The Miocene to Pliocene Ringold Formation and Associated Deposits of the Ancestral Columbia River System, South-central Washington and North-central Oregon

by Kevin A. Lindsey
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The Miocene to Pliocene Ringold Formation and Associated Deposits of the Ancestral Columbia River System, South-central Washington and North-central Oregon

Kevin A. Lindsey
Daniel B. Stephens and Associates, Inc.
1845 Terminal Drive, Suite 200
Richland, Washington 99352

INTRODUCTION

During the Late Neogene quartzo-feldspathic detrital sediments were deposited in and adjacent to the Columbia Basin of central Washington in a fluvial system interpreted to be the ancestor of the modern Columbia River system (Warren, 1941; Waters, 1955; Tallman and others, 1981; Tolan and Beeson, 1984; Tolan and others, 1984a, 1984b; Baker and others, 1987; Fecht and others, 1987; Smith, 1988; Reidel and others, 1994). This ancestral Columbia River system drained geologic terranes as varied as Precambrian to Paleozoic cratonic sedimentary and metasedimentary rocks to the east and northeast, accreted Paleozoic and Mesozoic oceanic terranes to the southeast, Mesozoic crystalline terranes to the north, and Late Neogene volcanic terranes to the east and west (Fecht and others, 1987). Evolution of the Late Neogene Columbia River system was influenced by many factors, including emplacement of the flood basalts of the Columbia River Basalt Group (CRBG), the evolving structure of the Columbia Basin, and uplift and volcanism in the ancestral Cascade arc (Warren, 1941; Waters, 1955; Reidel and Fecht, 1981; Reidel and others, 1989, 1994; Reidel, 1984; Tolan and others, 1984a, 1984b; Tolan and Beeson, 1984; Fecht and others, 1987; Smith, 1988).

One of the most extensive sedimentary units preserving a record of the Late Neogene Columbia River system is the late Miocene to middle Pliocene Ringold Formation. Ringold strata preserve an essentially continuous stratigraphic record for a period near the end of Columbia River Basalt Group volcanism, from 8.5 Ma until approximately 3.4 Ma. The Ringold Formation is unique within the regional Late Neogene stratigraphic record because other Late Neogene sedimentary units are repeatedly interrupted by Miocene volcanic rocks, deposited peripheral to the main tract of the ancestral Columbia River system, or less widespread.

The thickest and laterally most extensive occurrences of the Ringold Formation occur on and adjacent to the U.S. Department of Energy (DOE) Hanford Site in the Pasco Basin of south-central Washington (Fig. 1). At the Hanford Site the Ringold Formation forms the majority of the shallowest aquifer system generally referred to as the suprabasalt or unconfined aquifer (DOE, 1988; Reidel and others, 1992; Lindsey and others, 1994a). The base of this aquifer is at the top of the uppermost basalt underlying the Ringold Formation. The water table within this unconfined aquifer usually is found at or very near the top of the Ringold Formation beneath the Hanford Site. Most of the ground-water contaminant plumes at the Hanford Site occur at least partially within saturated Ringold strata (DOE, 1988; Pacific Northwest Laboratories, 1993; DOE, 1994; Lindsey and others, 1994a).

Data upon which this study is based were collected during post-doctoral stratigraphic and sedimentologic research in the Pasco Basin and regionally and environmental investigations at the Hanford Site. This report describes the stratigraphy and sedimentology of the Ringold Formation and its relationship with correlative units in the region.
Basins discussed in text:
- QB = Quincy Basin
- OB = Othello Basin
- PB = Pasco Basin
- UB = Umatilla Basin
- SG = Sentinel Gap
- SNG = Sunnyside Gap
- WG = Wallula Gap
- SP = Satus Pass

Structures discussed in text:
- FH = Frenchman Hills
- SM = Saddle Mountains
- UR = Umatum Ridge
- TYR = Yakima Ridge
- RH = Rattlesnake Hills
- HHH = Horse Heaven Hills
- CH = Columbia Hills
- HR-NR = Hog Ranch-Naneum Ridge Uplift

Washington
- Columbia River
- Yakima Fold Belt
- Simcoe Mountains
- The Dalles

Oregon
- Spokane
- Blue Mountains

Idaho
- Spokane
- Snake River

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SETTING

The Hanford Site and Pasco Basin (Figs. 1 and 2) are situated in the part of south-central Washington commonly referred to as the Columbia Basin. The Columbia Basin is an intermontane basin situated between the Cascade Range on the west, Okanogan Highlands to the north, Rocky Mountains to the east, and the Blue Mountains anticlinorium to the south (DOE, 1988) (Fig. 1). The Pasco Basin is located in the south-central Columbia Basin. The Hanford Site, in the central Pasco Basin, is divided into a series of areas designated the 100 Areas (in the northern part of the Hanford Site adjacent to the Columbia River), the 200 Areas (divided into 200 East and 200 West and situated in the central part of the Hanford Site), and the 300 and 400 Areas (situated in the southern part of the Hanford Site) (Fig. 2). Gable Mountain and Gable Butte divide the Hanford Site into northern and southern halves.

Structural Geology

The Columbia Basin is divided into three geologic subprovinces, the Yakima Fold Belt, Palouse Slope, and Blue Mountains (Fig. 1) (DOE, 1988). The Yakima Fold Belt is characterized by a series of segmented, narrow, asymmetric, generally east-west-trending anticlines that have wavelengths between 5 and 32 km (3.1 and 19.9 mi) and amplitudes commonly less than 1 km (0.62 mi) (Reidel, 1984; Reidel and others, 1989, 1994). The northern limbs of these anticlines generally dip steeply to the north or are vertical to even overturned. Most southern limbs dip at relatively shallow angles to the south. Thrust and high-angle reverse faults with fault planes that generally strike parallel to fold axes commonly are found on the north sides of these anticlines. The anticlinal ridges are separated by broad synclinal troughs or basins, many of which contain Neogene to Quaternary sediment (Fecht and others, 1987; DOE, 1988; Smith and others, 1989; Reidel and others, 1994). The main study area is in the Pasco Basin, one of the larger structural basins in the Yakima Fold Belt. A single major north-south structure, the Hog Ranch-Naneum Ridge uplift, occurs in the western fold belt (DOE, 1988; Tolan and Reidel, 1989). Deformation in the Yakima Fold Belt began prior to the emplacement of the Columbia River Basalt Group (beginning approximately 17 Ma), occurred throughout Columbia River basalt volcanism (which ended approximately 6.5 Ma), and continues to the present (Reidel and Fecht, 1981; Reidel, 1984; Fecht and others, 1987; Reidel and others, 1989, 1994).

The Pasco Basin (where the Hanford Site is located) is bounded on the north by a series of anticlines forming the Saddle Mountains, on the west by the Hog Ranch-Naneum Ridge anticline, and on the south by the anticlines forming Rattlesnake Mountain and the Horse Heaven Hills (Fig. 3) (Tallman and others, 1981; DOE, 1988; Tolan and Reidel, 1989). The western edge of the Palouse Slope (occasionally referred to as the Jackass monocline (DOE, 1988)) bounds the Pasco Basin on the east. The Pasco Basin is divided into a series of smaller synclines by east-west-trending anticlines that project into the western Pasco Basin. The two main synclines are the Wahluke syncline and Cold Creek syncline (Fig. 3). Each syncline is asymmetric and relatively flat bottomed, with the north limbs dipping gently (approximately 5 degrees) to the south and the south limbs dipping steeply to the north (Reidel and Fecht, 1981; DOE, 1988).

Figure 1 (facing page). Regional geographic setting of the Columbia Basin and Hanford Site, south-central Washington and north-central Oregon showing major basins, anticlinal structures, and locations discussed in text (modified from Tolan and Reidel, 1989).
Late Neogene Depositional Framework

Late Neogene sediments (including the Ringold Formation) are found in structural lows and linear tracts across much of the Columbia Basin. Facies mapping in these sediments has established that a drainage system similar to the one found today existed in the Columbia Basin during the Late Neogene (Warren, 1941; Waters, 1955; Newcomb, 1958; Baker and others, 1987; Fecht and others, 1987; Smith, 1988; Reidel and others, 1994; Lindsey and others, 1993, 1996; Tolan and others, 1996). This Late Neogene Columbia River system consisted of the ancestral Columbia River and four main tributaries, the ancestral Salmon-Clearwater, ancestral Snake, ancestral Yakima, and ancestral Palouse Rivers. The modern river names are used here following the conventions outlined in Waters (1955), Fecht and others.
Figure 3. Geologic structures in and near the Pasco Basin, and Hanford Site. Map shows major structural elements in the area (modified from Reidel and others, 1989).
Throughout the middle Miocene (prior to Ringold deposition) the Columbia River flowed from north to south along the western margin of the Columbia Basin adjacent to volcanic terranes that predate the modern Cascade volcanic arc (Warren, 1941; Baker and others, 1987; Fecht and others, 1987; Smith, 1988). Throughout the rest of this paper this volcanic terrane is informally referred to as the ancestral Cascades. At the same time the Salmon-Clearwater and Palouse Rivers flowed to the west down the sloping paleosurface referred to as the Palouse Slope (Fecht and others, 1987). The Yakima River generally flowed into the southwestern corner of the Columbia Basin. The Snake River did not begin to flow into the central Columbia Basin until the latest Pliocene or early Pleistocene (Baker and others, 1987). Prior to this the Snake River may have entered the Columbia River system to the south, in the western Umatilla Basin (Lindsey and others, 1993, 1996; Tolan and others, 1996).

Prior to 14.5 Ma the position of the Columbia River was controlled by the west-dipping paleoslope of the Columbia Basin and west-flowing flood basalts (Fecht and others, 1987). As flood basalt volcanism decreased in intensity (during Saddle Mountains time, 14.5 to 6.5 Ma), continued uplift in the western Columbia Basin centered on the Hog Ranch-Naneum Ridge anticline, relative to subsidence in the Pasco Basin, began to displace the Columbia River to the east (Waters, 1955; Fecht and others, 1987; Smith, 1988). Near the end of flood basalt volcanism in the late Miocene (approximately 8.5 Ma) the Columbia River began to encroach on the central Pasco Basin, and Ringold deposition began.

THE RINGOLD FORMATION

Suprabasalt terrigenous clastic sediments assigned to the Ringold Formation (and correlative Snipes Mountain Conglomerate) are present throughout much of the south-central Columbia Basin (Waters, 1955; Schmincke, 1964; Newcomb and others, 1972; Grolier and Bingham, 1978; Myers, Price, and others, 1979; Tallman and others, 1979, 1981; Fecht and others, 1987; Smith and others, 1989). Regionally, the Ringold Formation consists of interbedded, unconsolidated to cemented clay, silt, sand, and granule to cobble gravel (Newcomb, 1958; Newcomb and others, 1972; Fecht and others, 1987; Smith and others, 1989; Lindsey and Gaylord, 1990; Reidel and others, 1994). Exposures of the Ringold Formation are present in: (1) the White Bluffs adjacent to the Columbia River (Fig. 4), (2) on Eureka Flat north of Wallula Gap, (3) in the Quincy and Othello Basins north of the Saddle Mountains, and (4) on benches and slopes adjacent to basalt uplifts such as Rattlesnake Mountain, the Saddle Mountains, and the Frenchman Hills (Figs. 1 and 3). At and near the Hanford Site the Ringold Formation is largely restricted to the subsurface, and outcrops are limited to the flanks of anticlinal ridges, the White Bluffs, and Eureka Flat (Figs. 1 and 4).

Previous Studies

All post-Columbia River Basalt sediments (including strata now assigned to the Ringold) in the central Columbia Basin and in the adjacent Washington Cascades were originally assigned to the Ellensburg Formation by Smith (1901). Smith's stratigraphy was later modified by Merriam and Buwalda...
(1917), who assigned the clayey, silty, and sandy terrigenous clastic sediments exposed on the White Bluffs of the Columbia River north of Pasco to a new unit, the Ringold Formation. Culver (1937) mapped the Ringold Formation across the central Columbia Basin. Merriam and Buwalda (1917) and Culver (1937) restricted their definition of the Ringold Formation to strata exposed at the surface.

