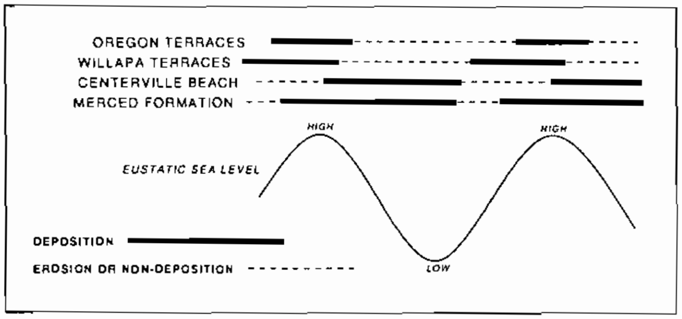

Figure 13. Patterns of deposition and erosion (or nondeposition) in the Pleistocene deposits described in this report, relative to eustatic sea-level fluctuations.

which landward-shifting shorefaces eroded previously deposited nearshore, foreshore, and nonmarine facies. These intervals of erosion could occur in any phase of the transgression. In the Centerville Beach section of the Rio Dell Formation, sediment ceased to accumulate only during the periods of most rapid sea-level rise, when condensed sections characterized by erosional surfaces and lag deposits developed. In the Willapa Bay setting, in contrast, the sediment that was deprived from the shelf during sea-level rise and highstand accumulated in alluvial valleys and coastal embayments; nondeposition in this setting took place during sea-level fall and lowstand, while the valleys were being reexcavated. In southern Oregon, marine deposition in emerging areas occurred at highstands, during the early phases of falling sea level, and possibly during the last phases of rising sea level. Nondeposition occurred here as the marine deposits were elevated tectonically above the eustatically falling sea level.

A common aspect of all these examples is that each sequence underwent an episode of tectonic uplift after deposition. This episode was crucial to make the deposits available for examination today. Successions of marine Pleistocene deposits comparable in thickness and complexity to those described here almost certainly exist elsewhere in northern California, Oregon, and Washington, buried beneath the shelf and the small segments of the coastal plain.

QUATERNARY STRATIGRAPHY AND GEOMORPHIC SURFACES OF THE WILLAMETTE VALLEY, OREGON

Patricia F. McDowell / 1991

INTRODUCTION

The landscape of the Willamette Valley is dominated by a broad, flat valley floor flanked by bedrock hills rising abruptly on the eastern and western margins. A mix of unusual erosional and depositional events during Quaternary time has left a complex record of lithostratigraphic units and geomorphic surfaces on the valley floor and in small terraces and pediments. Geomorphic processes internal to the Willamette River system have exerted a relatively minor influence on the Quaternary development of the valley floor. External controls, including (1) regional uplift, (2) local deformation, (3) base-level fluctuations controlled by the Columbia River and possibly by eustatic sea-level variations, (4) catastrophic floods and sediment input from the Columbia River system, and (5) sediment input from glaciers within the Willamette watershed, each have influenced this complex record.

Fluvial and lacustrine sedimentation alternated with episodes of incision since the Miocene epoch, but the exposed stratigraphic record is very fragmentary for early Pleistocene and earlier times. During Miocene to early Pleistocene time, lacustrine and fluvial deposition proceeded simultaneously with local uplift, structural deformation, and volcanic eruptions. By middle Pliocene time, aggradation allowed superimposition of the Willamette River on the Tualatin Mountains and on the Salem Hills (Fig. 14), and through drainage was established (Baldwin, 1957, 1981). Incision during Pleistocene time resulted in a series of progressively younger and lower pediments and fill terraces, which are described below.

Near the end of the Pleistocene epoch, glacier-outburst flooding from Glacial Lake Missoula in Idaho and Montana sent catastrophic floods down the Columbia River system (see Baker and others, this volume). The floods periodically inundated the Willamette Valley, depositing the Willamette Formation. The Willamette Valley is one of North America's largest examples of a settling basin for slackwater deposits. Following the main period of flooding, late Wisconsinan and Holocene events resulted in development of at least nine geomorphic surfaces, of erosional, depositional, and complex origin. The Holocene stratigraphic record, although little studied, indicates three major episodes of fluvial adjustment. The origin and stratigraphy of the upper Pleistocene and Holocene deposits have been controversial subjects since the 1870's, and continue to be so.[1]

PLIOCENE TO LATE PLEISTOCENE LANDFORMS AND DEPOSITS

Remnants of pediments and gravel terraces occur around the margins of the Willamette Valley, Tualatin Valley, and Portland Basin (Fig. 14), and loess deposits have been recognized in a few areas. The terrace deposits include units of gravel and mudflows. In some areas along the eastern margin of the Willamette Valley and the Portland Basin, the gravel is probably glaciofluvial in origin. Gravel units on the western margin include terraces and fans from local streams draining the unglaciated Coast Range, and probably deposits of the main stem of the Willamette River.

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[1] I have used stratigraphic nomenclature proposed or used in published literature, giving the original or most authoritative source of each name. Some of these names have not been formally established or fully defined. Their use here is not meant to imply that they are all formal stratigraphic terms.

