposited in a slackwater area. Flint (1938b) believed that the unit was a lake silt. He did suggest that this silt was approximately contemporaneous with the gravel of the main scabland channels, which are now considered to be approximately 13,000 years B.P. in age (Mullineaux and others, 1977).

The loess unit and petrocalcic paleosol capping the old flood gravels at all four sections probably correlates with the younger pre-Palouse Formation loess and soil described earlier. Unlike other pre-Bull Lake flood deposits recognized in the western scablands at George and Winchester (Baker, 1973a), there was a significant pre-Palouse loess accumulation on these early flood gravels prior to a major period of soil formation (an interglaciation?). Moreover, the reddish loess cobbles in the flood gravel probably were eroded from the older of the two pre-Palouse loess units. The first episode of scabland flooding appears to have occurred during a Pleistocene glacial maxi-

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mum prior to the maximum that produced the Bull Lake Glaciation. Subsequent loess accumulation probably included a relatively humid interval that produced the pronounced textural B horizon, and it was followed by an arid interval that superimposed a petrocalcic horizon on the loess. An erosional episode, probably deflation, then stripped the surface horizons down to the resistant petrocalcic layer. These latter events all characterized the latest pre-Bull Lake glacial and interglacial record on the Columbia Plateau.

Bull Lake time is represented at the Marengo profile (Fig. 2.5) by two of the three known Palouse Formation loess units. This circumstance is typical of the cycles of soil formation, deflation, and lateral accretion that characterize the Palouse Formation (Lewis, 1960; Fryxell, 1966). During the Bull Lake Glaciation loess was accreting behind pre-existing obstacles in a general northeastward direction. Typical exposures through loess hills show that accretion was followed by stability and soil formation. Subsequent

Figure 2.6. Stratigraphic section at Old Maid Coulee.

deflation would remove surficial soil horizons down to the resistant calcic layers. The cycle was then repeated as more deposition occurred upwind of the previous deposit. This pattern of lateral accretion plus the opportunity for stream dissection of the topography make it unlikely to find all three Palouse Formation loess units in one vertical section.

An unresolved problem is the correlation of the pre-Wisconsin Cheney-Palouse flood to the pre-Wisconsin flood deposits of the western Quincy Basin (Baker, 1973a, p. 8). The section there (NW ¼, Sec. 31, T. 19N. R.24E) shows a typical foreset flood gravel containing boulders as large as 1 m in diameter. The uppermost 60 cm of the gravel is capped by a horizontally laminated petrocalcic horizon (Fig. 2.7). This is underlain by 30-60 cm of carbonate-cemented gravel. Local carbonate cementation in the coarser foresets occurs to a depth of 3 m. Carbonate coatings on the underside of cobbles occur to a depth of 4 m. Weathering rinds on the basalt cobbles in the upper 1.5 m of the gravel exceed 7.5 cm in thickness. Many cobbles are completely rotten. The gravel below a depth of 3 m shows no evidence of weathering. This weathering profile is

much more intense than that noted on the pre-Wisconsin Cheney-Palouse flood deposits. However, the definitive sequence of loess units is absent in the western Quincy Basin, so a precise correlation remains speculative.

Richmond and others (1965) also recognize a Bull Lake episode of scabland flooding from widely scattered deposits on the Columbia Plateau. The best evidence occurs at Winchester Wasteway in the Quincy Basin, where the Bull Lake flood deposits overlie the older pre-Wisconsin flood deposits seen at George (Baker, 1973a, p. 8).

THE BONNEVILLE FLOOD

Malde (1968) studied the catastrophic flood produced by the overflow and rapid lowering of Pleistocene Lake Bonneville (Fig. 2.8). He traced the course of this flood through the Snake River Plain of southern Idaho to Hells Canyon. Malde interpreted the age of this event to be about 30,-000 years B.P., based on a radiocarbon date for molluscan fossils associated with flood debris and on the relict soil profile developed on the flood gravel (Melon Gravel). The soil has a thick calcic
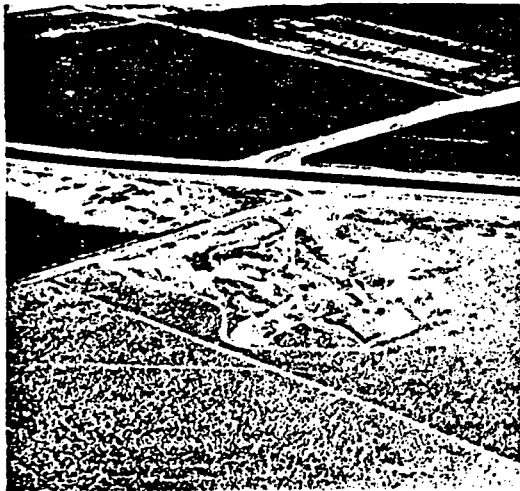

Figure 2.7. Oblique aerial photograph of a sanitary landfill at George, Washington. The white layer is a prominent petrocalcic horizon developed at the top of coarse flood gravel. The gravel was laid down by a deep catastrophic flood that crossed the western rim of the Quincy Basin and flowed southeastward into the Quincy Basin.