With the establishment of the Hanford Site and increased agricultural activity in the early 1940s, numerous wells were drilled for water production, ground-water analysis, and geologic investigations. Data from these wells revealed a thick sequence (up to 175 m) of conglomerate with lesser clay, silt, and sand overlying Columbia River basalt in the Pasco Basin. Drilling also indicated that these subsurface sediments were contiguous with Ringold exposures in the White Bluffs (Newcomb, 1958). Using subsurface data and surficial exposures Newcomb (1958) redefined the Ringold Formation to include all sediments in the Pasco Basin that overlie Columbia River basalt and underlie Pleistocene glaciofluvial deposits and Holocene surficial deposits.

Age

The Ringold Formation originally was thought to be Pleistocene (Merriam and Buwalda, 1917; Newcomb, 1958; Newcomb and others, 1972). However, detailed paleontologic investigations by Gustafson (1973, 1985) established that upper Ringold strata exposed on the White Bluffs are Pliocene. Paleomagnetic studies of core samples and upper Ringold exposures indicate a Miocene to Pliocene age range for the Ringold Formation (Packer and Johnston, 1979). The Ringold Formation disconformably overlies Miocene basalt dated at 8.5 to 10.5 Ma (Fecht and others, 1987), and Miocene pollen is present near the base of the Ringold (Puget Sound Power and Light Co., 1982). On the basis of these data Fecht and others (1987) state the Ringold Formation is no older than 8.5 Ma and no younger than 3.4 Ma, or late Miocene to middle Pliocene in age.

Stratigraphy

The Ringold Formation (Fig. 5) as currently mapped is found throughout the Pasco Basin (including Eureka Flat), north of the Saddle Mountains in the Quincy and Othello Basins, and locally on the south side of the Columbia Hills along the northeastern fringe of the Umatilla Basin. Regionally, strata correlative to the Ringold Formation and displaying many of the same geologic characteristics are found between the Pasco Basin and Portland, Oregon. The most extensive of these units are the Snipes Mountain Conglomerate between the Pasco Basin and The Dalles, Oregon (Schmincke, 1964; Baker and others, 1987; Fecht and others, 1987; Anderson, 1987; Smith, 1988; Smith and others, 1989), the Alkali Canyon Formation in the Umatilla Basin (Faroqui and others, 1981; Smith and others, 1989; Lindsey and others, 1993), the Dalles Formation near The Dalles, Oregon (Warren, 1941; Newcomb, 1966; Farooqui and others, 1981; Smith and others, 1989), and the Troutdale Formation between The Dalles and Portland, Oregon (Tolan and Beeson, 1984; Tolan and others, 1984a, 1984b).

The Ringold Formation and correlative units overlie the CRBG (and intercalated Ellensburg Formation) along a contact that is disconformable to locally an angular unconformity. Various informally named late Pliocene to Pleistocene strata overlie the Ringold Formation in and near the Pasco Basin. These strata are informally referred as the: (1) Pliocene and Pleistocene unit (Myers, Price, and others, 1979; Tallman and others, 1979, 1981; Fecht and others, 1987; DOE, 1988; Lindsey and others, 1994b), (2) pre-Missoula gravel (PSPL, 1982), and (3) Hanford formation (Tallman and others, 1979, 1981; DOE, 1988; Lindsey and others, 1994a). The Pliocene and Pleistocene unit consists of pedogenic calcium carbonate (stage III to VI of Machette, 1985), well-stratified silt (sometimes referred to as early Palouse soil), matrix-rich basalt gravel, and reworked Ringold lithologies deposited on alluvial fans on and adjacent to the Pasco Basin. Mixed lithology, gray to white, quartzose, uncremented sandy pebble to cobble gravel interpreted as a late Pliocene to early Pleistocene Columbia River deposit characterizes the
<table>
<thead>
<tr>
<th>Age</th>
<th>Epoch</th>
<th>Formation</th>
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<tbody>
<tr>
<td>0 ka</td>
<td>Holocene</td>
<td>Eolian and Alluvium</td>
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<tr>
<td>13 ka</td>
<td>Pliocene</td>
<td>Touchet Beds</td>
</tr>
<tr>
<td>500 ka</td>
<td>Pleistocene</td>
<td>Missoula Flood Gravels and Sands</td>
</tr>
<tr>
<td>700 ka</td>
<td>Pleistocene</td>
<td>Pre-Missoula, Plio-Pleistocene</td>
</tr>
<tr>
<td>3.4 Ma</td>
<td>Miocene</td>
<td>member of Savage Island</td>
</tr>
<tr>
<td></td>
<td></td>
<td>member of Taylor Flat</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unit E</td>
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<td></td>
<td></td>
<td>Unit C</td>
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<td></td>
<td></td>
<td>Unit B</td>
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<tr>
<td></td>
<td></td>
<td>Unit D</td>
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<tr>
<td></td>
<td></td>
<td>Unit A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Snipes Mountain Conglomerate</td>
</tr>
<tr>
<td>8.5 Ma</td>
<td>Miocene</td>
<td>Saddle Mountain Basalt</td>
</tr>
<tr>
<td>14.5 Ma</td>
<td></td>
<td>Wanapum Basalt</td>
</tr>
<tr>
<td>15.6 Ma</td>
<td></td>
<td>Grande Ronde Basalt</td>
</tr>
<tr>
<td>17.0 Ma</td>
<td></td>
<td>Imnaha Basalt</td>
</tr>
<tr>
<td>17.5 Ma</td>
<td></td>
<td>Flood-Basalt Flows and Interbedded Sediments</td>
</tr>
</tbody>
</table>

Figure 5. Late Neogene stratigraphy of the Pasco Basin emphasizing the Ringold Formation. Column not to scale.
pre-Missoula gravel. The Hanford formation consists predominantly of uncemented silt, sand, and basaltic to mixed lithology gravel deposited by Pleistocene cataclysmic floods (Fecht and others, 1987; Baker and others, 1991).

Traditionally the Ringold Formation in the Pasco Basin has been divided into several informal units: (1) gravel, sand, and paleosols of the basal unit, (2) clay and silt of the lower unit, (3) gravel of the middle unit, (4) mud and lesser sand of the upper unit, and (5) basaltic detritus of the fanglomerate unit (Newcomb, 1958; Newcomb and others, 1972; Myers, Price, and others, 1979; Tallman and others, 1979; Bjornstad, 1985; DOE, 1988). Ringold strata also have been divided on the basis of facies types (Tallman and others, 1981) and fining-upwards sequences (PSPL, 1982). All of these stratigraphic divisions are of limited use because they are defined over large areas based on limited information or defined in detail for relatively small areas (Lindsey and Gaylord, 1990).

Methods

Studies began in 1989 to redefine stratigraphic relations in the Ringold Formation across the Hanford Site and Pasco Basin. The initial results of these studies indicated that the Ringold Formation is best described and subdivided on the basis of sediment facies associations and their distribution (Lindsey and Gaylord, 1990; Lindsey, 1991). Later studies confirmed and refined these interpretations for locations on and adjacent to the Hanford Site (Lindsey and others, 1991, 1992, 1994b; Lindsey, 1992; Lindsey and Jaeger, 1993). This report presents a compilation of Ringold Formation geologic information gathered during these studies at the Hanford Site and in much of the surrounding area. The primary data sources are: (1) 25 measured sections from the White Bluffs (Appendix A), (2) detailed lithologic logging of core from 18 boreholes on the Hanford Site (Appendix B), and (3) drill cuttings and cuttings logs from hundreds of boreholes located on and near the Hanford Site (borings studied tabulated in Appendix D). This data set is used to establish the basic geologic characteristics of the Ringold Formation, identify in detail the sedimentary facies comprising the Ringold Formation, and determine physical properties of Ringold sediments. From these data sets geologic cross-sections were constructed (Appendix C) and subsurface data compiled (Appendix D). Additional data used to understand Ringold geology include previously published reports (referred to in text), borehole geophysics, and reconnaissance studies of Ringold correlative strata across the region. The measured sections and cores also are used to establish control points for stratigraphic interpretations and define analogues to use where core and outcrops are lacking.

The basic function of the analogues is to provide a basis for evaluating drill cuttings and cuttings logs. Conditions typically interpreted from cuttings with the aid of analogues include facies type, probable mud content, extent of interstratified lithologies, cementation and compaction, and grain-size range. Analogue analysis also aids in determining how representative samples from uncored boreholes are and to better interpret lateral and vertical continuity of bedding and cementation in the subsurface. Use of analogues also allows identification of geologic properties fundamental to hydrologic interpretations. Reconnaissance studies provide additional analogues for interpreting geohydrologic characteristics as well as regional geologic history.

SEDIMENT FACIES ASSOCIATIONS

Ringold strata are divided into five facies associations on the basis of sediment facies (Table 1) (such as defined by Miall, 1977, 1978, 1985; Rust, 1978; and Rust and Koster, 1984) observed in intact cores and outcrops. Sediment facies are identified from measured sections (Appendix A) and outcrop studies in the Saddle Mountains, on Yakima Ridge, on the White Bluffs, and at Eureka Flat. Facies data also are gathered from cores (Appendix B) and from drill cuttings and borehole geologic logs from sites across the Pasco Basin. (See Appendix D for list of boreholes having geologic logs studied for this
<table>
<thead>
<tr>
<th></th>
<th>Lithofacies</th>
<th>Sedimentary Structures</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gms</td>
<td>massive, matrix supported gravel</td>
<td>massive</td>
<td>debris flow deposition</td>
</tr>
<tr>
<td>Gm</td>
<td>massive to stratified</td>
<td>planar to low-angle bedding 0.5 to 12.5 m thick, imbrication</td>
<td>bedload deposition on longitudinal bars, lag deposits</td>
</tr>
<tr>
<td>Gt</td>
<td>stratified gravel</td>
<td>trough cross beds less than 2 m thick, dominantly low angle</td>
<td>bedload deposition on longitudinal bars in channels</td>
</tr>
<tr>
<td>Gp</td>
<td>stratified gravel</td>
<td>planar cross beds 1 to 3 m high</td>
<td>bedload deposition on linguoid and transverse bars</td>
</tr>
<tr>
<td>Sm</td>
<td>fine to coarse sand</td>
<td>massive</td>
<td>rapid deposition from suspension</td>
</tr>
<tr>
<td>St</td>
<td>fine to coarse sand, minor pebbles</td>
<td>asymmetric trough cross beds &lt;1.5 m high, (av. 1 m)</td>
<td>dunes deposited in channels</td>
</tr>
<tr>
<td>Sp</td>
<td>fine to coarse sand, minor pebbles</td>
<td>planar cross beds 10 cm to 1 m high</td>
<td>linguoid and transverse bar deposit</td>
</tr>
<tr>
<td>Sr</td>
<td>fine to medium sand, minor silt</td>
<td>ripple cross lamination</td>
<td>current ripples</td>
</tr>
<tr>
<td>Scr</td>
<td>fine to medium sand, minor silt</td>
<td>climbing ripple cross lamination</td>
<td>rapid deposition from suspension</td>
</tr>
<tr>
<td>Sh</td>
<td>fine to coarse sand, minor pebbles</td>
<td>planar bedding</td>
<td>deposition from high velocity currents in shallow water</td>
</tr>
<tr>
<td>Sg</td>
<td>silty, fine to coarse sand</td>
<td>normally graded beds with plane and ripple cross lamination</td>
<td>sediment gravity flow deposit</td>
</tr>
<tr>
<td>Se</td>
<td>erosional scour less than 3 m deep, intraclasts common</td>
<td>incised beds, crude cross bedding, and lateral truncations</td>
<td>scour cut-and-fill, channel incision</td>
</tr>
<tr>
<td>Fl</td>
<td>sand, silt, and clay</td>
<td>fine plane and ripple cross lamination</td>
<td>deposition from suspension under waning flow conditions</td>
</tr>
<tr>
<td>Fsc</td>
<td>silt, clay</td>
<td>laminated to massive</td>
<td>deposition from suspension</td>
</tr>
<tr>
<td>Fr</td>
<td>silt, clay</td>
<td>bioturbation and pedogenic alteration present</td>
<td>paleosol</td>
</tr>
<tr>
<td>P</td>
<td>calcite and silcrete</td>
<td>bioturbation and pedogenic alteration present, calcium carbonate precipitates</td>
<td>silica- and calcium carbonate-rich paleosol</td>
</tr>
</tbody>
</table>
Table 2. Summary of the characteristics and depositional environments of Ringold facies associations. Facies codes based on Miall (1978, 1985). See Appendix A for measured sections in sediments forming the various facies associations