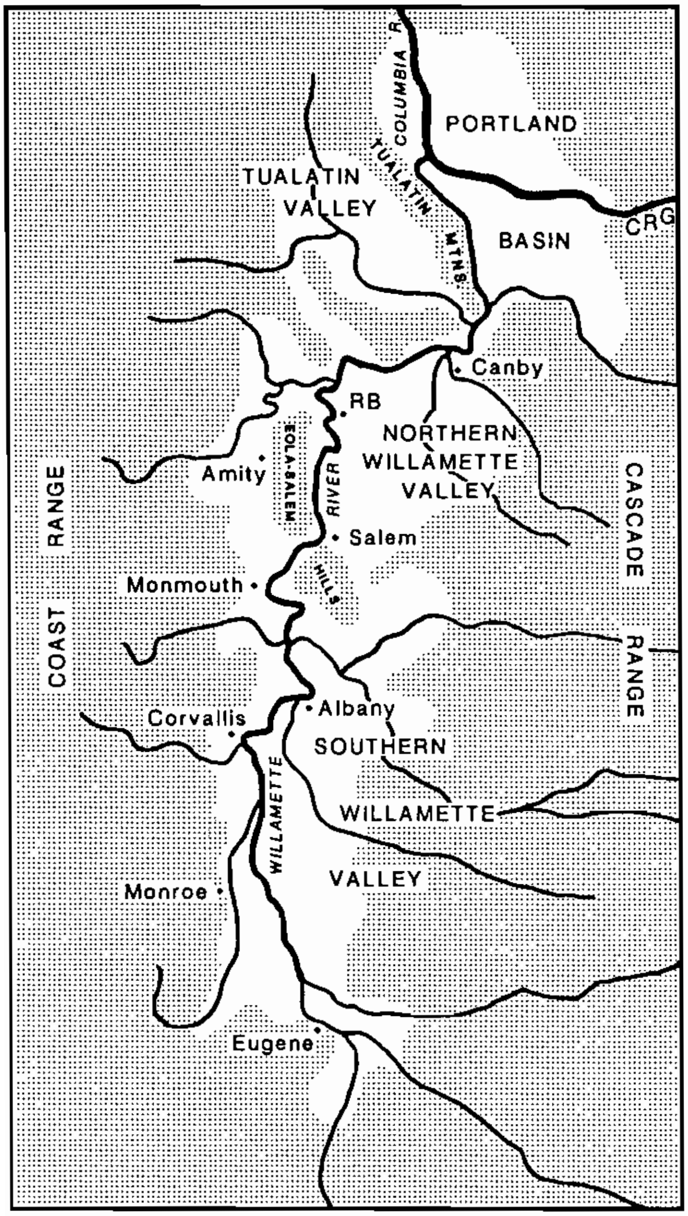


Figure 14. Willamette Valley region. CRG, Columbia River Gorge; RB, River Bend section of Glenn (1965).

Tentative correlations of stratigraphic units from the Portland Basin–Tualatin Valley area to the southern Willamette Valley are shown in Figure 15, but these correlations are not well established. Correlations among the sub-basins of the Willamette Valley are problematic, because the sub-basins may have had quite different histories of base-level and sediment supply. The essential questions that remain concerning these features are (1) the number and age of geomorphic surfaces and associated lithostratigraphic units, and (2) the genesis of each unit.

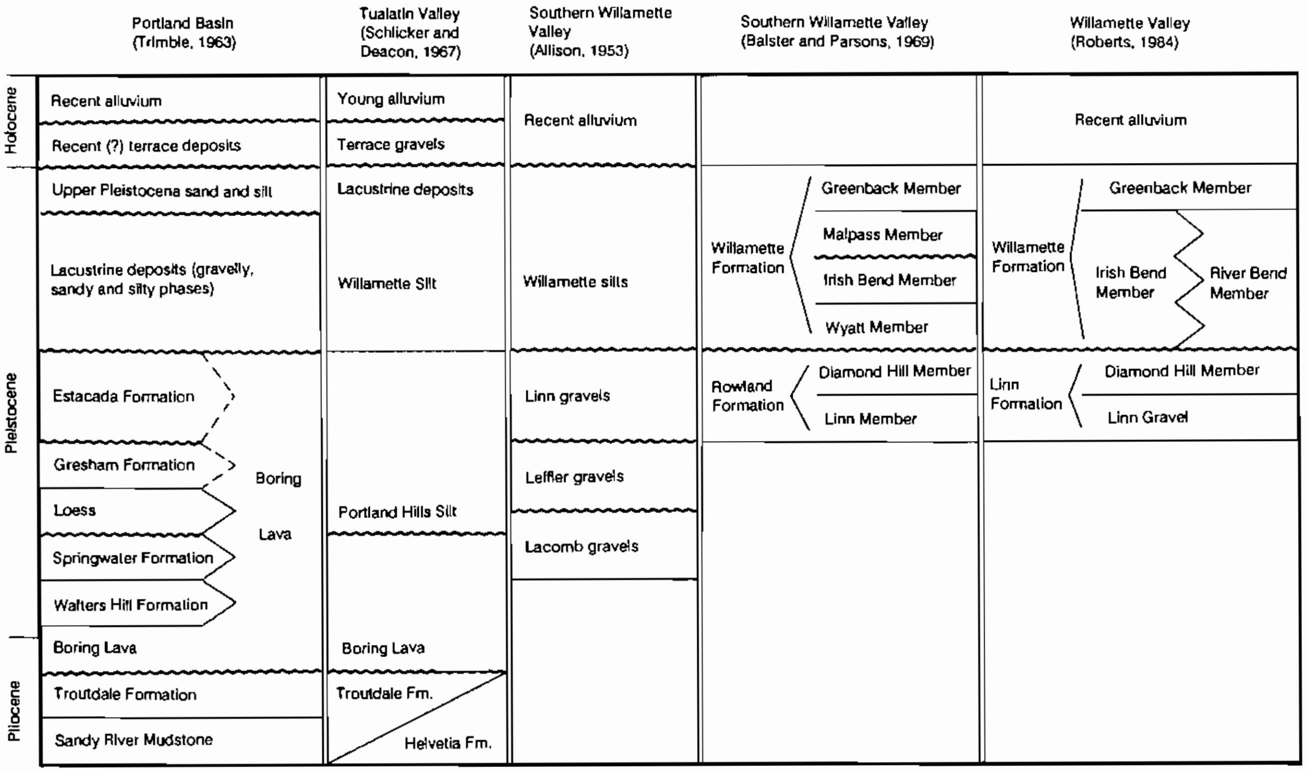
Early Pleistocene pediments

The highest Pleistocene landforms preserved in the Willamette Valley compose the Eola geomorphic surface (Balster and Parsons, 1968; Fig. 16). The surface consists of small pediment and strath-terrace remnants and rounded upland surfaces with hanging valleys. They are widely distributed around the margins of the Willamette Valley, typically occurring at 150 to more than 250 m above the present Willamette River level (Parsons and Balster, 1966; Balster and Parsons, 1968; Green, 1983; Parsons, 1985). Parsons and Balster (1966) recognized two topographically distinct pediment levels within the Eola surface, but it is not clear whether there are stratigraphic differences between them. The two levels presumably represent separate episodes of stability and geomorphic surface development as the Willamette River incised during Pliocene and early Pleistocene time. The pediments are characterized by distinctive soils—Haplohumults with deep, red profiles with thick argillic horizons—that are considered relict paleosols formed in pedisediment (Balster and Parsons, 1968; Green, 1983; Parsons, 1985). The Eola surface probably formed during early Pleistocene time. Lower, less dissected pediments mapped along the western margin of the southern Willamette Valley (Bela, 1979) are probably younger.