Figure 2.8. View of the Snake River Canyon downstream of Perrine Memorial Bridge in Twin Falls, Idaho. Scabland erosion of volcanic rocks, here produced by the Bonneville flood, is very similar to that produced by Missoula flooding of the Channeled Scabland.

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horizon extending to depths greater than 2 m (Fig. 2.9). The soil on the Bonneville Flood deposits is believed to have formed during and since the mid-Wisconsin (Bull Lake-Pinedale) interglaciation or within the last 30,000 years.

Downstream from Hells Canyon at Lewiston, Idaho, probable Bonneville flood deposits are overlain by slackwater surge deposits from the last major episode of scabland flooding (Fig. 2.10). Because Bonneville flooding was confined to the Snake River Canyon, it skirted to the south of the Channeled Scabland. Nevertheless, studies in the Pasco Basin should eventually recognize Bonneville Flood deposits in association with Missoula flood deposits.

THE LATE PLEISTOCENE DILUVIAN EVENTS

The late Pleistocene glacial record of northwestern Washington and southwestern British Columbia is very well documented through detailed radiocarbon dating (Armstrong and others, 1965; Fulton, 1971; Easterbrook, 1976). The last major glaciation, called the Fraser Glaciation, extended from about 20,000 to 10,000 years

ago. This is also the time interval that produced the last major episode of scabland flooding. At least one and probably two major outbursts of Lake Missoula occurred during this interval. Although the evidence for the floods is overwhelming, the precise dating of the events in this interval is a matter of current controversy. This section will attempt to summarize the diverse arguments.

Glacial Stratigraphy

The Fraser Glaciation is precisely dated on the western side of the Cascade Mountains. During the Evans Creek Stade large alpine glaciers advanced to their maxium extent into the Puget lowland. This was followed by an advance of Cordilleran ice into the lowland from the north sometime after 19,000 years B.P. (Easterbrook, 1976). If the Pend Oreille Lobe of the Cordilleran Ice Sheet correlated with the Puget Lobe, then Lake Missoula could not have formed until after 19,000 years B.P. The Puget Lobe reached its maximum extent 14,000 to 15,000 years ago, during the Vashon Stage.

Figure 2.9. Exposure of Melon Gravel in large boulder bar at mile 161 in the Melon Valley area of the Snake River Canyon, Idaho (Malde, 1968, p. 33). The relict paleosol here is moderately strong, lacking the petrocalcic horizons of pre-Wisconsin flood gravels in the Channeled Scabland.

Figure 2.10. Slackwater facies of the last episode of scabland flooding overlying probable flood gravel of the Bonneville Flood at a gravel pit 5.5 km south of Lewiston, Idaho. The foresets and lithologies indicate that the gravel was deposited by flows coming *down* the Snake River through Hells Canyon. The slackwater deposits were deposited by backwater flooding *up* the Snake River from the mouth of the Palouse River, a distance of over 120 km. This deposit was described as Tammany Bar by Bretz (1969, p. 531-532).

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Between 14,000 and 13,000 years B.P. a major recession occurred in the Vashon glacier of the Puget lowland. The interval from 13,500 to 11,500 years ago is characterized by relative stability of Cordilleran ice during the Everson Glaciomarine Interstade, which was followed by a rather minor readvance perhaps between 11,500 and 11,000 years B.P.