<table>
<thead>
<tr>
<th>Facies Ascc.</th>
<th>Lithology</th>
<th>Facies</th>
<th>Stratification and Contacts</th>
<th>Bed Geometry</th>
<th>Depositional Environments</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>clast- to matrix-supported pebble to cobble gravel; fine to coarse grained sand matrix; lenticular sand and silt interbeds</td>
<td>Gm, Gp, Gt, St, Fsc</td>
<td>crudely defined Gm and low angle Gt common; Gp locally well developed; contacts dominated by low angle scour</td>
<td>Gm in 0.5 to 1.5 m thick lenses; Gm, Gt, and Gp form lenticular bodies less than 5 m thick</td>
<td>gravel bedload deposition on braided plain characterized by shallow shifting channels</td>
</tr>
<tr>
<td>II</td>
<td>fine to coarse sand; locally pebbly; silt interbeds may be present</td>
<td>Sp, St, Se, Sh, Sr, Sm</td>
<td>lenticular Sp over Se; Sh and Sr form planar sets and cosets; lenticular sand bodies dominated by St, Sp, and Se; sheet-like sand bodies consisting of Sh and Sr</td>
<td>channel fill deposits combine to form sheet-like sand bodies 30 m thick and 0.5 km across; intertongues with tabular intervals dominated by facies assoc. III</td>
<td>sandy bedload deposition in low sinuosity braided channels</td>
</tr>
<tr>
<td>IIIa</td>
<td>silty fine sand to silt</td>
<td>Sr, Sh, Fl I</td>
<td>moderately to poorly stratified; disrupted and mottled beds common; root and burrow fills common; gradational contacts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IIIb</td>
<td>silt to clay; rare silty sand; peds and calcium carbonate present</td>
<td>Fsc, Fr, P</td>
<td>bedding generally disrupted; calcium carbonate forms stringers, nodules, and concretions; root and burrow fills common; gradational contacts</td>
<td>laterally persistent intervals 5-10 m thick; intertongues with facies assoc. IIIa and IIIc</td>
<td>distal overbank and crevasse splay; paleosols</td>
</tr>
<tr>
<td>IIIc</td>
<td>calcium carbonate rich clay, silt, and sand; silica also present</td>
<td>Fr, P</td>
<td>extensive calcium carbonate; bedding rare; root and burrow fills common; silcrete may be associated</td>
<td>laterally persistent intervals marked by numerous internal truncations; intertongues with facies assoc. IIIa and IIIb</td>
<td>calcic to silicic paleosols</td>
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<tr>
<td>IVa</td>
<td>clay, silt, and sandy silt, commonly distomaceous</td>
<td>Fl, Fsc, Sg</td>
<td>laterally persistent strata dominated by Sg, contacts sharp and planar</td>
<td>laterally persistent geometries forming coarsening upward sequences 10 to 20 m thick; base commonly diatomaceous</td>
<td>deposition from suspension and sediment gravity flow of lacustrine basin plain</td>
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### Table 2. Summary of the characteristics and depositional environments of Ringold facies associations (continued)

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<th>Facies Assc.</th>
<th>Lithology</th>
<th>Facies</th>
<th>Stratification and Contacts</th>
<th>Bed Geometry</th>
<th>Depositional Environments</th>
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<tr>
<td>IVb</td>
<td>interbedded silt, silty sand, and fine to medium sand</td>
<td>Fsc, Fl, Sh, Sr, Sg</td>
<td>form fining upward beds &lt;3 m thick; these combine to form coarsening upward intervals 10 m thick</td>
<td>sheet-like geometries dominate; grades into facies assc. IVa and II</td>
<td>deposition from suspension mixed with sediment gravity flow deposition in front of prograding delta</td>
</tr>
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<td>V</td>
<td>matrix and lesser clast-supported basaltic gravel; muddy matrix</td>
<td>Gms, Gm, Gp</td>
<td>massive bedded; Gp and Gt rare</td>
<td>sheet-like tabular geometries dominate</td>
<td>debris flow, sheet flood, and minor fluvial deposition proximal to distal subaerial fan</td>
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</table>
Supplemental regional data were taken from reconnaissance studies throughout the region and from previously published reports. The five Ringold facies associations are numbered I, II, III, IV, and V (Table 2).

**Facies Association I**

Facies association I (Table 2) consists of clast- and matrix-supported, pebble to cobble gravel with a fine to coarse sand matrix and intercalated fine to coarse sand and silt lenses (Fig. 6). Although the facies association is typically well compacted, cement content ranges from none to well developed. The main cements are calcium carbonate, iron oxides, and silica. Individual cemented zones observed in outcrop generally are less than 1 m thick and rarely extend laterally more than 100 m. Cemented zones several meters thick and continuous laterally over several hundred meters were identified from drill cuttings from several wells in the northern and southeastern part of the 200 West Area (notably wells 699-48-77A; 299-W6-3, -4, -5, -6, -7, -9, -10, -11, and -12; and W299-W7-6 and -8). Evidence of cement in these wells included red coloring of samples, aggregated gravel in some samples, and low water production. Cemented gravel also is directly observed in Basalt Waste Isolation Project (BWIP) cores of Ringold gravel (Appendix B). Based on these observations cemented Ringold gravel is inferred to be present as discontinuous (less than 250 m across) lenses and zones of variable thickness (less than 1 m to 10 m). Unfortunately, subsurface characterization efforts at Hanford have largely failed to provide the information necessary to determine the physical characteristics and extent of these cemented zones, their influence on contaminant migration, and their influence on well performance during pumping and injection operations. This failing is typical of geologic logs for wells drilled on the Hanford Site as well.

Analysis of samples from outcrops and intact core indicate grain-size distributions for Ringold gravel typically are bimodal (Tables 3, 4, 5). Generally, the facies association contains greater than 67 weight percent pebbles and cobbles, less than 5 weight percent granules, and the balance is medium to fine grained sand. Mud content is typically less than 5 weight percent, although it may locally exceed 10 percent. This trend suggests that muddy gravel lithologies typically reported on boring logs in Ringold gravel over-represent the abundance of mud in Ringold gravel samples.

The grain-size distribution described here differs notably from those reported from samples acquired by driven split spoon sampling techniques (Last and others, 1989), which typically have lower pebble-cobble and higher granule and mud contents. The increased granule and mud concentration probably is the direct result of mechanical breakage of clasts during the driving of the split spoon. The presence of broken clasts in split spoon samples directly affects analytical measurements requiring intact samples (e.g., hydraulic conductivity, density).

Gravel clasts are dominated by weathered and unweathered basalt, quartzite, and intermediate to felsic volcanic rocks (Table 6). Less common clast types include greenstone, volcanic and tectonic breccia, silicic plutonic rocks, gneiss, and mud rip-ups. Matrix sand typically is quartzo-feldspathic with a subordinate basalt lithic fraction (Table 7) (Goodwin, 1993).

Stratification in the association includes massive (Gms), planar bedded (Gm), and cross-bedded (Gp, Gt). Clast imbrication is common in the stratified gravel. Low-angle scour channels less than 1.5 m (4.9 ft) deep and at least 10 m (32.8 ft) across also are found. Facies Gms generally forms 0.5-m to 1.5-m (1.6 to 4.9 ft)-thick lenses less than 20 m (65.6 ft) across that are interstratified with and grade
Figure 6. Outcrop photo of facies association I showing large-scale cross bedding at the base of outcrop, sand interbeds next to Jacob's staff, varied cementation emphasized by the discontinuous overhanging ledges, and grain size variations from sand exposed behind staff to cobble rich zone coming across middle of outcrop. Jacob's staff is 1.3 m high. This outcrop is located on eastern bank of Columbia River opposite Wooded Island near the base of measured sections B-5 and B-6.
Table 3. Grain-size distributions (weight percent) from facies association I cores of unit E, member of Wooded Island

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<th>pebble</th>
<th>granule</th>
<th>v. coarse sand</th>
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<th>medium sand</th>
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<th>v. fine sand</th>
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Table 4. Grain-size distributions (weight percent) from outcrops of facies association I comprising unit E of the member of Wooded Island

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Table 5. Grain-size distributions (weight percent) from facies association I core of unit A, member of Wooded Island

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Table 6. Pebble count data for Ringold Formation facies association I gravel exposed in the Pasco Basin. Samples are from the member of Wooded Island unit E. See Appendix A for location and stratigraphic position of specific samples

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Abbreviations used in table:
- Sample # - sample number or location identified on outcrop measured section.
- bslt - basalt
- and - andesite
- fv - felsic volcanic rocks (exclusive of rhyolite)
- rhy - rhyolite
- qt - quartzite, various colors
- vq/p - vein quartz and pegmatite
- fp - felsic to intermediate plutonic rocks
- gn - gneiss
- gns - greenstone
- brec - breccia
- cht - chert
- fmet - fine-grained metamorphic rock and hornfels
- wtf - welded and banded tuff
- msed - banded, fine-grained metasedimentary rock (argillite and siltite)
Table 7. Whole rock XRD data for sand in Ringold unit E from cores in unit E near the 100-N Area (BH numbers), the 200 West Area (DH numbers), and east of the 200 East Area (G numbers) (See Figure 1 for locations of these facilities)

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Abbreviations used in table:
- k-spar - potassium feldspar
- plag - plagioclase
- carb - calcium carbonate
- amph - amphibole minerals
- mica - mica minerals
- clay min - clay minerals
into stratified gravel (Gp, Gt, Gm). These massive and stratified gravels commonly combine to form lenticular bodies up to 5 m (16.4 ft) thick that overlie low-angle scours. Laterally discontinuous fine to coarse, cross-bedded sand (Sp, St) interbeds up to 2 m (6.6 ft) thick (Fig. 6) are intercalated in the gravel (Fig. 7). The presence of interstratified sand in the subsurface probably is the primary cause for gravelly sand lithologies reported on borehole cuttings logs. Thin (typically <2 m, <6 ft) intercalated silty deposits displaying some motting and bedding disruption also are present.

The features displayed by facies association I are similar to those described by Miall (1978, 1985), Rust (1978), Kraus (1984), Rust and Koster (1984), and Collinson (1986) for gravelly, bedload-dominated fluvial systems. Bimodal grain-size distribution is interpreted to be the result of sand deposition during relatively low flow and gravel deposition during relatively high flow. The rare sand interbeds found are the erosional remnants of sand channel fills deposited during relatively low flow. Rare muddy gravel horizons are the uneroded remnants of gravel bar surfaces and abandoned channels subject to mud infiltration as a result of subaerial exposure and pedogenic processes. The abundance of low-angle bedding geometries and grain-size distribution indicate facies association I formed in a depositional system characterized by rapid deposition in shallow channels shifting across a gravelly braidplain.

Deposition of facies association I was characterized by alternating periods of high and low flow. During relatively long periods of low flow sand deposition occurred in channels cut into gravelly braidplains. Subaerially exposed gravel flats and bars also underwent pedogenic alteration during low flow. Periodically, high flow events led to incision of broad, shallow channels across the gravel flats, deposited gravel sheets, low-angle gravelly bedforms, and gravel channel fills, and reworked low-flow sand channel deposits and pedogenically altered gravel flats.