Mid- and Late Pleistocene gravel deposits

Intermittently throughout Pleistocene time, a series of gravelly fluvial or fluvioglacial sediments was deposited in the Willamette Valley, and they are preserved today as high gravel terraces standing 30 to 100 m above the present Willamette River level. Allison (1953) recognized three terrace gravel units—the Lacomb (oldest and highest), Leffler, and Linn (youngest and lowest)—along the eastern margin of the southern Willamette Valley. He tentatively correlated them with the pre-Kansan, Kansan, and Illinoisan or early Wisconsinan glaciations, respectively (Allison 1936, 1953), but actual correlations are uncertain. The gravel units generally are considered to range in age from middle to late Pleistocene (Beaulieu, 1971). The Lacomb and Leffler gravels form high terrace remnants and dissected fans at the mouths of tributary valleys, and the Linn gravels occur at or below the level of the main valley floor. Allison (1953) indicated that the three gravel units have progressively deeper and more intense weathering, from younger to older, and he distinguished them on the basis of depth of weathering and topographic position.

In other parts of the Willamette Valley, later workers generally have correlated gravel units and terraces with Allison's stratigraphy, or they have used a simpler stratigraphic scheme (Schlicker and Deacon, 1967; Beaulieu and others, 1974; Bela, 1979). Piper (1942) compiled the most extensive map of the Pleistocene gravel, covering the entire Willamette Valley, but he recognized only one gravel unit. Working in the Portland Basin, Trimble (1963) identified three terrace gravel units. He named them the Springwater, Gresham, and Estacada Formations, al-



	Portland Basin (Trimble, 1963)		Tualatin Valley (Schlicker and Deacon, 1967)	Southern Willamette Valley (Allison, 1953)	Southern Willamette Valley (Balster and Parsons, 1969)	Willamette Valley (Roberts, 1984)
Holocene	Recent alluvium		Young alluvium	Recent alluvium		Recent alluvium
	Recent (?) terrace deposits		Terrace gravels			
Pleistocene	Upper Pleistocene sand and silt		Lacustrine deposits	Willamette silts	Willamette Formation: Greenback Member	Willamette Formation: Greenback Member
	Lacustrine deposits (gravelly, sandy and silty phases)		Willamette Silt		Malpass Member Irish Bend Member Wyatt Member	Irish Bend Member River Bend Member
	Estacada Formation	Boring Lava	Portland Hills Silt	Linn gravels	Rowland Formation: Diamond Hill Member Linn Member	Linn Formation: Diamond Hill Member Linn Gravel
	Gresham Formation			Leffler gravels		
	Loess					
	Springwater Formation			Lacomb gravels		
	Walters Hill Formation					
	Boring Lava		Boring Lava			
Pliocene	Troutdale Formation		Troutdale Fm.			
	Sandy River Mudstone		Helvetia Fm.			

Figure 15. Correlation of Quaternary stratigraphic units of the Willamette Valley and adjacent areas. Alternative stratigraphic schemes for the Willamette Silt/Willamette Formation are shown in the three columns to the right.

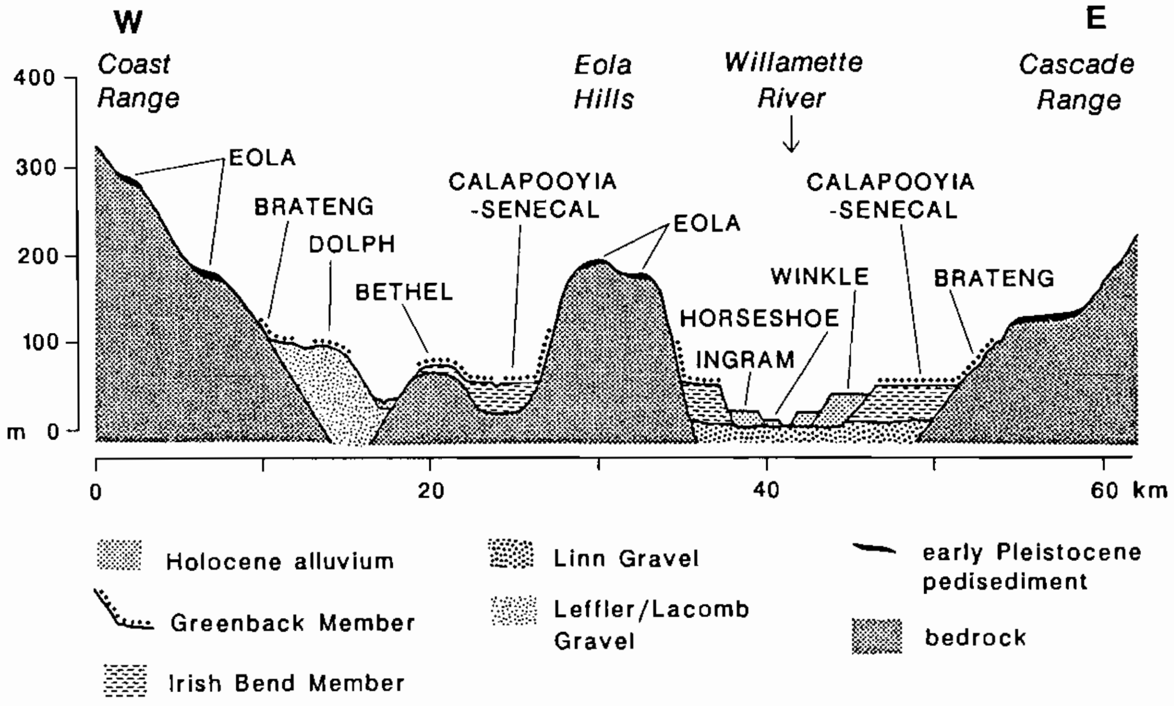


Figure 16. Generalized cross section of geomorphic surfaces at about the latitude of Salem. Subsurface distribution of the Linn Gravels shown here is speculative.