The glacial chronology on the Columbia Plateau is severely hampered by a lack of radiocarbon dating. Work on the Waterville Plateau by Hanson (1970) and Easterbrook (1976) shows that an episode of major scabland flooding occurred prior to the major advance of the Okanogan Lobe on to the Columbia Plateau. That advance produced a spectacular moraine, the Withrow Moraine (Waters, 1933; Flint, 1935). This is estimated to have formed about 14,000 to 15,000 years B.P. (Fryxell, 1962; Waitt, 1972a; Easterbrook 1976). Relationships near Jamison Lake show the moraine overlying a Moses Coulee flood gravel bar (Fig. 2.11). Subsequent outwash (Fig. 2.12) and dramatic ice stagnation features record a rapid retreat of the Okanogan Lobe (Hanson, 1970; Waitt 1972a), perhaps contemporaneous to the analogous phase of the Puget Lobe.
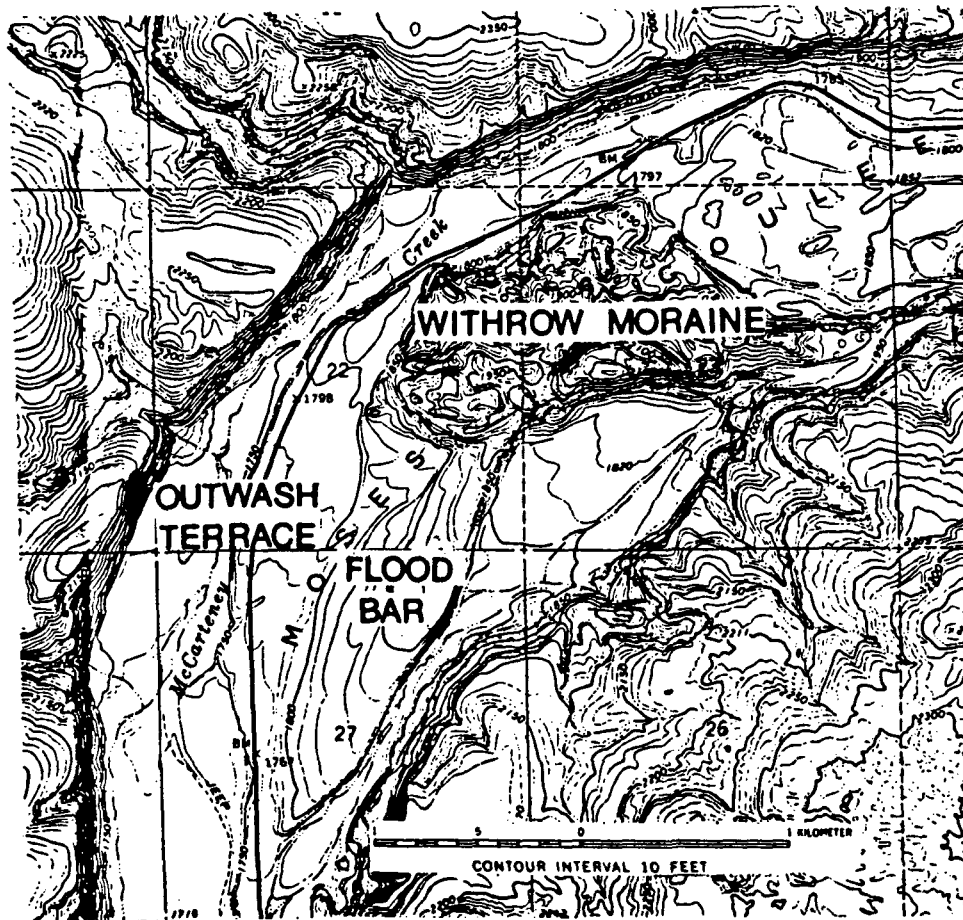

Figure 2.11. Topographic map of upper Moses Coulee, showing the physiographic relationships between the Withrow Moraine, a pendant bar of flood gravel, and an outwash terrace (from Easterbrook, 1976).

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Late-Quaternary Vegetation

A pollen sequence in a mire on the Telford-Crab Creek scabland tract near Creston, Washington records the vegetation changes on the Columbia Plateau that followed the scabland flooding of that region (Hansen, 1947). Mack and others (1976) have reinterpreted the pollen sequence at this locality using improved palynological techniques. The postflood vegetation during the Glacier Peak ash fall (12,000-13,000 B.P.) and slightly earlier consisted of steppe vegetation dominated by sagebrush (*Artemisia*) occupying extensive areas of stony patterned ground. Nearby loess hills were occupied by pine forest. A warming trend is indicated to have begun about 9,000 years ago.

The Creston fen accumulated 60 cm of sediment between 9,390 ± 480 and 6,700 years B.P. and 70-100 cm between 12,000-13,000 and 9,-390 ± 480 years B.P. (Mack and others, 1976; their Fig. 2). These accumulation rates range from 1.75 to 2.6 cm per 100 years. Since the mire accumulated 30-50 cm of sediment after scour by the scabland flooding and prior to Glacier Peak ash accumulation (12,000-13,000 years B.P.), that flooding must have occurred at least 13,500-16,000 years B.P. Of course, the depositional rates could have been different in this interval, so this very tenuous age estimate must be compared to other data.

Figure 2.12. Oblique aerial photograph of the outwash terrace that extends downstream from the Withrow Moraine in Moses Coulee.

Weathering and Soils

Near Vantage, Washington, wood, dated by radiocarbon at 32,700 ± 900 years B.P., was found in deposits of the last major flood (Fryxell, 1962). The wood was probably derived from a preflood, interstadial bog on a scabland surface (Bretz, 1969). Soil-stratigraphic evidence (Baker, 1973a) implies that the flooding occurred much later than this lower limiting date, but when?