**Facies Association II**

Facies association II (Table 2) consists of fine to coarse (Tables 8a, 8b, 8c), generally quartzofeldspathic sand similar in composition to sand in facies association I (Goodwin, 1993). The facies association typically is light tan to buff; other colors observed include brown, red-brown, and yellow-brown. Salt-and-pepper colors also may be present where basalt content is above approximately 20 percent. Intercalated silt and pebble beds may be present. Cement is notably absent in most occurrences of the facies association identified in outcrop and core. Where uncemented sand horizons are saturated in the subsurface they will typically flow into borings. The only cemented sand observed is restricted to spherical, tabular, and platy concretions found in outcrops.

Facies association II displays: (1) sandy bedforms consisting of planar (Sp) and trough (St) cross-bedded sand lenses overlying scoured bases (Se), (2) sandy bedforms consisting of tabular sheets and lenses of plane laminated (Sh) to ripple cross-laminated (Sr) sand, (3) massive bedded fine sand and silty sand (Sm), and (4) interstratified plane and ripple laminated silt and sand (Fl). Deposits composing the association commonly combine to form channel-fill sequences 1 to 5 m (3.3 to 16.4 ft) thick and as much as 100 m (328 ft) across (Fig. 8). These channel-fill sequences occur intercalated in facies association I and stacked together to form sand bodies that are up to 30 m (98 ft) thick and 0.5 km (0.3 mi) or more across (Fig. 9). Typical thickness to width ratios for these sand bodies are approximately 1:100.

Facies association II is interpreted to have been deposited in a sandy bedload-dominated fluvial system such as discussed by Cant and Walker (1976), Walker and Cant (1984), and Collinson (1986). The thickness to width ratios of the preserved sand bodies indicate deposition was dominantly in low-sinuosity channels similar to those discussed by Galloway (1985b). Avulsion and channel abandonment are recorded by fining-upwards transitions from this facies association to facies association III.
Figure 7. Interstratified sand and gravel of facies association I. Gravelly sand reported on borehole logs probably consists of interbedded sand and gravel such as seen here. The gravelly cliff face is approximately 10 m high. This outcrop is located on eastern bank of Columbia River opposite Wooded Island at the base of measured section B-3.

Facies Association III

Facies association III is divided into three types (IIIa, IIIb, IIIc) (Table 2) which grade into each other. The coarsest (IIIa) consists of sheets of slightly mottled and bioturbated, brown to light-gray, laminated to massive sand and silt (Sr, Sh, Fl) and rarely gravel. Facies association IIIc consists of green to black, unstratified, crumbly weathering silt and clay displaying medium to strongly developed, fine to medium, subangular to angular blocky peds (terminology based on Birkeland and others, 1991). Soil slickensides, cohesive clay-rich blocky peds (referred to as lumps in measured sections), and calcium carbonate and silica precipitates also are found. Facies association IIIb displays features intermediate between IIIa and IIIc. Red-brown, massive, fine to coarse, quartzo-feldspathic to slightly basaltic sand can be found mixed with silt and clay and as thin (<10 cm/4 in.) interbeds. Filamentous, branching root casts less than 2 mm thick to large burrows 1 to 2 cm thick (<1 in.) and 5 to 10 cm (2-4 in.) long are found in the facies association. CaCO₃ is rare in facies association IIIa, stage I and II CaCO₃ of Machette (1985) is found in facies association IIIb. Stage III, IV, and locally V CaCO₃ can be in facies association IIIc.
Table 8a. Grain-size distributions (weight percent) from sand and silt interbeds in facies association I gravel. Cores from member of Wooded Island

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<td>7-49</td>
<td>1-15</td>
<td>2-16</td>
<td>0-3</td>
</tr>
</tbody>
</table>

Table 8b. Grain-size distributions (weight percent) from outcrops of sand and silt interbeds in facies association I gravel of unit E of the member of Wooded Island

<table>
<thead>
<tr>
<th>Sample</th>
<th>granule</th>
<th>v. coarse sand</th>
<th>coarse sand</th>
<th>medium sand</th>
<th>fine sand</th>
<th>v. fine sand</th>
<th>silt</th>
<th>clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC-3</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>63</td>
<td>32</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>SC-8</td>
<td>0</td>
<td>12</td>
<td>12</td>
<td>64</td>
<td>9</td>
<td>1</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>SC-9</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>6</td>
<td>30</td>
<td>30</td>
<td>27</td>
<td>4</td>
</tr>
<tr>
<td>SC-19</td>
<td>0</td>
<td>4</td>
<td>4</td>
<td>20</td>
<td>50</td>
<td>18</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>RANGE</td>
<td>0-1</td>
<td>1-12</td>
<td>1-12</td>
<td>6-64</td>
<td>9-50</td>
<td>1-30</td>
<td>0-27</td>
<td>0-4</td>
</tr>
</tbody>
</table>

Table 8c. Grain-size distributions (weight percent) from sand and silt beds of facies associations II and III in the member of Taylor Flat

<table>
<thead>
<tr>
<th>Sample</th>
<th>granule</th>
<th>v. coarse sand</th>
<th>coarse sand</th>
<th>medium sand</th>
<th>fine sand</th>
<th>v. fine sand</th>
<th>silt</th>
<th>clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>DH6/137</td>
<td>0</td>
<td>3</td>
<td>4</td>
<td>26</td>
<td>19</td>
<td>10</td>
<td>15</td>
<td>3</td>
</tr>
<tr>
<td>SC-13</td>
<td>0</td>
<td>7</td>
<td>8</td>
<td>68</td>
<td>13</td>
<td>2</td>
<td>2</td>
<td>&lt;1</td>
</tr>
<tr>
<td>SC-14</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>29</td>
<td>50</td>
<td>12</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>SC-26</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>69</td>
<td>25</td>
<td>2</td>
<td>2</td>
<td>&lt;1</td>
</tr>
<tr>
<td>SC-27</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>21</td>
<td>48</td>
<td>20</td>
<td>7</td>
<td>&lt;1</td>
</tr>
<tr>
<td>SC-28</td>
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<td>40</td>
<td>51</td>
<td>5</td>
<td>3</td>
<td>&lt;1</td>
</tr>
<tr>
<td>RANGE</td>
<td>0-1</td>
<td>0-7</td>
<td>1-8</td>
<td>21-69</td>
<td>13-51</td>
<td>2-20</td>
<td>2-15</td>
<td>&lt;1-3</td>
</tr>
</tbody>
</table>
Figure 8. Diagram illustrating interstratified facies relationships between fluvial sands (facies association II) and paleosol-overbank deposits (facies association III) of the member of Taylor Flat. Diagram also illustrated the facies architecture typical of the fluvial sand of facies association II. See Appendix A for locations of measured sections.
Figure 9. Facies association II (the two prominent ledges) interbedded with facies association III (the slopes). Each ledge consists of cross bedded sand that fines upwards and overlies a basal scour incised into underlying strata. Jacob's staff (leaning against upper sand ledge in the middle of photo) is 1.3 m (4.3 ft) high. Measured section B-1 goes through this outcrop. Outcrop lies on the eastern bank of Columbia River opposite Wooded Island above the outcrops pictured in Figures 6 and 7.

Silcrete is found in facies association IIIc deposits near the top of the Ringold Formation. Although dominantly superimposed on silt and sand lithologies the features described here also are locally found superimposed on gravel. Where this occurs the gravel has a mud-rich matrix, CaCO$_3$ is present, bedding disruption is prevalent, and clasts are typically weathered.

Facies association III formed in a floodplain-overbank environment where pedogenic alteration occurred. Facies association IIIa was deposited as crevasse splays in proximal overbank areas such as discussed in Bown and Kraus (1987), Kraus (1987) and Kraus and Bown (1988). Evidence of paleosols similar to that described by Collinson (1986), Kraus and Bown (1988), Miall (1978, 1985), and Retallack (1986, 1988) is seen in facies association IIIb, which formed on floodplain and subaerial surfaces that rarely were submerged. The calcium carbonate-rich and silica-rich deposits in facies association IIIc are calcic and silicic paleosols formed relatively far from active channel tracts.
Facies Association IV

Stratified clay, silt, and sand divided into two end members (IVa and IVb) form facies association IV (Table 2). Laterally continuous, white, diatomaceous clay gradationally over lain by gray, tan, and brown, laminated, sandy silt (Fl) (Figs. 10 and 11) dominates facies association IVa. Gray, tan, and brown, plane cross-bedded sand (Sp), ripple cross-laminated sand (Sr), normally graded sand (Sg), and laminated sand, silt, and clay (Fl, Fsc) typify facies association IVb. Bedding in both end members is dominated by planar tabular sheet geometries continuous across tens to hundreds of meters of outcrop (Fig. 10). Locally, facies association IVb has primary bedding dips of 5 to 10 degrees (Fig. 10). Overall, strata in facies association IV form laterally continuous (>30 km [19 mi] across) coarsening-up sequences as much as 40 m (130 ft) thick (Fig. 12). Where the facies association is found in the subsurface, gray to blue-gray colors predominate.

Thin calcium carbonate- and iron oxide-cemented intervals are found in outcrops. Cement is not observed in core of the facies association. Subsurface occurrences and outcrops of the facies association are well consolidated.

Facies association IV was deposited in a hydrologically open lake such as described in Allen and Collinson (1986). The diatomites (IVa) record deposition in clear water, relatively distant from fluvial distributaries. Upward coarsening from IVa to IVb reflects increased detrital sedimentation as the result of fluvial-deltaic progradation into the lake.

Facies Association V

Massive to poorly stratified, weathered basaltic pebble-cobble gravel (Gms, Gm) forming sheet-like bodies dominates facies association V (Table 2). Cross-bedded gravel (Gp) intercalated with these can be found locally. Color typically is gray to black, and matrix varies from sand-size basalt grains to clay. Stage I and II CaCO₃ development can be present. Campbell (1979) describes strata typical of this facies across much of the north side of the Saddle Mountains. Exposures of this facies association are rare in the Pasco Basin, although it can be found in core (most notably DH-33).

The abundance of facies Gms and Gm indicates deposition dominantly by debris flow processes such as described by Bull (1972), Rust and Koster (1984), and Galloway (1985a). These debris flow deposits are inferred to have been part of alluvial fan systems prograding into the Pasco Basin off surrounding highlands such as described by Tallman and others (1981). Rare stratified horizons (Gp) were deposited in channel systems superimposed on fan surfaces by sheet flood and minor stream flow processes. Local pedogenic carbonate indicates subaerial exposure.

FACIES ASSOCIATION DISTRIBUTION

The Ringold Formation is divided into three informal members that are designated the member of Wooded Island, member of Taylor Flat, and member of Savage Island (Fig. 5). Each is characterized by different facies associations. Data upon which the following discussion is based are found in Appendix A (outcrop measured sections), Appendix B (corehole logs), Appendix C (basin-wide cross-sections), and Appendix D (structure contour and isopach data).

The member of Wooded Island is dominated by fluvial gravel (facies association I) and forms the majority of the lower half of the Ringold Formation (Appendices B and C). The member of Taylor Flat forms most of the middle part of the Ringold Formation and is dominated by fluvial sands (facies association II) and overbank-paleosol deposits (facies association III) (Fig. 8 and Appendix A). It interfingers with the member of Wooded Island in the northern Pasco Basin where fluvial gravel pinches
Figure 10. Two lake-fill sequences of facies association IV found on measured section B-11. The lower half of the slope (the darker colored area below the band of sagebrush in the middle of the slope) consists of paleosols of association III. The upper half of the slope consists of well stratified silt and sand of facies association IV. Topographic relief between bottom and top of photo is approximately 130 m (426 ft). This outcrop is located on bluffs east of the Columbia River and approximately 1 km north of Savage Island.

out (Appendix C). Strata dominated by lacustrine deposits (facies association IV) form the upper member, the member of Savage Island (Appendix A).