though formation status is probably not appropriate (J. Beaulieu, written communication, 1986), and suggested that they are correlative with the Lacomb, Leffler, and Linn gravels, respectively. The Springwater, Gresham, and Estacada Formations consist of boulder and cobble gravels, probably glaciofluvial in origin, with interfingered mudflows; all are derived from the Cascade Range. The Springwater Formation forms a gently sloping piedmont surface, and the Gresham and Estacada Formations occur as terraces set into it. In the northwestern part of the southern Willamette Valley, Baldwin (1964) and Brownfield (1982a, b) found one or two high terrace levels that they tentatively correlated with the Lacomb and/or Leffler gravel units.

Allison's definitions of the Lacomb and Leffler gravels implied that each originally formed till terraces, now preserved as discontinuous remnants. Balster and Parsons (1968), however, combined the Lacomb and Leffler gravels and small pediments graded to their surface in a single geomorphic surface, which they named the Dolph surface. On the western margin of the southern Willamette Valley, south of Corvallis (Fig. 14), Bela (1979) mapped bedrock pediments that may be related to the Lacomb or Leffler base level of the Willamette River.

Following deposition of the Lacomb and Leffler gravels, the Willamette River deeply incised before depositing the Linn gravels. Balster and Parsons (1969) proposed a redefinition of Allison's Linn gravels, renaming it the Rowland Formation (Fig. 15) and recognizing two members, the lower Linn Member and the upper sandy Diamond Hill Member. The Linn Member consists of cross-bedded gravel with sand lenses, and ranges in thickness from 5 to more than 70 m. It grades upward into the Diamond Hill Member, typically 2 to 3 m thick and composed of fluvial sand and clay with pebbles. A strongly developed paleosol at the top of the Diamond Hill Member is called the post–Diamond Hill paleosol (Balster and Parsons, 1969). The post–Diamond Hill paleosol was partly eroded before or during deposition of the Willamette Formation, which commonly overlies the Linn gravels (Balster and Parsons, 1969). Where it crops out at the surface, the post–Diamond Hill paleosol is a Vertisol (Parsons, 1979). Balster and Parsons (1969) reported that wood samples from the post–Diamond Hill paleosol gave infinite dates (>40,000 B.P.). In the southern Willamette Valley near Monroe (Fig. 14), however, Roberts (1984) considered a sandy unit nearly 30 m thick to be the Diamond Hill Member of the Linn Formation (equivalent to Balster and Parson's Diamond Hill Member of the Rowland Formation; see Fig. 15). Glenn (1965) reported a date of 34,410 ± 3,450 B.P. on a log from the upper part of a gravel deposit near Salem that presumably represents the Linn gravels. Roberts obtained ages of 28,480 ± 1,810 B.P. at 4 m below the top of the unit, 34,300 ± 1,400 B.P. at 7 m, and 36,000 ± 3,000 B.P. at 21 m. The Linn Member is locally absent at this location, and the sand unit overlies the Monroe Clay. The sand unit is anomalously thick for the Diamond Hill Member. If Balster and Parson's date on the Diamond Hill Member is correct, this sand unit may be alluvium, from Coast Range tributaries, related to the Willamette Formation (discussed below).

The relation of glaciofluvial gravel in the Willamette Valley to glacial deposits in the Cascade Range is poorly established. The glacial history of the west side of the Cascade Range in Oregon is poorly known. According to Thayer (1939), deposits of three glacial episodes occur in the Santiam River watershed, on the west side of the Cascade Range. No recent mapping of glacial deposits has been done on the western side of this range. Carver (1972) and Scott (1977) each recognized three major glacial episodes on the east side of the Cascade Range. They made tentative age assignments and correlations to deposits in the Cascade Range of Washington, Puget Lowland, and other areas of the western United States, but did not attempt to correlate Thayer's (1939) work on the west side of the range.

In summary, at least three geomorphic surfaces related to former higher base levels are preserved above the main level of the Willamette Valley floor. The uppermost surface (Eola geomorphic surface) consists of erosional bedrock pediments mantled with pedisediment, whereas the two lower surfaces (Lacomb and Leffler gravels) probably are constructional gravel surfaces. Detailed mapping and tracing of terrace longitudinal profiles may reveal that there are more than three surfaces. A fourth episode of landscape development is represented by the late Wisconsinan Linn Formation. The Linn Formation probably was deposited sometime during oxygen-isotope stages 2 to 4, but ages of the earlier deposits are unknown.

Portland Hills Silt

The Portland Hills Silt is massive, yellow-brown, micaceous silt (Lowry and Baldwin, 1952) that occurs as a mantle as much as 37 m thick on the Tuatalin Mountains and other hills around the Portland Basin and Tualatin Valley (Lentz, 1981a). It was derived from the Columbia River system, as were the Helvetia Formation, Troutdale Formation, and parts of the Willamette Formation (Lentz, 1981a). The origin of the Portland Hills Silt has been controversial, with loessial, fluvial, and residual soil origins attributed to it. Libbey and others (1945), Lowry and Baldwin (1952), and Parsons (1981) argued for a fluvial origin, based on the occurrence of pebbles in the silt and evidence of slight tectonic deformation of the Portland Hills Silt and overlying deposits. Lentz (1981a, b) found that the Portland Hills Silt is largely free of pebbles and favored an eolian origin; he argued that sparse pebbles may have been introduced by colluviation. Trimble (1963) and Schlicker and Finlayson (1979) concurred with Lentz. The Portland Hills Silt is overlain by the Willamette Formation and may possibly interfinger with the Boring Lava. This would suggest an age range from 700,000 years ago to mid-Wisconsinan (Lentz, 1981a). The soil stratigraphy of the Portland Hills Silt is spatially variable, and includes multiple episodes of soil development (Whittig and others, 1957; Parsons, 1981). At one location, Lentz recognized four depositional units within the silt, separated by paleosols. Beyond the recognized areal range of the Portland Hills Silt, Glasmann and others (1980) reported a thin (less than 40 cm) silty loess in the Coast Range foothills at the southwestern edge of the northern Willamette Valley. This suggests that thin eolian deposits, possibly related to the Portland Hills Silt, may be found elsewhere in the Willamette Valley.