On the Columbia Plateau, one indication of the age of the flooding is provided by the weathering of the basalt boulders on the surfaces of scabland flood bars. Weathering rinds on these boulders never exceed 3 mm in thickness. By contrast, rinds on similar basalt boulders deposited by the Bonneville Flood on the Snake River Plain of Idaho may be greater than 1.2 cm thick (Malde, 1968). Since the Snake River Plain has a similar climate to that of the Columbia Plateau, the Missoula Flood deposits probably considerably postdate the Bonneville Flood, which Malde (1968, p. 10) believes occurred 30,000 years ago.

The relict soils on the scabland floor gravels are poorly developed. There are only a few centimeters of near-surface oxidation. Buried cobbles and boulders lack weathering rinds. The Cca horizon dominates the soil profile, but shows only weak development. Calcium carbonate occurs as coatings on the undersides of pebbles and cobbles to a depth of about 1 m. There is no platy caliche as found on the Bonneville Flood deposits (Fig. 2.9), which were weathered in a similar soil-forming environment.

In the eastern Channeled Scabland the last major flood scoured channel ways through the entire sequence of brown loess units that comprise the Palouse Formation (Fig. 2.13). Small channels eroded into the flood deposits by postflood streams contain pale loess and loess-derived alluvium. The oldest soil profiles on postflood loess deposits show textural B horizons, with the $<2\mu$ size fraction increasing from 8% to 11% (Baker, 1973a).

Bretz' early studies concluded that the eastern Channeled Scabland (Cheney-Palouse tract) was somewhat older than the western Channeled Scabland (Grand Coulee region). The interpretation was developed by physiographic evidence (Bretz and others, 1956; Bretz, 1969). Every scabland channel way entering from the east is

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clearly blocked by bars that were deposited by later flooding down the Grand Coulee system. Because the weathering of the flood gravel in these bars differs little from that of bars in the Cheney-Palouse scabland, either these floods are consequences of the same outburst event or they are only separated by a few thousand years in time.

Unpublished observations of post-flood eolian silt accumulation on scabland surfaces may be relevant to this question. Bars and giant current ripples in the west scablands typically have 0.15 to 0.30 m of post-flood eolian accumulation on exposed areas and no more than 0.5 in protected swales. In contrast, the eastern scabland bars have 0.5 to 1.2 m of silt in exposed areas and up to 2.5 m in swales. This would appear to indicate greater age for the eastern scablands, but a prob-

lem remains. Silt thickness on scabland surface follows a northeasterly gradient such that

$$y = 0.46e^{0.03x}$$

where y is the thickness of postflood eolian silt (ft.) and x is the linear distance (miles) in a northeastward direction from Hanford in the Pasco Basin. Thus, silt thickness may reflect source area and wind-direction controls rather than age.

Post-flood silt is so thick at the TSCR ripple field, in the eastern scablands near Tokio Station, that it completely buries the giant current ripples (Fig. 2.14). The TSCR ripples apparent on aerial photographs are actually the silt accumulations over the former ripple troughs. The textural data indicate that this silt contains two weakly devel-
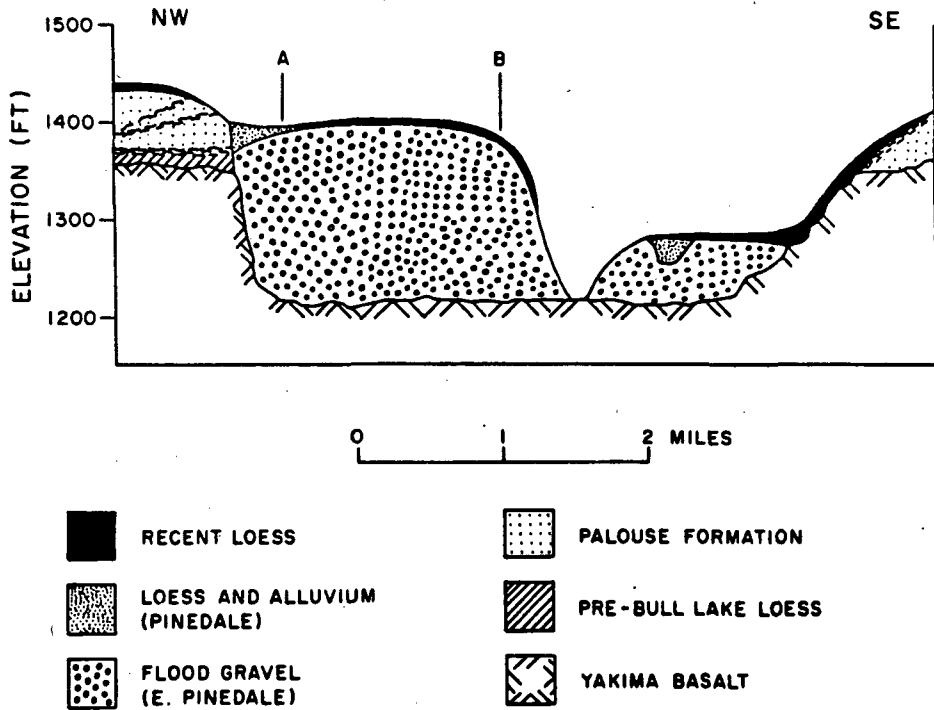

Figure 2.13. Diagramatic cross section showing stratigraphic relationships at Staircase Rapids Bar. Thickness of the loess is slightly exaggerated.