**Informal member of Wooded Island**

The lowermost fluvial deposits of the member of Wooded Island are fluvial gravel and lesser fluvial sand referred to as unit A. Unit A ranges from 0 to approximately 41 m (0-134 ft) thick and is found in the subsurface in an elongate belt from Sentinel Gap to the east end of Rattlesnake Mountain (Fig. 13A) (Appendices C and D) (Lindsey, 1995, plate 1). This belt crosses the Umtanum Ridge anticline west of Gable Mountain. Fluvial sand is common directly overlying basalt in the lower part of the unit in much of the western Pasco Basin (Appendix B: DH-20, DH-22, DH-25, DH-33). Basalt is overlain by similar sand exposed in Sunnyside Gap in the southwest corner of the Pasco Basin. In the northern Pasco Basin unit A gravel interfingers with paleosols and overbank deposits of the member of Taylor Flat. Unit A is younger than 8.5 Ma, the age of the youngest CRBG flow underlying the Ringold Formation (Fecht and others, 1987), and older than 6.7 Ma, the approximate age of a tephra horizon.
Figure 11. Closeup of well stratified diatomite (facies association IVa) at the base of one lake fill sequence near measured section B-11. Darker colored strata (marked by unlabeled arrows) in upper half of photo are sand interbeds that mark the beginning of the coarsening upwards transition from the diatomaceous (IVa) (labeled A) into clastic lake deposits (IVb). Jacob's staff is 1.3 m (4.3 ft) high. Outcrop is located on the bluffs along the east side of the Columbia River approximately 2 km north of Savage Island.
Figure 12. Measured sections in strata typical of facies association IV. Sections show the vertical trends and characteristics of the association. See Appendix A for detailed measured sections and locations of measured sections.

Legend

Grain size scale, indicates dominant grain size in interval

- Boulders
- Pebble/cobble
- Sand
- Silt/clay

- Ripple cross-lamination
- Planar cross-bedding
- Trough cross-bedding
- Low angle bedding
- Planar stratification
- Scours

- Facies contacts
- Pedogenic calcium carbonate
- Peds and other soil structures
- Strong cementation
- Burrows
- Root castes

IV Intervals dominated by different facies associations

Vertical scale
5 meters
Figure 13. Simplified isopach maps for the main units forming the member of Wooded Island in the subsurface of the western to central Pasco Basin: A) fluvial gravel-dominated unit A, B) lacustrine and paleosol-dominated lower mud unit, C) fluvial gravel-dominated units B and D, and D) fluvial gravel-dominated units C and E. Modified from plates in Lindsey (1995) and based on data presented in Appendix D.
Table 9. $^{40}$Ar/$^{39}$Ar radiometric dates from tephra beds in the lower mud unit, member of Wooded Island. Data are from an unpublished report provided by Lewis Hogan, College of Oceanography, Oregon State Univ., Corvallis, OR, to Rockwell Hanford Operations in 1984.

<table>
<thead>
<tr>
<th>Borehole #/depth (ft)</th>
<th>Isochron Age</th>
<th>Geologic unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>GE19/621.7</td>
<td>6.79±0.13 Ma</td>
<td>lower mud unit</td>
</tr>
<tr>
<td>G73/273.9</td>
<td>6.62±0.09 Ma</td>
<td>lower mud unit</td>
</tr>
<tr>
<td>DH18/504.9</td>
<td>6.67±0.18 Ma</td>
<td>lower mud unit</td>
</tr>
</tbody>
</table>

(Table 9) in deposits overlying unit A. Quartz-feldspar-lithic (QFL) plots for unit A show higher quartz contents than the other gravel units (Goodwin, 1993). In addition, volcanic lithics are less abundant (Goodwin, 1993).

Unit A is interpreted to have been deposited in a Columbia River braidplain that existed from approximately 8.5 Ma to 7.0 (?) Ma. It extended from Sentinel Gap across the area now occupied by Gable Butte and into the western Cold Creek syncline. This fluvial system exited the Pasco Basin at both Sunnyside Gap and around the eastern end of Rattlesnake Mountain. Floodplains and upland subaerial surfaces flanked the main channel belt in the northern Pasco Basin (Figs. 14A and 14B). The distribution of this unit and its mineralogy (described in Goodwin, 1993) indicate Salmon-Clearwater River deposits are not present in unit A.

Unit A is overlain by a basinwide sequence of paleosols (facies association III) and lacustrine deposits (facies association IV) referred to collectively as the lower mud unit (Appendices B and C). The lower mud unit is the only unit containing widespread lacustrine deposits in the lower half of the Ringold Formation. The lower mud unit is found throughout most of the Pasco Basin and is as much as 25 m (80 ft) thick (Fig. 13B). Paleosols are rarer in the lower mud unit in the south-central Pasco Basin than in the western Pasco Basin (Appendix B: G-1, G-78, G-E-19/E-1, DH-18). The extent of interfingering between the lacustrine and overbank deposits is not known. Sandy deposits of facies association IVb present in the lacustrine strata in the east-central Pasco Basin become thinner and less common to the west (Appendices B and C). The lower mud unit underlies almost the entire Hanford Site and Pasco Basin (Lindsey, 1995, plate 2). The only localities where it is absent are the northern part of the 200 East Area, locally just north of the 200 West Area, and in the area between the 200 Areas and Gable Mountain. The absence of the unit is because of post-depositional erosion and not non-deposition. Three $^{40}$Ar/$^{39}$Ar determinations from tephra in lacustrine deposits in the central Pasco Basin yield ages of 6.62±0.09 Ma to 6.79±0.13 Ma for the lower mud unit (Table 9). The lower mud unit was deposited in a lake and on an adjacent subaerial surface that filled most of the Pasco Basin. Intercalated sands are interpreted to have been deposited by sediment gravity flows derived from Columbia River and Salmon-Clearwater River distributaries entering the lake from the west and east, respectively.

The lower mud unit is overlain in most areas by two fluvial gravel-dominated (facies association I) units, B and D, and intercalated overbank/paleosol deposits (facies association III) (Appendices B and C). Unit B is a westward-thinning unit in the eastern to east-central Pasco Basin ranging from 0 to 20 m (0-66 ft) thick (Fig. 13C) (Lindsey, 1995, plate 3). Unit D is an eastward-thinning unit found in the southwestern Pasco Basin and ranging from 0 to 20 m thick (Fig. 13C) (Lindsey, 1995, plate 3). Where units B and D are absent (in the central Cold Creek syncline) laterally equivalent overbank deposits and paleosols (facies association III) containing thin, indistinct, fluvial sands (facies association II) overlie the lacustrine lower mud unit (Appendix C; Q-Q'). The area where units B and D are absent corresponds to
Figure 14. Distribution of main depositional systems in the member of Wooded Island in the Pasco Basin during deposition of: A) sands at the base of unit A (<8.5 Ma), B) gravelly part of unit A approximately 7.5 Ma, C) fluviatile gravel of units B (east) and D (west) approximately 6.5 Ma (?), and D) fluviatile gravels of units C and E approximately 6.0 to 5.0 Ma.
an area of thinning in underlying basalt described by Reidel and Fecht (1981) and to the easternmost extent of the sand-rich intervals in the underlying unit A. Unit D is interpreted as having been deposited by the Columbia River as it flowed from north to south across the western Pasco Basin (Fig. 14C). Unit B is interpreted to have been deposited by the Salmon-Clearwater River as it flowed across the southeastern corner of the Pasco Basin (Fig. 14C). The area separating the two units is interpreted to have been a paleotopographic high because of the apparent pinchout and separation of the two units and thinning in the underlying basalt.

Units B and D are differentiated from overlying gravel-bearing units (C and E) by a locally thick (>10 m [33 ft]) paleosol sequence typical of facies association IIIb. This paleosol sequence is referred to as the sub C+E interval in Appendix D. In the eastern and westernmost Cold Creek syncline and the Wahluke syncline the sub C+E interval can be traced over distances of several kilometers in core holes and closely spaced wells (Appendix B: G-1, G-73, G-78, G-E-19/E-1, DH-18, DH-20, DH-22, DH-33; Appendix C: B-B', F-F', G-G', H-H', I-I', K-K', L-L', M-M', N-N', O-O', P-P', Q-Q'). Where the sub C+E interval is absent units B and D are not differentiated from overlying gravel of units C and E. In this case the C+E interval directly overlies the lower mud unit.

The uppermost fluvial gravel-dominated units, C and E (Appendices B and C), are separated in the eastern Pasco Basin by an unnamed, but widespread paleosol sequence (Appendix C: F-F', G-G', H-H', I-I', N-N', O-O', P-P', Q-Q') similar in character to the paleosol sequence overlying units B and D and referred to as the sub E interval in Appendix D. In the western Pasco Basin the sub E interval is absent and units C and E are not differentiated (Appendix C: A-A', B-B', C-C', D-D', E-E', O-O', Q-Q'). Combined, the C and E interval forms a northwest-to-southeast-oriented subsurface linear body as much as 100 m (328 ft) thick and stretching across the Pasco Basin from Sentinel Gap to Wallula Gap (Fig. 13D) (Lindsey, 1995, plate 4). The gravel outcrops at Taylor Flat are of unit E. Basalt-rich gravel (facies association V) is found locally in units C and E. Unit C and E gravel interfingers with muddy paleosols (facies association IIIa and b) around the fringe of the Pasco Basin, especially to the north where units C and E pinch out (Appendix C: J-J', K-K', M-M') (Lindsey and Jaeger, 1993). Units C and E are older than the 5.0 Ma age of overlying strata determined by Packer and Johnston (1979). Strata near the top of unit E also have been assigned a late Hemphillian age (6.7 to 4.8 Ma) on the basis of vertebrate fauna (Gustafson, 1985). Units C and E are interpreted to have been deposited by the Columbia River which flowed into the northeastern corner of the Pasco Basin at Sentinel Gap and by the Salmon-Clearwater River as it flowed into the eastern Pasco Basin across the Eureka Flat area (Fig. 14D). The confluence of the two ancestral rivers is thought to have migrated across the area between Taylor Flat and Wallula Gap because of the presence of gravel and sand displaying lithologies indicative of both rivers (Goodwin, 1993). This depositional system is estimated to have existed approximately 6.5 to 5.5 Ma

Fluvial gravel, sand, and overbank fines typical of the member of Wooded Island are found in the easternmost Pasco Basin at and east of Pasco, Washington (Brown, 1979). These strata are not directly correlated to the units described above because of gaps in the borehole coverage of the eastern Pasco Basin, the lack of clearly defined marker horizons in the borehole logs from the area, and the quality of the drillers logs that comprise the vast majority of the data available for the eastern Pasco Basin. However, the presence of facies association I in the eastern Pasco Basin does indicate that fluvial systems like those that deposited the member of Wooded Island in the central to western Pasco Basin also occurred in the eastern Pasco Basin.

Informal member of Taylor Flat

Approximately 90 m (295 ft) of interbedded fluvial sand (facies association II) and overbank fines (facies association III) (Fig. 8) form the member of Taylor Flat (Appendix A). Outcrops of the member extend the length of the White Bluffs and are found on Eureka Flat (Fig. 4). West of the White Bluffs (in
the central to western part of the Pasco Basin) most of the member was removed by post-Ringold erosion and only a thin (<15 m [50 ft]), discontinuous section remains (Lindsey, 1995, plate 5) (Appendices B and C). This thin erosional remnant has been referred to as the Ringold upper unit (Myers, Price, and others, 1979; Tallman and others, 1979, 1981; DOE, 1988; Lindsey and others, 1991, 1992). The member of Taylor Flat fines from south to north, with sand being rare north of Ringold Coulee and Gable Mountain. Although the member is now absent from much of the Pasco Basin, the distribution of erosional remnants indicates the member once extended across the entire basin.