THE LATE WISCONSIN WILLAMETTE FORMATION AND RELATED DEPOSITS

Early work

Much of the floor of the Willamette Valley is underlain by horizontally bedded silt and associated deposits, whose petrology indicates derivation from a source outside the Willamette watershed. Condon (1871, 1902) originally proposed that these are estuarine deposits that accumulated in a "Willamette Sound" created by eustatic sea-level rise. Allison (1933, 1935, 1936, 1953, 1978) postulated that they are lacustrine slackwater deposits that followed glacier-outburst floods down the Columbia River from Glacial Lake Missoula and during the Wisconsinan Stage (Bretz, 1925). Allison named them the Willamette Silt. The Willamette Valley deposits are very similar to the Touchet Beds of southern Washington, which also are slackwater deposits of the catastrophic floods.

The Willamette Silt originally was defined as parallel-bedded silt and fine sand, with erratic pebbles and boulders (Allison, 1953; Allison and Felts, 1956). It is thickest beneath the valley floor at 60 to 90 m above sea level, but a thin layer extending up to an elevation of 122 m at the valley margins also was included. The Willamette Silt occurs as fill over the Linn gravels and older deposits. Erratic boulders to pebbles, of granite, granodiorite, gneiss, slate, and other rock types foreign to the Willamette River watershed, are widespread on the surface of the Willamette Silt at all elevations. Allison (1935) recognized the glacial origin and upper Columbia River basin provenance of these erratic boulders and concluded that they were ice-rafted into the Willamette Valley through ponded water of the "Spokane Flood" on the Columbia River. Pugh (1986) proposed that the Willamette meteorite, the largest meteorite found in the United States, was ice-rafted into the Willamette Valley during these floods.

Description and origin of the Willamette Formation

Deposits overlying the Linn Formation are known to be stratigraphically more complex than Allison's original concept of the Willamette Silt (Glenn, 1965; Balster and Parsons, 1969). A developmental model has evolved that includes two distinct phases of flood deposition from the Columbia River in the Willamette Valley (Allison, 1933, 1935, 1978; Glenn, 1965; Schlicker and Deacon, 1967; Roberts, 1984). In the first phase, a thick body of low-energy, silty to sandy deposits was laid down, probably by multiple floods. The second phase, resulting from a single very large flood, resulted in erosion and deposition of smaller volumes of (1) sandy to bouldery high-energy deposits near gaps where the flood entered the valley, and (2) silty low-energy deposits across the valley floor. Several additional models have been proposed, including deposition of both phases by a single large flood (Trimble, 1963), and deposition of the first-phase deposits in an environment similar to Condon's proposed Willamette Sound (Lowry and Baldwin, 1952; Balster and Parsons, 1969; Beaulieu, 1971; Parsons, 1985). The latter explanation requires uplift and/or eustatic sea-level fall to elevate the deposits to 60 to 120 m above sea level. The alternative models are not as strongly supported as is Allison's two-phase model. Following is my synthesis of the stratigraphy and origin of these deposits, based on the work of these researchers.

TABLE 2. WILLAMETTE FORMATION CHARACTERISTICS*

Willamette Formation Member	Geometry and Distribution	Lithology	Provenance
Greenback	<1 m thick; continuous mantle over valley floor and foothills as much as 122 m a.s.l.†	Pale gray massive silts, with erratic pebbles and rock chips	Columbia River system
Malpass	Discontinuous lenses <1 m thick, widespread over valley floor	Dark gray massive clay	Willamette River system
Irish Bend	6 to 15 m thick body underlying the valley floor below 80 m a.s.l.†,§	Parallel-bedded tan silt and fine sand	Columbia River system
Wyatt	A few lenses ≤2 m thick, in center of valley	Fluvial-bedded sands and silts§	Willamette River system§

*Based on Balster and Parsons (1969), except as noted.
†Glasmann and others (1980). a.s.l. = above mean sea level.
§Glenn (1965).

Balster and Parsons (1969) proposed that the Willamette Silt be renamed the Willamette Formation, consisting of four members: in ascending order, the Wyatt, Irish Bend, Malpass, and Greenback. The morphology, lithology, and provenance of these members are collated in Table 2. The lowermost Wyatt Member probably represents infilling of river channels, caused by damming or ponding of the Willamette River at the beginning of the first phase of slackwater flooding. Unit II at Glenn's (1965) River Bend section may be equivalent to the Wyatt Member.

The Irish Bend Member also was deposited during the first phase of flooding. This member accounts for most of the Willamette Silt as conceived by Allison, but it does not include the thin silt mantle that lies on slopes above the valley floor. Based on

Glenn's (1965) work at the River Bend section (Fig. 14), Roberts (1984) proposed the name River Bend Member for the more distinctly bedded, slightly coarser facies of the Willamette Formation in the northern Willamette Valley, which is the equivalent of the Irish Bend Member in the southern Willamette Valley.

Allison (1978) believed that the first-phase backflooding was due to aggradation in the Portland Basin and diversion of the Columbia River into the Tualatin and Willamette Valleys, but that the second-phase flooding, which reached a higher level in the Willamette Valley, required hydraulic or ice-jam damming of the Columbia River downstream from the Portland Basin. According to Allison, during the beginning of the first phase of flooding the Portland Basin was infilled with as much as 75 m of fluvial sand now called the Portland Sand (formerly Portland Gravels or "lacustrine deposits"; Lowry and Baldwin, 1952; Treasher, 1943; Trimble, 1963; Beaulieu, 1971). Later in the first phase of flooding, flood waters from the Columbia River entered the Willamette Valley over the surface of the aggrading Portland Sand and deposited the Irish Bend and River Bend Members. Following this period, the Willamette Valley drained, probably due to incision of the Portland Sand fill. Soil development sufficient to allow clay translocation and argillan development occurred on the Irish Bend Member before deposition of the overlying Malpass and Greenback Members (Parsons and others, 1968).