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Figure 2.14. Exposure of post-flood eolian silt overlying flood gravel just north of Tokio Station. The gravel pit occurs at SW ¼ sec. 15 T. 20 N., R. 36E.

oped paleosols (Fig. 2.15). This section presents a marked contrast to flood surfaces in the western Channeled Scabland.

Tephrachronology

Eruptions of volcanoes in the Cascade Mountains showered ash over wide areas of the northwestern U. S. during the late Quaternary. Where these ashes can be distinguished, they provide a valuable series of marker beds for dating the associated sedimentary deposits and for tying together the geologic history of widely separated provinces.

Two of the most useful and widespread ash falls for work in the Channeled Scabland are those from Glacier Peak and Mt. Mazama (Fryxell, 1965). Extensive radiocarbon work dates the Mazama ash approximately 7,000 years B.P. (Kittleman, 1973). The Glacier Peak tephra is older than 12,000 and younger than 13,000 years B.P. Lemke and others (1975) designate it as younger than 12,500 years. These two ashes are easily distinguished by their refractive indices (Mazama > 1.502; G.P. < 1.502), but electron microproble analysis of the shards is necessary to avoid confusion of Glacier Peak and certain Mount St. Helens ashes. In the field the Mazama ash is usually granular, while the Glacier Peak ash forms lentils or pods with the texture of tapioca.

Most prolific of the ash sources in the Northwest was Mount St. Helens. The individual eruptions of this volcano have been dated by the detailed work of Mullineaux, Crandell, and Rubin, using the carbonaceous material in the coarse airfall material on the flanks of the volcano. The tephra occur in distinct groups, called "sets." The oldest is set S, erupted between 18,000 and 12,000 years B.P. Mullineaux and others (1975) present arguments for the most widespread members of the set S eruption (layers Sg and So) being dated at about 13,000 years B.P. Mount St. Helens tephra set J was erupted from slightly less than 12,000 to slightly more than 8,000
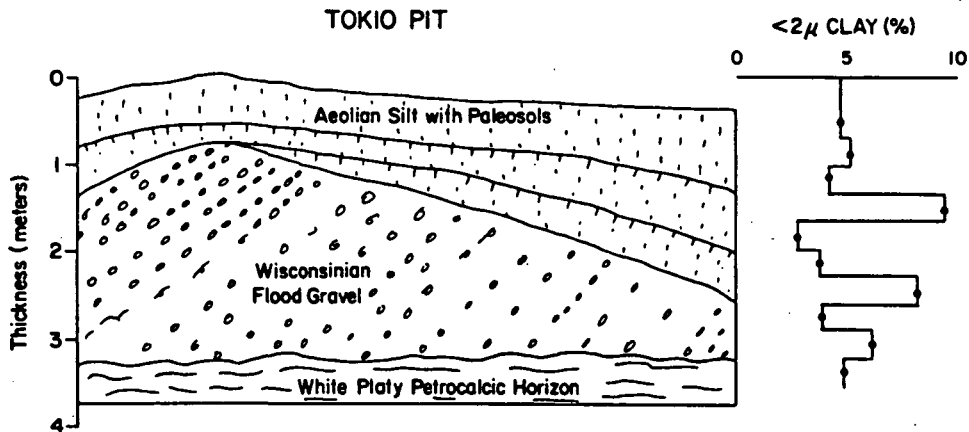
TOKIO PIT

Figure 2.15. Stratigraphic relationships at the Tokio section.

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years ago. Tephra set Y was extensively distributed in the Northwest between 4,000 and 3,400 years ago. Set W is the most recent, dated at about 450 years B.P. All these tephra units were carried east of Mount St. Helens and all have now been recognized in Quaternary sediments of eastern Washington (Mullineaux and others, 1975).

The Mount St. Helens set S ash occurs as "couplets" and "triplets" in fine-grained clastic sediments, often designated as "slackwater facies." Moody (1977) finds the triplet north of the Saddle Mountains at sites such as Sentinel Gap, Lind Coulee (Table 2.1), and Lynch Coulee (Fig. 2.16). South of this range only the upper and middle ash are recognized, forming a "couplet." The couplet is well exposed in "slackwater" sediments on the northern slopes of the Horse Heaven Hills, just south of Kiona, Washington. Mullineaux and others (1977) have concluded that tephra set S dates the last major scabland flood. They support the age estimate of 13,000 years B.P. for the flood with a radiocarbon date of 13,080 ± 350 on peat directly overlying the "Portland delta," a Missoula Flood deposit at Portland, Oregon.