On the basis of vertebrate fauna (Gustafson, 1985) and paleomagnetic data (Packer and Johnston, 1979) the base of the member is approximately 5.0 Ma where it overlies the member of Wooded Island south of Ringold Coulee and Gable Mountain/Gable Butte. Where the member of Wooded Island is absent in the northern Pasco Basin, the member of Taylor Flat consists almost entirely of facies association III deposits; it extends downwards to the top of basalt (Appendix C, M-M'), and the two members interfinger. Where this occurs, the member of Taylor Flat may be as old as 8.5 Ma (youngest basalt underlying the Ringold Formation).

The member of Taylor Flat records deposition in sandy fluvial channels and on adjacent floodplains and overbank areas that formed between 5.5 and 4.5 Ma. The change from the underlying gravels of the member of Wooded Island to this member indicates a change from fluvial gravel depositional systems to fluvial systems characterized almost exclusively by sand deposition. During deposition of the member the Columbia River followed a northwest-to-southeast-oriented path (Fig. 15) similar to that followed during deposition of units C and E of the member of Wooded Island. The presence of Salmon-Clearwater sand is yet to be detected in the member of Taylor Flat, but its presence is suspected because of west-directed paleocurrent indicators in the eastern Pasco Basin that are consistent with a Salmon-Clearwater drainage.

**Informal member of Savage Island**

Lacustrine deposits (facies association IV) dominate the uppermost part of the Ringold Formation, the 90-m (295 ft) thick member of Savage Island. The member's age is approximately 4.8 to 3.4 Ma on the basis of paleomagnetic studies and vertebrate paleontology (Packer and Johnston, 1979; Gustafson, 1985; Fecht and others, 1987). Three successive lake-fill sequences are present in the member in the east-central Pasco Basin (Fig. 12). Each of the sequences has a basal diatomaceous interval (facies association IVa) that grades upwards into interstratified silt and sand (facies association IVb). The member has been almost completely removed by post-Ringold erosion from the central and western Pasco Basin (Appendix C). Small outcrops are locally found in shallow ravines along the northwest base of Rattlesnake Mountain.

The lower or first lake-fill sequence is the most laterally restricted of the three sequences, being found only in the northern to central White Bluffs (Appendix A: B-11 to B-22). Comparing measured sections from north of Ringold coulee (Appendix A: B-11 to B-22) to those from south of Ringold Coulee (Appendix A: B-1 to B-10) indicates the lowest lake-fill sequence interfingers to the southeast into fluvial and overbank deposits (facies associations II and III) of the member of Taylor Flat. These fluvial and overbank deposits in turn occupy a stratigraphic position similar to that of fluvial gravel (unit E?) of the member of Wooded Island found on Eureka Flat in the easternmost Pasco Basin. The basal diatomite for the first lake sequence is 0.5 to 1.0 m (1.6-3.3 ft) thick. The first lake appears to have been restricted to the northern and western Pasco Basin, forming adjacent to a fluvial braidplain and adjacent floodplain system located in the southeastern Pasco Basin (Fig. 16). The fluvial system and associated floodplain record progradation of a Salmon-Clearwater generated fluvial and deltaic (?) systems into the basin.
Figure 15. Distribution of depositional systems in the Pasco Basin during deposition of the member of Taylor Flat approximately 5.0 Ma.

Deposits forming the second and third lake-fill sequences are found in outcrops across most of the eastern Pasco Basin. The second lake-fill sequence is distinguished by a thick (2-6 m [6.5-19.5 ft]) basal diatomite (facies association IVa) and a capping fluvial-paleosol system (facies association II and III) (Fig. 12). The diatomite is present throughout the eastern, central, and western Pasco Basin. It coarsens upsection into sandy, well-stratified lacustrine deposits (facies association IVb), which are in turn capped by a well-developed sandy fluvial and paleosol system (facies associations II and III). The paleosol is a readily identified marker horizon characterized in outcrop by red resistant ledges of sand and silt displaying pedogenic calcium carbonate and silica development (facies association IIc) and bioturbation extending as deep as 6 m (19.5 ft) into underlying strata. The fluvial deposits at the top of the second lake-fill sequence record complete filling of the lake with sediment. There is no evidence of post-depositional incision into the fluvial-overbank cap overlying the second lake-fill sequence. The lake in which the second lake-fill sequence was deposited appears to have inundated much, if not all of the Pasco Basin (Fig. 16).

The third lake-fill sequence is found in Ringold outcrops across the central and eastern Pasco Basin above an elevation of approximately 274 m (800 ft) above sea level. The basal diatomite (facies association IVa) is less than 1.5 m (5 ft) thick and grades up-section into well-bedded lacustrine sand and silt of facies association IVb. Deposition of the third lake-fill sequence appears to have terminated with basinwide incision.
Figure 16. Distribution of depositional systems in the Pasco Basin during deposition of the member of Savage Island: (A) first lake-fill sequence approximately 4.6 Ma and (B) the second lake-fill sequence approximately 4.0 Ma.
Top of the Ringold Formation

Post-Ringold stage IV and V pedogenic carbonate (of Machette, 1985) overlies and truncates the Ringold Formation member of Savage Island along the length of the White Bluffs and on Eureka Flat (Appendix A). These carbonates are interpreted to be correlative to calcium carbonate- and silt-rich strata (referred locally as the Plio-Pleistocene unit) beneath the 200 West Area and to multilithologic gravel (referred to locally as the pre-Missoula gravel) southeast of the 200 East Area which overlies the lower part of the member of Taylor Flat and upper part of the member of Wooded Island beneath the Hanford Site (Lindsey, 1995, plate 6; Appendix C). This stratigraphic relationship is described further in Lindsey and others (1994a, 1994b). Locations in the central Pasco Basin where the "Plio-Pleistocene" unit and pre-Missoula gravel overlie the Ringold Formation correspond to where approximately 120 m of Ringold section is absent. Late Pliocene incision by the Columbia River is the cause of this. This post-Ringold erosion represents a fundamental change within the ancestral Columbia River drainage system, which was dominated until the end of Ringold deposition by regional aggradation. Erosion by Pleistocene cataclysmic flood waters also has removed part of the Ringold section. This erosion is interpreted to have occurred where "Plio-Pleistocene" strata are absent and cataclysmic flood deposits (of the informal Hanford formation) directly overlie the Ringold Formation.

Ringold Correlatives Outside the Pasco Basin

Strata assigned to the Ringold Formation also are found north of the Pasco Basin in the Quincy and Othello Basins. These strata consist of basaltic gravel, paleosols, lacustrine deposits, and minor fluvial sand (Packer and Johnston, 1979; Reidel, 1988; Smith and others, 1989; N. P. Campbell, unpub. data). Packer and Johnston's paleomagnetic data indicate these strata are correlative to the member of Savage Island. The basaltic gravel is thought to have been deposited on alluvial fans formed adjacent to active faults bounding the north side of the Saddle Mountains during the Pliocene (Tallman and others, 1981). Lacustrine deposits younger than 4.7+0.3 Ma (making them correlative to the member of Savage Island) also are found near Yakima, Washington (Smith, 1988).

Quartzose sand and gravel, similar to that forming the member of Wooded Island, are found overlying the CRBG in a linear belt stretching from the western Pasco Basin to Hood River, Oregon (Warren, 1941; Schmincke, 1964; Anderson, 1987; Fecht and others, 1987; Reidel, 1988; Smith, 1988). These clastic deposits, now known as the Snipes Mountain Conglomerate (also referred to as the Hood River conglomerate by Warren [1941]), are younger than 10.5 Ma, the age of the youngest underlying basalt, the Elephant Mountain Member of the Saddle Mountains Basalt (Anderson, 1987; Fecht and others, 1987). South of Satus Pass the Snipes Mountain Conglomerate is overlain by the 4.5 Ma to 1.0 Ma Simcoe Volcanics (Anderson, 1987), indicating it is older than the lacustrine deposits of the member of Savage Island. Sand mineralogy and clast types in the Snipes Mountain Conglomerate are similar to those in unit A of the member of Wooded Island (Goodwin, 1993). The Snipes Mountain Conglomerate is interpreted as having been deposited in a Columbia River channel tract that extended from the western Pasco Basin, across the area now occupied by the Horse Heaven Hills, to the position of the modern Columbia River west of The Dalles, Oregon (Warren, 1941; Waters, 1955; Fecht and others, 1987; Smith, 1988). The Snipes Mountain Conglomerate is interpreted to be at least in part correlative to unit A of the member of Wooded Island because they have similar mineralogy and petrology, they overlie the same basalt unit, and they appear to be contiguous along the western side of the Pasco Basin.

An additional quartzo-feldspathic clastic unit correlative to the Ringold Formation is found west of Snipes Mountain outcrops. Throughout the late Miocene and Pliocene the Columbia River cut a series of canyons through the ancestral Cascade Range between The Dalles and Portland, Oregon (Fig. 5) (Tolan and Beeson, 1984; Tolan and others, 1984a, 1984b). The Troutdale Formation (<12 Ma to 2 Ma) fills one of these paleocanyons (Tolan and Beeson, 1984; Tolan and others, 1984a, 1984b). Tolan and Beeson
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(1984) divide the Troutdale Formation into an informal lower member dominated by quartzose Columbia River silt, sand, and gravel (similar to the Snipes Mountain Conglomerate and Ringold Formation) and an upper informal member dominated by ancestral Cascade-derived volcaniclastic sediments. An early Pliocene age of approximately 5 Ma is placed on the contact between these two informal members. This age makes the lower member correlative to the member of Wooded Island and the upper member correlative to the members of Taylor Flat and Savage Island.

At The Dalles, Oregon, as well as south and east of The Dalles, Oregon, a sequence described by Newcomb (1966), Farooqui and others (1981), and Smith (1988) as largely locally derived andesitic to dacitic volcaniclastic detritus overlies the CRBG. These deposits, referred to as the Dalles Formation, originally were described as containing pebble lithologies foreign to the region, including quartzite, at the base of, as well as within the unit (Warren, 1941). The Dalles Formation overlies CRBG basalt (Priest Rapids Member of the Wanapum Basalt at 14.5 Ma) and underlies and interfingers with younger lavas dated at 5.1 to 8.0 Ma (Farooqui and others, 1981; Smith, 1988). This indicates that at least the upper part of the Dalles Formation is correlative with the Ringold Formation member of Wooded Island.

Ringold-age sedimentary rocks also are found in the Umatilla Basin (and adjacent areas) south and east of a line defined by The Dalles, Oregon, and Wallula Gap. They are the Alkali Canyon Formation in the Umatilla Basin and the Mackay Creek Formation near Pendleton, Oregon. Locally derived basaltic gravel dominates the Alkalai Canyon Formation in the eastern Umatilla Basin and the Mackay Creek Formation (Farooqui and others, 1981; Lindsey and others, 1993). However, quartzite-bearing mixed lithology gravel is common in the Alkali Canyon Formation in the western Umatilla Basin, although a quartzite-rich lithology indicative of the Columbia River is not present (Lindsey and others, 1993; Lindsey and Tolan, 1996). Reconnaissance studies in the Klickitat Valley between Satus Pass and The Dalles, Oregon, indicate Alkali Canyon-like gravel underlies the Snipes Mountain Conglomerate (T. Tolan and K.A. Lindsey, unpub. data). In addition to exotic clast-bearing gravel, Hodge (1932, 1938, 1942) described as much as 30 m of stratified sand, silt, and diatomite overlying and interstratified with Alkali Canyon Formation gravel (referred to by him as the Shutler Formation) in the western Umatilla Basin. Later investigators (Farooqui and others, 1981; Dames and Moore, 1987; Smith, 1988) did not report the presence of diatomite-bearing strata. Reconnaissance of the western Umatilla Basin (T. Tolan and K. A. Lindsey, unpub. data) confirms the presence of at least two diatomite intervals. One is as much as 4 m thick and interstratified with mixed lithology gravel near the base of the Alkali Canyon Formation. The other is approximately 2 m thick, consists of laminated fine facies similar in appearance to Ringold facies association IV, and directly underlies thick (>2 m) pedogenic CaCO$_3$ that caps the Alkali Canyon Formation. The Alkali Canyon Formation ranges from less than 14.5 Ma (age of underlying Priest Rapids Basalt) to at least late Hemphillian age (6.7 to 4.8 Ma) (Martin, 1979; Farooqui and others, 1981). This indicates that at least a part of the Alkali Canyon Formation is correlative with the members of Wooded Island and Taylor Flat. The diatomaceous lacustrine deposits at the top of the Alkali Canyon section that directly underlie thick pedogenic carbonate mimics a stratigraphic relationship similar to that found at the top of the member of Savage Island. This suggests the possibility that the uppermost Alkali Canyon Formation also may be correlative to the uppermost Ringold Formation.