The Irish Bend and River Bend Members resemble the Touchet Beds (Waitt, 1980, 1985) of southern Washington in many details, including (1) number of beds, (2) bed thickness, (3) within-bed grading, (4) within-bed sequence of sedimentary structures, and (5) decrease in bed numbers, thickness, and grain size up-valley. Given the strong similarity between these deposits, their genesis is probably similar. Two distinct mechanisms of formation have been proposed in southern Washington. Waitt (1980, 1985) proposed that (1) each bed in the Touchet sequence was formed from separate, catastrophic, glacial-outburst floods from Glacial Lake Missoula; (2) between floods, the surface of the Touchet Beds was subaerially exposed; and (3) about 40 such floods occurred at recurrence intervals of decades, during 2,000 to 3,000 years. Baker and Bunker (1985), however, argued that several beds could have been emplaced during a single flood by hydraulic surges. They suggested that there were indeed multiple floods, of varying size, from Glacial Lake Missoula and other proglacial lakes at the margin of the Columbia Plateau, but that each rhythmite bed is not necessarily the product of a separate flood. Discussion of this hypothesis is presented in Baker and others (this volume).

For the Willamette Valley, Glenn (1965) and Allison (1978) believed that each rhythmite bed reflects a separate flood event on the Columbia River, but that a perennial lake ("Willamette Lake;" Allison, 1978) existed during at least the early part of the multiple-flood interval, and an intermittent lake in the later part.

The Malpass Member was deposited in swales on the surface of the Irish Bend Member after erosion had partly removed an intervening paleosol (Balster and Parsons, 1969). The Malpass extends beyond the edges of the Irish Bend Member. The genesis of the Malpass Member is not clear; Green (1983) and Parsons (1985) argued that it is an estuarine deposit of the Willamette Sound of Condon (1871, 1902).

During the second phase of flooding, a single, large-volume, glacial-outburst flood from the Columbia River system entered the Portland Basin. From there it flowed into the Tualatin Valley, and then into the Willamette Valley (Allison, 1978). The slackwater level in the Willamette Valley reached to 122 m, apparently higher than the level of first-phase flooding. Cross-bedded bouldery gravel and plane-bedded sand beds were deposited at the downstream end of the narrow entry to each successive basin. These beds form the upper part of the Portland Sand of Lowry and Baldwin (1952), "lacustrine deposits, gravelly phase" of Trimble (1963), and "lacustrine deposits" of Schlicker and Deacon (1967). Away from the entry points, the coeval silty Greenback Member of the Willamette Formation (Balster and Parsons, 1969) was deposited. Balster and Parsons (1969) originally limited the Greenback Member to the valley floor, but Glasmann and others (1980) showed that it extends as as thin drape upslope to about 122 m elevation, presumed to be the upper limit of slackwater flooding in the Willamette Valley. Quartz grains in the Greenback Member have surface micromorphology indicating glacial derivation (Glasmann and Kling, 1980). The glacial erratic boulders of Allison (1935) apparently are associated with the Greenback Member.

After draining of the second-phase flood about 13,000 years ago, drainage networks and the main channel of the Willamette River became reestablished on the floor of the Willamette Valley. Initially the Willamette River flowed northeastward from Salem to Canby (Fig. 14). This channel was abandoned about 11,000 years ago when the river shifted to its present location, and valley-floor tributaries experienced piracy and diversions in response to the new local base level (Glenn, 1965).

Age of Columbia River flooding in the Willamette Valley

There are no ages determined directly from the catastrophic flood deposits in the Willamette Valley. A date of 13,080 ± 300 B.P., from the base of bog deposits on the Portland Sand at 60 m altitude, indicates that floods large enough to pond in the Willamette Valley could not have occurred after this date (Mullineaux and others, 1978). Dates on deposits adjacent to the Irish Bend Member in the Willamette Valley provide possible lower age limits for this member. Glenn's (1965) date of 34,400 B.P. (discussed above) presumably represents the Linn gravels, but the gravel at this site is not directly overlain by the Willamette Formation. Dates by Roberts (1984) on sand strata that he correlated with the Rowland (Linn) Formation (discussed above) indicate that the flooding began after 28,000 B.P., but it is not clear whether the sand beds correlate with the Rowland (Linn) Formation or the Willamette Formation. According to Balster and Parsons (1969), the age of the post-Diamond Hill paleosol of the

Rowland (Linn) Formation is >40,000 B.P. The dates of Glenn and Roberts are consistent, however, and if they are correct, the Willamette Formation was deposited later than 28,000 years ago.

The age(s) of the catastrophic flood events in the Columbia Basin is also problematic. Waitt (1985) argued that the sequence of flood events in the Columbia River system began no earlier than 16,000 years ago, and probably not before 15,000 years ago, based on dated glacial deposits at the southern edge of the Cordilleran ice sheet in Canada. Given the upper limiting date of 13,000 B.P. (Mullineaux and others, 1978), according to Waitt's hypothesis, emplacement of the entire Willamette Formation must have occurred within 2,000 to 3,000 years. This does not allow enough time for the multiple events of deposition and soil development that are recorded in the Willamette Valley. If the early phase of the Irish Bend Member resulted from multiple glacier-outburst floods from Glacial Lake Missoula, deposition of this member alone could have taken 2,000 to 2,500 years (Waitt, 1985). Yet the two phases are separated by an interval that included (1) soil development advanced enough for clay illuviation, followed by (2) erosion, and (3) deposition of the Malpass Member (Balster and Parsons, 1969). More recent evidence from the Columbia Basin suggests that two episodes of catastrophic flooding occurred during the Wisconsinan stage: one at about 35,000 to 40,000 years ago, and another at 18,000 to 11,000 years ago (McDonald and Busacca, 1988; Baker and others, this volume). Based on tephrachronology, Moody (1989) tentatively correlated the Irish Bend Member at the River Bend site in the Willamette Valley (Fig. 14) with the 35,000 to 40,000 B.P. flood episode in the Columbia Basin. During this earlier flood episode, however, there is no evidence in southern British Columbia of an ice sheet that could have impounded Glacial Lake Missoula.