Slackwater Sediments

The dating of the last major scabland flood is complicated by the fact that the catastrophic flood deposits occur in two facies. The main-channel facies can always be recognized as unequivocal flood deposition by its coarseness, sedimentary structures, angular boulders, broken rounds, erratics, etc. However, some of the slackwater facies are easily confused with lacustrine deposits. An unequivocal flood origin can be established by continuous tracing between main-channel areas and slackwater areas, as in the Tucannon Valley sequence (Baker, 1973a). At the Tucannon valley one can follow a complete transition from chaotically deposited boulder and cobble gravel in the main channel to rhythmically bedded silt in slackwater areas 15 km up a preflood tributary of the main channel (Baker, 1973a; p. 42-47).

Carl Gustafson (1976) divides "slackwater deposits" into 2 groups, one contemporaneous to scabland flooding and the other postflood. The postflood slackwater sediments contain articulated bivalve mollusks that lived in a lacustrine

environment. At Lind Coulee, Gustafson (in Webster and others, 1976, p. 15) interprets deposits of the major scabland flood (18,000-20,000 years B.P.), consisting of main-channel and slackwater facies, to be unconformably overlain by younger "slackwater sediments" of lacustrine origin. This lacustrine unit contains the distinctive "triplet" of volcanic ash layers from Mt. St. Helens, which is interpreted as the Mt. St. Helens "S" set by Moody (1977).

Working in the Lower Snake River Canyon, Hammatt and others (1976) interpreted two flood events and one lacustrine phase for the

Figure 2.16. Exposure of the Mount St. Helens ash "triplet" in fine-grained "slackwater" sediment that immediately overlies scabland gravel at the mouth of Lynch Coulee, near its junction with the Columbia River at West Bar. A coarse white ash layer occurs at "B" and a fine-grained thinner layer occurs at "A." The lowest of the three layers occurs discontinuously in the granule gravel "C." The sediment containing the ash (Mt. St. Helens set S) is either time equivalent to or slightly younger than the last major catastrophic flood to affect the Columbia River Canyon northwest of the Channeled Scabland.

Table. 2.1. Correlation of some late-Quaternary deposits and events on the Columbia Plateau.

Age (Approximate years B.P.)	Lind Coulee (various sources)		Creston Mire (Mack et al., 1976)	Marmes Rockshelter (Fryxell)	Okanogan Lobe (Easterbrook, 1976)
	"Holocene Loess"		Pollen Zone II	ROCKFALL —transition— LOESS	
6700—	XXXXXXXXXX MAZAMA XXXXXXXXXXXXXXX ASH XXXXXXXXX				Holocene
			(Increase in diploxylon pine; decrease in Artemisia and Picea)	Shell Midden	
	Unconformity STREAM GRAVEL			Loess Rockfall	
	Overbank Silt	Archeol. Site		Human Burial	
~9000—				ROCKFALL	
		St. Helens "J" XXXXXXXXX	Pollen Zone I		Sumas Stade
	Unconformity			disconformity	
12,500—	Overbank Silt	XXXXXX GLACIER XXXXXX PEAK XXXXXX ASH XXXXXX			
		St. Helens "J" XXXXXXXXX	(Artemisia on patterned ground; haploxylon pine on loess)		Everson Interstade
	Unconformity				
	"Slackwater Silt"	St. Helens XXXXXXXXX XXXXXXXXX XXXXXXXXX Set "S"	and		
13,000— ±500					Recession
	Unconformity		?	?	
		Flood Slackwater Silt			Vashon Stade — — —
	Flood				Advance
14,000— 18,000?		Gravel			

XXXX Volcanic Ash

early post-glacial period. Flood gravel, which they interpret as 20,000 years B.P., is unconformably overlain by thin bedded silt containing Mt. St. Helens tephra. The silt, interpreted as lacustrine, is unconformably overlain by sandy facies interpreted as a flood slackwater deposit laid down approximately 14,000 years B.P. This upper unit forms an undulating mantle over earlier deposits and is characterized by distinctly graded bedding. All three units are cut by clastic dikes.

Sedimentological criteria must be established to distinguish slackwater facies of flood origin (Baker, 1973a) from lacustrine deposits. Work on this problem is currently in progress.

Flood Deposits Northwest of the Channeled Scabland

Waitt (1977b) presents detailed evidence for late Pleistocene catastrophic flooding coming down the Columbia River, through the region that was blocked by the Okanogan lobe until about 13,500 years B.P. Ice-rafted erratics and upvalley-dipping crossbeds in gravel show that this down-Columbia flood was as deep as 400 m at the junction with the Methow River (Waitt, 1977a). These depths require water at Coulee Dam to have had a surface elevation of 760 m. Waitt (1972b, 1977a) suggests that these relationships require hydraulic ponding of a Lake Missoula outburst at the Columbia gorge downstream from Coulee Dam. Because of the chronology of the Okanogan lobe, this flood could only have occurred about 13,500 to 13,000 years ago (Waitt, 1977b).