CONCLUSIONS

The Miocene-Pliocene Ringold Formation in and around the Pasco Basin and at the Hanford Site in south-central Washington consists of a variety of interstratified alluvial-lacustrine sediments. These sediments comprise the majority of the suprabasalt "unconfined" aquifer at the Hanford Site. Previous work in the Ringold Formation was too generalized or too localized to adequately document the character of these sediments across the entire region. This report presents a stratigraphic interpretation for the Ringold Formation filling that gap. The data presented in this report show that Ringold sediments can be grouped into five facies associations, which are grouped together into three informal members. This report
also briefly discusses Ringold correlatives throughout the region, setting the stage for future regional sedimentologic interpretations.

Ringold Formation facies associations I, II, III, IV, and V are summarized as follows:

I. Fluvial gravel—Clast-supported and lesser matrix-supported pebble to cobble gravel with a sandy matrix characterizes the association. Localized intercalated sand and mud also are found. Clast composition varies, with basalt, quartzite, porphyritic volcanic rocks, and greenstone being the most common types. Sand in the association generally is quartzo-feldspathic. Low-angle to planar stratification, massive bedding, wide, shallow channels, and large-scale cross-bedding are found in outcrops. The association was deposited in a gravelly fluvial braidplain characterized by shallow, shifting channels. Calcium carbonate, iron, and silica cements are present. Variations in the amount and distribution of cement probably account for much of the variation seen in aquifer properties.

II. Fluvial sand—Quartzo-feldspathic sand displaying cross-bedding and cross-lamination dominates this association. Intercalated strata consist of lenticular silty sand and clay beds up to 3 m (9.6 ft) thick and thin (<0.5 m [1.5 ft]) gravels. Fining-upward sequences less than 1 m to several meters thick are common in the association. Strata comprising the association were deposited in wide, shallow fluvial channels.

III. Overbank-paleosol—This association consists of laminated to massive silt, silty fine sand, and paleosols containing various amounts of pedogenic calcium carbonate. Overbank-paleosol deposits occur as thin (<0.5 to 2 m [1.5-6.4 ft]) lenticular interbeds in the fluvial gravel and fluvial sand associations and as thick (up to 10 m [32 ft]) laterally continuous stratigraphic sequences. These sediments record deposition on floodplains and the formation of paleosols.

IV. Lacustrine—Plane laminated to massive clay with thin, ripple cross-laminated and normally graded silt, silty sand, and sand interbeds displaying some soft-sediment deformation characterize this association. Coarsening-upward packages less than 1 m thick to 10 m thick (<3-32 ft) are common. Strata of the association were deposited in lakes under standing-water to deltaic conditions.

V. Basaltic alluvium—Massive to crudely stratified, weathered to unweathered basaltic sand and gravel dominate this association. These basaltic deposits generally are found near the basin periphery. The association records deposition by debris flows in alluvial fan settings and in sidestreams.

Sediments comprising the Ringold Formation are divided into three informal members. The lowest member, the member of Wooded Island, contains five separate stratigraphic intervals, designated units A, B, C, D, and E, dominated by fluvial gravel (facies association I). Units A, B, C, D, and E, are separated by fine-grained intervals consisting largely of paleosol-overbank deposits (facies association III) and lesser lacustrine deposits (facies association IV). The lowermost of these fine-grained intervals overlies unit A and is designated the lower mud unit. The lower mud unit extends across most of the Pasco Basin and is the only one of the fine-grained intervals within the member that is typified by lacustrine deposits. Although generally widespread, the other fine-grained sequences in the member of Wooded Island are not given names because of a lack of other distinguishing features. The member of Wooded Island is overlain by the member of Taylor Flat, which is dominated by interbedded fluvial sand and overbank-paleosol deposits. Around the periphery of the Pasco Basin and in the northern Hanford Site the member of Wooded Island pinches out, interfingering with the member of Taylor Flat. The third
member, the member of Savage island, consists dominantly of lacustrine deposits that are basinwide in extent. Lacustrine strata in this member generally sharply overlie underlying deposits.

Strata correlative to the Ringold Formation exist in many basins across the region. These correlatives, found from Portland, Oregon, to north of the Pasco Basin, include the Troutdale Formation, Snipes Mountain Conglomerate, Dalles Formation, and Alkali Canyon Formation. These units display fluvial, paleosol-overbank, and lacustrine facies relationships and lithologies similar to those typical of the Ringold Formation. The distribution of these strata indicates Ringold deposits found in the Pasco Basin were part of a regional drainage system extending across the Columbia Basin region, into and through the area now occupied by the Cascade Range.

The data and interpretations presented in this report are the result of an integrated study of outcrops, cores, cuttings, borehole logs, and the geologic literature. Such studies are necessary for accurate and realistic interpretation of both regional and local geology. Locally, these data and insights are central to understanding the geologic characteristics that influence ground-water flow in the suprabasalt aquifer at the Hanford Site. Regionally, these data can be used to address many of the fundamental issues related to the timing of subsidence and uplift in the Yakima fold belt, paleodrainage history of the ancestral Columbia River system, and the uplift and unroofing history of source terranes adjacent to the Columbia Basin throughout the Late Neogene.

ACKNOWLEDGMENTS

Discussions with Terry Tolan, Steve Reidel, Karl Fecht, Bruce Bjornstad, Pat Spencer, Dave Gaylord, Shannon Goodwin, and Gary Smith about local and regional geology were invaluable. This report benefitted from reviews at various times by Steve Reidel, Karl Fecht, Newell Campbell, Terry Tolan, Eric Schuster, Kitty Reed, and Leslie Brown. The line drawings in the text and Appendix C were drafted by Denise Dillon, Jeff Ammennan, and Gary Hammond. Research and manuscript preparation was supported in part by a Post-Doctoral grant from the Northwest College and University Association for Science (Washington State University) (now Associated Western Universities, Northwest Division) under Grant DE-FG06-89ER-75522 from the U.S. Department of Energy and DOE grant DE-FG06-91ER14172 to S. P. Reidel at Washington State University.

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APPENDIX A. OUTCROP MEASURED SECTIONS

Explanation of Symbols and Abbreviations used on Measured Sections

Grain Size Scale, indicates dominant grain sizes

- boulder gravel
- cobble gravel
- pebble gravel
- coarse sand
- medium sand
- fine sand
- silt
- clay

Sedimentary Structures

- large-scale trough cross-bedding
- small-scale trough cross-bedding
- large-scale planar cross-bedding
- small-scale planar cross-bedding
- ripple cross-lamination
- climbing ripple cross-lamination
- planar bedding
- wavy bedding
- clay/silt rip up clasts
- load casts and deformed bedding
- mottled bedding
- soil peds and slickensides
- clay balls and lumps
well indurated (cemented)
calcium carbonate
petrified wood
pebbly sand
paleocurrent directions, 0° is straight up to page
sample point for pebble count samples
small (<1 cm diameter) root and burrow trace fossils
large (>1 cm diameter) root and burrow trace fossils

Abbreviations
bn - brown; bk - black; bslt - basal; carb - calcium carbonate; cmt - cement; concr - concretions; dk - dark; Fe - iron stains; frags - fragments; gn - green; gy - gray; lo ang - low angle bedding; lt - light; ol - olive; or - orange; rd - red; rp - rip-up clast; slicks - soil slickensides; tn - tan weath - weathering; wh - white

Vertical scale on left side of each column is in meters above base of measured section. Elevation above sea level is given for bottom of sections in feet and meters.

Locations of Measured Sections

<table>
<thead>
<tr>
<th>Sec.</th>
<th>Quadrangle - Location Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-1</td>
<td>Wooded Island 7.5' and Matthews Corner 7.5' - SE1/4 SW1/4 sec. 12, T11N, R28E, 1st ravine N of Baxter Cn.</td>
</tr>
<tr>
<td>B-2</td>
<td>Wooded Island 7.5' and Matthews Corner 7.5' - NW1/4 SW1/4 sec 12, T11N, R28E, next ravine N of B-1.</td>
</tr>
<tr>
<td>B-3</td>
<td>Wooded Island 7.5' and Matthews Corner 7.5' - NE1/4 SW1/4 sec. 12, T11N, R28E, next ravine N of B-2.</td>
</tr>
<tr>
<td>B-4</td>
<td>Wooded Island 7.5' and Matthews Corner 7.5' - NW1/4 SW1/4 sec. 12, T11N, R28E, next ravine N of B-3.</td>
</tr>
<tr>
<td>B-5</td>
<td>Wooded Island 7.5' and Matthews Corner 7.5' - SW1/4 NW1/4 sec. 12, T11N, R28E, slope W of Baxter BM.</td>
</tr>
<tr>
<td>B-5A</td>
<td>Wooded Island 7.5' and Matthews Corner 7.5' - SW1/4 NW1/4 sec 12, T11N, R28E, slope SW of Baxter BM.</td>
</tr>
<tr>
<td>B-6/6A</td>
<td>Wooded Island 7.5' and Matthews Corner 7.5' - NW1/4 NW1/4 sec. 12, T11N, R28E, A-2</td>
</tr>
</tbody>
</table>
slope W of Baxter BM.
B-7/7A Wooded Island 7.5' and Matthews Corner 7.5' - SE1/4 SW1/4 sec. 1, T11N, R28E, ravines S of Parsons Cn.
B-8 Wooded Island 7.5 - NW1/4 SE1/4 sec. 25, T11N, R28E, ravine W of Bluff BM.
B-9 Wooded Island 7.5' and Matthews Corner 7.5' - SW1/4 NW1/4 sec. 1, T11N, R28E, slope N of Parsons Cn.
B-10 Wooded Island 7.5' - SW1/4 SE1/4 sec. 25, T11N, R28E, ravine SW of Bluff BM.
B-11 Hanford 15' - SE1/4 NE1/4 sec. 33, T13N, R28E, ravine N of Savage Island landslide.
B-11A Hanford 15' - SW1/4 NE1/4 sec. 33, T13N, R28E, open slope N of B-11.
B-12 Hanford 15' - NE1/4 SW1/4 sec. 3, T12N, R28E, slopes E of Savage Island.
B-13 Hanford 15' - NE1/4 SW1/4 sec. 3, T12N, R28E, S end of Savage Island landslide.
B-14 Hanford 15' - SE1/4 NW1/4 sec. 33, T13N, R28E, ravines N of B-11 and B-11A.
B-15 Hanford 15' - SE1/4 NE1/4 sec. 14, T12N, R28E, slope W of Ringold BM.
B-16 Hanford 15' - W1/2 SE1/4 sec. 29, T13N, R28E, ravines N of bluff.
B-17 Hanford 15' - NW1/4 SE1/4 sec. 11, T13N, R27E, slope above road S of gate.
B-18 Locke Island 7.5' - SE1/4 NW1/4 sec. 21, T14N, R27E, bluffs S of Locke Island.
B-20 Hanford 15' - NW1/4 NW1/4 sec. 24, T13N, R27E, bluffs opposite old Hanford.
B-21 Hanford 15' - SE1/4 SE1/4 sec. 3, T12N, R28E, bluffs S of Savage Island landslide.
B-22 Hanford 15' - SW1/4 SE1/4 sec. 19, T13N, R28E, bluff NW of Savage Island.
B-D1 Hanford 15' - NE1/4 NE1/4 sec. 30, T13N, R28E, bluff S of Savage Island.
B-D2 Hanford 15' - SE1/4 SE1/4 sec. 9, T13N, R28E, bluff E of Savage BM.
Sec B-1 Top Elev 640 ft (195 m)