There are two possible hypotheses, therefore, for the age of the Willamette Formation. First, the Willamette Valley first-phase flooding could be the result of middle Wisconsinan flooding in the Columbia River system, and the Willamette Valley second-phase flooding could be the result of the late Wisconsinan flooding. This hypothesis implies that the dates of Glenn and Roberts are not from deposits of the Rowland (Linn) Formation. Second, both phases of flooding in the Willamette Valley could be associated with the late Wisconsinan flooding in the Columbia River. This alternative hypothesis requires some means of reconciling the flood chronology of Waitt with the soil chronology of Balster and Parsons (1969).

QUATERNARY GEOMORPHIC SURFACES

The Willamette Valley has been the site of one of the most detailed applications of the concept of mapping geomorphic surfaces within North America. Roger Parsons and C. A. Balster, and later other co-workers, performed the work from the late 1960s into the 1980s. Their purpose was to use geomorphic surfaces as an aid in soil mapping by the U.S. Soil Conservation Service. Balster and Parsons (1968, p. 2), following the practice of Ruhe (1956, 1969), defined a geomorphic surface as "a landform or group of landforms that represents an episode of landscape development." Early in the work, Balster and Parsons (1969) developed the lithostratigraphic model of the Willamette Formation described above and in Table 2. They then defined and mapped geomorphic surfaces on the basis of topographic relationships, surface morphology, and photo-tonal patterns, using aerial photographs supported by field checking.

Parsons and coworkers recognized 15 Quaternary geomorphic surfaces of varied genesis in the Willamette Valley (Balster and Parsons, 1968, 1969; Parsons and others, 1968). They developed a detailed model of stratigraphic units, geomorphic surfaces, and relationships between soils and lithostratigraphy, but they did not develop adequate geomorphic-process models to explain the stratigraphic record. A summary of the characteristics of 12 major geomorphic surfaces is presented in Table 3. Spatial relationships of eight of these are shown in Figure 16. One-to-one relation between geomorphic surfaces and lithostratigraphic units do not exist. For example, the Dolph surface is associated mainly with the Lacomb and Leffler gravels, but it also includes pediments and upland remnants. The higher and older Eola surface is associated chiefly with early Pleistocene pediment remnants, but Balster and Parsons (1968) state that the Lacomb and Leffler gravels also occur under it.

Six separate surfaces with widely varying morphology occur on deposits of the Willamette Formation. The Calapooyia, Quad, Bethel, Champoeg, and Brateng geomorphic surfaces all resulted chiefly from deposition by the last catastrophic flood (Greenback Member), although they differ in surficial morphology. The Calapooyia surface is a smooth, broad, and level surface (local relief less than 1 m) that occurs extensively in the northern and southern Willamette Valley, and has younger surfaces set into it. Despite its smooth morphology, Balster and Parsons (1968) concluded that it is not a simple depositional surface. Rather it is an erosional/depositional surface, associated primarily with the poorly understood events that created the Malpass Member, and it is capped by the Greenback Member. The Senecal surface consists of the Calapooyia surface modified by development of local small drainageways. It is generally level, with slightly incised drainageways, in contrast to the very smooth, unincised Calapooyia surface. The Quad surface and the Bethel surface consist of deposits of Willamette Formation in the form of small rounded or flat-topped hills and benches standing above the main level of the Calapooyia surface. Formation of the Quad surface was attributed to uplift by faulting of part of the Calapooyia surface (Balster and Parsons, 1968), but there is no field evidence to support local faulting, and the area originally mapped as Quad surface probably should be assigned to the Bethel surface. The Bethel surface consists of Willamette Formation deposits draped over bedrock knolls and benches (Gelderman and Parsons, 1972). The Bethel surface has been recognized only in the Amity area (Fig. 14), but it may be more widespread. In the Portland Basin, surfaces morphologically equivalent to the Quad recently have been correlated with the Bethel surface (Green, 1983; Parsons, 1985). Two additional surfaces, the Brateng and the Cham-

TABLE 3. GEOMORPHIC SURFACES OF THE WILLAMETTE VALLEY*

Geomorphic Surface	Surface Type	Dominant Surface-forming Process	Final Surface-forming Event	Major Associated Deposits	Approximate Age (B.P.)	Typical Soils
Horseshoe	Depositional	Fluvial lateral accretion	Fluvial lateral accretion	Recent alluvium	<300	Fluventic Haploxeroll
Ingram	Depositional	Fluvial lateral accretion	Fluvial lateral accretion	Recent alluvium	<5,000	Cumulic Ultic Haploxeroll
Winkle	Depositional	Fluvial lateral accretion	Fluvial lateral accretion	Recent alluvium	12,000 to 5,000	Pachic Ultic Argixerol
Champoeg	Depositional	Phase 2 flood proximal facies deposition	Phase 2 flood proximal facies deposition	"Lacustrine deposits"†	13,000	Argiaquic Xeric Argialboll, Aquic Xerocherpt
Senecal	Erosional	Local fluvial incision of Calapooyia surface	Deposition of Greenback Member	Willamette Formation	13,000	Aquultic Argixerol, Pachic Ultic Argixeroll
Calapooyia	Erosional/ depositional	Plantation of Irish Bend Member and older deposits	Deposition of Greenback Member	Willamette Formation	13,000	Typic Albaqualf, Argiaquic Xeric Argialboll
Quad§	Uplifted(?)	Uplift of Willamette Formation deposits	Deposition of Greenback Member	Willamette Formation	13,000	Pacific Ultic Argixeroll
Bethel**	Depositional/ draped on erosional	Willamette Formation deposits draped on low bedrock knolls	Deposition of Greenback Member	Willamette Formation	13,000	Aquultic Argixeroll
Brateng‡	Depositional/ draped on erosional	Greenback Member deposits draped on hillslopes	Deposition of Greenback Member	Greenback Member over Tertiary bedrock	13,000	Ultic Haploxeralf
Dolph	Depositional/ some erosional	Fluvial/glaciofluvial aggradation	Deposition of Greenback Member	Lacomb and Leffler gravels, with Greenback Member in places	Mid-Pleistocene or younger	Ultic Haploxeroll, Ultic Haploxeralf
Eola	Erosional	Pedimentation	Deposition of loess, gravels, or pedisediment	Unnamed pedisediment, Lacomb and Leffler gravels, Helvetia Formation, Portland Hills Silt§§	Early Pleistocene	Xeric Haplohumult
Looney	Erosional	Mass movement	Ongoing mass movement and slope erosion	Colluvium	Time-transgressive	Typic Haplohumult, Typic Haplumbrept

*Based on Balster and Parsons (1968, 1969) and Parsons and others (1970), except as noted.