Flood sediment relationships at Lynch Coulee (Waitt, 1977b, p. 15) suggest that the Columbia flood was approximately contemporaneous to flooding in the Quincy Basin (presumably derived from the Grand Coulee). The Columbia flood deposits indicate transport up Lynch Coulee. These are overlain by flood deposits dipping downcoulee (having flowed from Crater Coulee). The contact shows no weathering. At Moses Coulee, however, the downcoulee deposits came first and even surged up the Colombia (Waitt, 1977b, p. 17). The Moses Coulee flood deposits are overlain by Columbia flood deposits that surged up Moses Coulee near its mouth.

Discussion

The emerging stratigraphic evidence summarized above has not yet completely resolved the number and timing of floods in the last episode of scabland flooding (19,000-13,000 years ago). The tephrachronology suggests that the last major flood affected the Columbia River, northwest of the scablands, and probably the western Channeled Scabland itself. This flood occurred just prior to or nearly coincident with the eruption of Mt. St. Helens tephra set S (approximately 13,000 years B.P.). This event probably coincided with the wastage and breakup of the Okanogan ice sheet on the Waterville Plateau.

It is also probable that another major episode of scabland flooding preceded the Okanogan breakout by several thousands years. This flood probably affected Moses Coulee, the Grand Coulee, the Telford-Crab Creek scabland, and the Cheney-Palouse. The dating of this event is less precise, but includes the following: (1) the Withrow Moranie overlying flood gravel in Moses Coulee (Fig. 2.11), (2) physiographic relationships in the Grand Coulee (Bretz, 1932a, 1969), (3) the amount of sedimentation at the Creston mire prior to the Glacier Peak ashfall, (4) the more extensive silt deposition on the Cheney-Palouse bars, (5) the younger event (13,000 years B.P.?) has bars blocking the mouths of eastern scabland distributaries (Bretz and others, 1956), and (6) stratigraphic relationships in the Snake River Canyon (Hammatt and others, 1976).

A tentative scenario that has yet to be fully tested in the field is as follows. The largest outburst of Lake Missoula occurred just prior to the Vashon glacial maximum, but while the Okanogan lobe was advancing. This flood flowed around the Okanogan lobe through the "Mansfield channels" (Hanson, 1970) and down Moses Coulee. This route was possible because (1) the advancing Okanogan lobe had just recently blocked the Columbia gorge, and (2) the upper Grand Coulee cataract had not yet receded to Coulee Dam (Bretz, 1932a). It is likely that this flood initiated the 250 m cataract in the upper Grand Coulee and that it receded to the Steamboat Rock position during the course of the "early Vashon" flooding. The same flood would also put water into the Telford-Crab Creek and

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Cheney-Palouse scabland tracks. Slackwater deposits from this flood would be the lower sequence recognized by Hammat and others (1976) along the Snake River.

The Okanogan lobe advanced to its maximum position, the Withrow Moraine, very shortly after the above flood. Wastage of the Okanogan lobe then led to a second flood that also included a burst from Lake Missoula. Richmond and others (1965) refer to this as the "middle Pinedale" final flood on the Columbia River. However, that flood probably also put water over the Grand Coulee cataract head. During the course of this flood, which was mainly influencing the Columbia River in its early phases, the upper Grand Coulee cataract broke through to the Columbia gorge at Coulee Dam. This sent a final surge of water down the Grand Coulee and into the Quincy Basin. Thus, the Lynch Coulee relationships are explained by the dynamics of the last major scabland flood. That flood affected both the Columbia River and the western Channeled Scabland, but not the eastern scablands. Moses Coulee did not operate because the cataract recession of the Grand Coulee in the earlier flood had pirated the channels that fed its upstream end.

One variation of the above scenario is possible by using Waitt's (1972b, 1977a) hypothesis of hydraulic ponding at Coulee Dam. This would allow completion of the upper Grand Coulee in the earlier flood. Water would then be simultaneously flowing in the Columbia Canyon (free of the Okanogan lobe) and in the Grand Coulee.

POSTDILUVIAN STRATIGRAPHY OF THE COLUMBIA PLATEAU

Post-flood conditions in the Channeled Scabland region have been studied extensively by Roald Fryxell, Carl E. Gustafson, and other workers at the Department of Anthropology, Washington State University. Current data suggest that man entered the region as early as 12,000 years B.P. He encountered a cold dry steppe with considerable lacustrine areas. Deranged drainage conditions and high water tables were the legacy of recently wasted glaciers and catastrophic flooding.