†Schlicker and Deacon (1967).

§No direct evidence for uplift; probably should be subsumed under the Bethel geomorphic surface.

**Recognized by Gelderman and Parsons (1972) near Amity (Fig. 14).

‡Recognized by Glasmann and others (1980) in a small study site 3 miles south of Monmouth (Fig. 14), but probably widespread.

§§Green (1983), Parsons (1985).

poeg, are associated only with deposits of the phase-two catastrophic flooding.

Since the last catastrophic flood and initial establishment of drainage networks on the valley floor, incision and deposition by the Willamette River and its tributaries have formed three geomorphic surfaces below the main Calapooyia-Senecal surface: the Winkle, Ingram, and Horseshoe (Balster and Parsons, 1968). These surfaces apparently are erosion terraces with alluvial veneers (generally mapped as Holocene/Recent alluvium). The Holocene alluvium consists of a few meters or less of locally derived gravel, which grades upward into sand and silt. These surfaces can be distinguished by topographic position, soil development, and to a lesser extent by surface morphology. Surface morphology of the Winkle surface suggests that it may have formed when the Willamette River channel pattern was more braided and less sinuous than the present anastomosing-to-meandering channel. The Ingram surface has bar-and-swale topography that appears to be braided in some areas and meandering in others; oxbow lakes are common. The Horseshoe surface consists of the modern channel and bars of the Willamette River and its major tributaries.

Soil development on each surface varies spatially, but typical soils of each surface (Table 3) show increasing soil development with increasing age of the surface. Argillic horizons are developed on the Winkle and older surfaces, and the percent of base saturation decreases with increasing age (Parsons and others, 1970). Within a single geomorphic surface, soil variability commonly reflects the varying thicknesses of several thin lithostratigraphic units, including the Portland Hills Silt, the Greenback and Malpass Members, and younger natural levee deposits (Parsons and others, 1968; Parsons, 1979). For example, on the Calapooyia surface where thin layers of the Greenback and Malpass Members overlie the Irish Bend Member, the Dayton soil series, a typic albaqualf, occurs. This is a compound soil that has two lithologic discontinuities and a truncated paleosol within the profile (Parsons and Balster, 1967). Where the Malpass Member is absent, the Amity series, an Argiaquic Xeric Argialboll, occurs.

This complex assemblage of geomorphic surfaces is the result of a combination of normal and exceptional processes. Normal terrace-building and erosion terrace development, probably in response to regional base-level decline and changes in sediment supply from uplands, created the Holocene surfaces, and the early Dolph and Eola surfaces. Exceptional processes associated with catastrophic flooding from the Columbia River system are responsible for the surfaces of intermediate age. Tectonic warping and faulting may also have played a role in the formation of so many surfaces, but evidence for this is not clear. Balster and Parsons (1968, 1968) presented at least four arguments for minor structural deformation following emplacement of the Irish Bend Member. First, the Calapooyia and Senecal surfaces approximate a plane sloping N25°W, oblique to the main axis of the valley. Second, the inset Winkle surface diverges from the Calapooyia/Senecal surfaces down-valley. If Allison's catastrophic flood model is correct, however, the slope of the Calapooyia/Senecal surfaces is the result of sediment deposition in a slackwater basin, whereas the slope of the Winkle surface is the result of the hydraulics of flood-plain construction. Structural deformation is not necessary to account for the difference in gradients. Third, Balster and Parsons argued that while the Irish Bend Member generally thickens down-valley, it thins down-valley in an area from just south of Corvallis to Albany. The data they presented, however, are not adequate to show whether this is due to relief on the upper or lower boundary of the Irish Bend Member. Fourth, they proposed that the Quad surface was created by uplift of blocks of Willamette Formation sediments. No faults cutting Willamette Formation deposits in the Willamette Valley have been recognized, however.

CONCLUSIONS

The most-studied aspect of the Quaternary units of the Willamette Valley has been the Willamette Silt/Willamette Formation. Significant contributions to understanding its history and stratigraphy were made by Allison, Glenn, Balster and Parsons, Roberts, and others, but correlations have been hampered by lack of communication between geologists and the soil scientists/soil geomorphologists. Detailed studies have revealed progressively more complex stratigraphy, which has not been thoroughly interpreted. When the stratigraphic and chronologic problems discussed in this section are resolved, the implications of this stratigraphy for geomorphic processes should be readdressed. These problems can be solved only through multidisciplinary cooperation and application of the techniques of soil science, geomorphology, and geology.

Little attention has been paid to the Holocene history of the Willamette Valley, but available evidence indicates major drainage changes occurred near the beginning of Holocene time and significant fluvial adjustment between mid-Holocene and the late Holocene time. The role of climatic change, tectonic events, and other external factors, as well as internal changes in hydraulic competence, base-level, and drainage-network development, should be examined.

QUATERNARY GEOLOGY OF THE GREAT VALLEY, CALIFORNIA

W. R. Lettis and J. R. Unruh

INTRODUCTION

This section reviews the Quaternary stratigraphy of the Great Valley of California and the relation between depositional episodes and climatic changes, considers the problems and implications of using the correlation of stratigraphic units within the valley to assess late Cenozoic deformation in the valley and its margins, and identifies several key problems that require further study in the valley.