The most intensive study of a post-flood lake in the Channeled Scabland was made by Landye (1973). Lake Bretz, whose shoreline altitude was 350 m (1160 ft.) occupied the closed depression in the lower Grand Coulee upstream from the bar at Soap Lake. The lake probably lasted a few hundred years, long enough to accumulate an abundant population of mollusks and fish. At the maximum extent, the lake extended northward about 30 km from Soap Lake, Washington, to the head of Dry Falls, near Coulee City.

The lake was probably maintained by high ground-water levels in the basalt associated with the recent deglaciation of the Waterville Plateau. The decline in water tables eventually resulted in the lake's demise. Its former basin is now occupied by a chain of somewhat saline lakes, including Deep Lake, Fall Lake, Park Lake, Blue Lake, Lake Lenore, and Soap Lake.

Fryxell (1965) recovered coarse volcanic ash from the sediments of Lake Bretz. This ash was identified as Glacier Peak ash. A radiocarbon date of 12,000 ± 30 years B. P. was obtained on the Lake Bretz mollusk shells. This analysis provides an upper limit to the age of the ash, and it also dates the lacustrine phase. However, new data on the Glacier Peak ash show that this eruption may have been the oldest of several. Mehringer and others (1977) describe two Glacier Peak ashfalls in Montana dated at about 11,250 years B.P. and separated by 10 to 25 years.

Marmes Rockshelter, located near the confluence of the Snake and Palouse rivers, produced a long history of occupation (Fryxell and others, 1968; Rice, 1972). Artifacts discovered include bone needles, bone points, stemmed and lanceolate projectile points, and bola stones. A complex burial sequence was found beneath a shell midden dated by radiocarbon at 7,550 ± 100 years B.P. The midden, in turn, is overlain by Mazama ash (6,700 years B.P.). Carl Gustafson (1972) investigated faunal remains from the site and found bones including those of Arctic fox, large elk, pronghorn antelope, deer, bison, rodents and salmonid fish. These vertebrates belonged mainly to an early postglacial steppe fauna that characterized the region prior to 7,500 years B.P. Marshall (1971) analyzed nearby floodplain sediments and interpreted precipitation and steam run-off to have been greater than now prior

to 7,500 years ago. Frost polygons were found in the overbank silt deposits in which the early Marmes cultural material was discovered, but do not form in the area at present. Rockfall frequencies also showed that a cool moist climate was present during the time of the early occupation in the site (Fryxell and others, 1968). Because lacustrine sediment containing Glacier Peak ash was found immediately beneath the cultural zone, it is likely that occupation occurred over a long phase of cool, wet conditions between 12,000 and 7,500 years ago.

The Lind Coulee archeological site near Warden, Washington was the first locality in eastern Washington to yield evidence of paleo-Indian hunters. The early excavation work by Dougherty (1956) was one of the first to use the radiocarbon method, dating the earliest occupation at 8,700 years B.P. A new series of excavations at the site began in 1972. Although those studies are not yet complete, the preliminary results and correlations (Table 2.1) give an excellent late-glacial and post-glacial record. C. E. Gustafson (in Webster and others, 1976) recognizes a catastrophic flood phase unconformably overlain by lacustrine(?) silt containing the St. Helens "triplet" (set S). Inset into this slackwater silt is another silt unit. An overbank unit is set into the silts and contains two discrete ash layers including ashes from St. Helens set J and Glacier Peak (Moody, 1977). Another younger overbank sequence contains another St. Helens J ash dated at 8,700 years B.P. Mazama ash occurs in the eolian silt that blankets the overbank sequence.

CONCLUSION

Based primarily on physiographic evidence, Bretz (1969) has proposed as many as eight separate scabland floods, of which at least four encountered an ice-blocked Columbia River and spilled over the northern margin of the Columbia Plateau. Bretz' other four floods were not diverted by ice and flowed down the Columbia River valley. Bretz (1969, p. 513) believed that the earliest plateau-crossing flood occurred during the Bull Lake Glaciation. Subsequent floods then enlarged and altered segments of this established drainage.

Baker (1973a) noted that some of the physiographic relationships described by Bretz (1969) could be produced during the dynamic progression of a single flood. Only flood deposits recognized in a firm stratigraphic sequence can be considered unequivocal evidence for multiple flooding. The best stratigraphic information to date suggests that there certainly were five major floods in the general vicinity of the Channeled Scabland and perhaps six or seven. One, possibly two, floods were pre-Bull Lake and are overlain either by thick caliche or by Palouse Formation. Another flood occurred during the Palouse deposition (Bull Lake Glaciation). The third flood was the Bonneville event, restricted to the Snake River. The final flood phase, 18,000-13,000 years ago, seems to include two floods. One of these precedes the Vashon maximum, and the other occurred during or just prior to the Mount St. Helens set "S" eruptions.