- 0 ft / 0 m: ox
- 135 ft / 443 m: sand float
- 150 ft / 45 m: poor outcrop
- 170 ft / 51 m: gy bn, wh-gy, lt gy bn, crumbly
- 190 ft / 58 m: mbr of Taylor Flat, rd-bn banding
- 210 ft / 64 m: mbr of Wooded Is.
- 230 ft / 70 m: fissile, gy-wh tn
- 250 ft / 76 m: silt rp

Popcorn weathering, clay balls, dk gy, lt gy, dk gy crumbly, bn, crumbly.
Sec B-1 (cont)

- 190 m
- 180 m
- Scoured top
- Ashy
- Scoured contacts

A-5
Sec B-2 Top Elev 640 ft (195 m)

- Dip to N
- 140 m
- 130 m
- PL3
- 121.5 m/399 ft

- Dunky
- 160 m
- Ash
- Dunky
- Bn-Tn-Gy
- Bn Gy
- Popcorn weath
- 150 m
- Wh-Gy
- Ash
- Poor outcrop
- Mbr of Taylor Flat
- Mbr of Wooded Is.
Sec B-4  Top Elev 661 ft (202 m)

10

poor outcrop

wh gy

wh
dk gy
dk gy

mbr of Taylor Flat

PL10

140 m

138.5 m/454 ft

170 m

mottled

sand float

dk gy
tn
tn

A-9
Sec B-5 Top Elev 653 ft (199 m)

Fe and carb cmt
140 m

130 m

125 m/411 ft

gy
gy-ol
nodules

dk gy
160 m

tn crumbly

rd ol

poor outcrop

mbr of Taylor Flat
mbr of Wooded Is.
150 m

A-11
Sec B-6 (cont)

243 m/796 ft

fissile

alt rd-bn and wh-gy
fissile

230 m

crumbly
wh-gy

2nd lake

mbr of Wooded Is.
mbr of Taylor Flat

A-17
Sec B-7 (cont)

- 60 m
- 40 m
- 1111
- ~-
- ~-
- ~-
- ~-
- popcorn weath
- 180 m
- 80 m
- 200 m
- sandy float
- clay balls
- tn bn
- dk gy
- 170 m
- lt gy
- dk gy
- 190 m
- lo ang
- mottled
- bn rd to tn bn
- 170 m
- 190 m

A-21
Sec B-7 (cont)

slope wash

poor outcrop
210 m

diatomaceous
dk gy
mbr of Savage Is.
dk gy
mbr of Taylor Flat

nodules
bn rd to tn gy
mottled

popcorn weath
Sec. B-9 Top Elev 600 ft (183 m)

siltier

low silt

peb lenses 140 m

mbr of Taylor Flat
mbr of Wooded Is.

float

PL4 130 m

128 m/420 ft

mottled

poor outcrop

rd bn

rd bn 160 m

gy

gy

gy

gy clay balls

tn-rd

rd-bn 150 m

lo ang

A-27
Sec B-9 (cont)

180 m

170 m

gy
rd bn
rd bn
sandy IB's
wh
lt-dk gy
popcorn weath
Sec. B-11 Top Elev 754 ft (230 m)

0-140 m/460 ft

- float
- bn-ol
- lt-dk ol
- crumbly
- clay balls
- rd-bn wood frgs
- mottled
- wh
- lt gy
- rd-bn

150 m/500 ft

- 10-15% bslt
dk gy
lt ol
dk gy
clay balls
popcorn weath
fissile gy
fissile clay balls
popcorn weath rd bn
dk gy

170 m

- 1st lake
- mbr of Savage Is.
mbr of Taylor Flat
- rd bn
- ol
- rd bn
- drapes
- poor outcrop
- mica

180 m
Sec B-11 (cont)

- Massive rd-bn
- Diatomaceous
- Fissile
- Wh 2nd lake
- Soft sed
- Alt rd bn to gy

Traverse 0.25 mi north to B-11A

Poor outcrop
Sec B-13 (cont)

- Poor outcrop
- lt gy fissile 260 m
- Diatomaceous
- bsitc
- bsit gm muddy
- rd bn rd bn silcrete
- float 250 m
- lt gy massive
- 3rd lake

A-37
Sec. B-16  Top Elev 920 ft (281 m)

1. Wh-lt gy mbr of Savage Is.
2. Mbr of Taylor Flat
3. Carb veinlets
4. Rd-bn gy
5. Mottles
6. Poor outcrop
7. Silt rp
8. Crumbly
9. Poor outcrop
10. Covered contact 170 m
11. GY-bn Fe
12. 1st lake 40 ft
13. 165m/541 ft
14. Landslide deposits
15. 2nd lake
16. 170 m
17. 190 m
18. 200 m
19. 220 m
20. 210 m
21. Rd
Sec B-16 (cont)

- diatomaceous
- wh-gy
- 3rd lake
- fissile
- weath
- rd-bn
- gy
- 240 m
- bioturbated
- mottled
- poor outcrop
- 230 m
- 250 m
- 270 m

A-42
Sec. B-18 Top Elev 620 ft (189 m)

- Clay balls dk ol
- ol
- Clay balls
- dk gy-bl
- Popcorn weath gy/tn

140 m

- Popcorn weath
- GY/tn

126 m/413 ft

- Popcorn weath
- GY/bn

130 m

- Slope wash

160 m

- Tn/bn
- Orgs
- Wood frags
-.ol gy
- Mottled

150 m

- Fissile
- Poor outcrop

160 m

- Ltt gy
- Popcorn weath
- Bk
Sec B-19 (cont)

- lt gy-ol
- bn
- lt tn
- dk gy
- mottled
- crumbly

- bn 170 m
- wh-gy
- 160 m
- rubble
- 180 m
Sec. B-20 Top Elev 720 ft (220 m)

- Landslide deposits and slope wash
- 130 m
- 140 m

- Ol gy
- Fe
- Carb nod
- Bn-tn

- Ol gy

- Or-gy

- Gy
- Gy bn
- Crumbly
- Rp

- Fe

- 1st lake
- Mbr of Savage Is.
- Mbr of Taylor Flat

- 170 m
- 180 m

A-48
Sec B-21 (cont)

240 m

sandier

poor exposure

230 m

rd

rd

silty rd

gy

sandier
APPENDIX B. CORE GEOLOGIC LOGS

Explanation of Symbols and Abbreviations used on Core Geologic Logs

Grain Size Scale, indicates dominant grain size

- boulder gravel
- cobble gravel
- pebble gravel
- coarse sand
- medium sand
- fine sand
- silt
- clay

Vertical scale is in feet below ground surface.

Sedimentary Structures and Subordinate Lithologies

- normally graded
- small-scale planar cross-bedding
- ripple cross-lamination
- plane bedding
- root and burrow trace fossils
- soil peds and slickensides
- calcium carbonate
- silty
- silt and clay rip up clasts
- pebbly
- pebbly to cobbly
- basalt
- member and formation boundary
mappable informal unit boundary within a member, arrows indicate direction
named unit extends

bk - black; bn - brown; bslt - basalt; carb - calcium carbonate (caliche); cl - clay; cmt - cement present; cmted - cement well developed; decre - decreasing; dk - dark; dom - dominated; Fe - iron stains; Frag - fragments; gn - green; gy - gray; hd - hard; hi - high; incr - increasing; lith - lithology; lt - light; lo - low; N - normal magnetic polarity; ol - olive; orgs - organic debris; por volcs - porphyritic volcanic clasts; R - reversed magnetic polarity; rd - red; rp - rip up clasts; tn - tan; weath - weathered; wh - white; wood grags - wood fragments; z - silt


<table>
<thead>
<tr>
<th>Corehole #</th>
<th>Hanford well number</th>
<th>Northing (WSC82S)</th>
<th>Easting (WSC82S)</th>
</tr>
</thead>
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<tr>
<td>Golder 1</td>
<td>699-40-13</td>
<td>135649.9</td>
<td>585939.4</td>
</tr>
<tr>
<td>Golder 73</td>
<td>699-42-30</td>
<td>136213.8</td>
<td>580785.9</td>
</tr>
<tr>
<td>Golder 78</td>
<td>699-30-25C</td>
<td>132593.5</td>
<td>582358.4</td>
</tr>
<tr>
<td>Golder E-19/E-1</td>
<td>699-17-26</td>
<td>128581.9</td>
<td>581882.4</td>
</tr>
<tr>
<td>DH-6</td>
<td>299-W11-26</td>
<td>135563.7</td>
<td>567044.7</td>
</tr>
<tr>
<td>DH-9B</td>
<td>699-54-18C</td>
<td>139998.7</td>
<td>584471.6</td>
</tr>
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<td>DH-11</td>
<td>299-W15-14</td>
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<td>566092.9</td>
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<td>DH-12</td>
<td>299-W14-7</td>
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<td>135688.0</td>
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quartz gneiss and granitics common

pre-Missoula gravel
mbr of Taylor Flat

bn mica
mbr of Taylor Flat
mbr of Wooded Is.
unit E

B-4
G-E-19 and G-E-1 (cont)

- pre-Missoula gravel
- mbr of Taylor Flat
- ashy?
- gy
- gy mottled
- 1-2ft graded beds
- 5% bslt
- wood Fe

mbr of Taylor Flat
mbr of Wooded Is.
unit E

hi qtz
lo bslt
DH-6 (cont)

- Mica
- Plio-Pleistocene unit
- Carb
- >25% bslt
- 20% bslt
- Mbr of Taylor Flat
- Mbr of Wooded Is.
- Units C & E
- Bslt >25%
- Bn
- Bsttic
- Bn
- Incr bslt
- Decr bslt
- Incr bslt

B-13
DH-19 699-70-17 Elev 875 ft (est.) (267 m)

Elephant Mountain Member

unit B

lower mud unit

wavy bedding

Fe

wh

wavy bedding

gy

mica

burrows

bn

dk gy

burrows

rd bn

crumbly

rd bn

unit B
DH-22 (cont)

---

units C & E

---

~ ~ ~

bsltic

---

Plio-Pleistocene unit

---

mbr of Taylor Flat

---

mbr of Wooded Is.
units C & E

---

bslt inclr

---

top at 54 ft

carb rinds

---

bsltic

---
muddy

---
muddy bn

---

300

---

350

---

units C & E

---

200

---

250

---

B-30
DH-24 699-43-84 Elev 634 ft (193 m)

gy bn lower mud unit
unit A

gy Fe

wood frags mica

units C & E
lower mud unit

wavy bedded

bsltic Fe wood frags

mbr of Wooded Is.

Elephant Mountain Member

burrows
ol gy
mottled wh-gy

rd bn

500
550
450
400
350
570

B-31
APPENDIX C. GEOLOGIC CROSS SECTIONS SHOWING DISTRIBUTION OF RINGOLD FORMATION STRATIGRAPHIC UNITS.

Locations of cross sections are shown on inset maps of the Hanford Site on each cross section page.

Explanation of Symbols and Abbreviations used in Cross Sections

Grain Size Scale, indicates dominant grain size

- cobble-boulder gravel
- granule-cobble gravel
- fine to coarse sand
- clay and silt

699-72-92, example of typical well number for geologic logs used in cross-section.

Subordinate lithologies and other lithologic symbols

- bouldery
- pebbly
- sandy
- silt-rich
- clay-rich
- paleosols
- calcium carbonate
- well indurated
- ash (tephra)
- basalt
- no record
- unit contacts, ? where inferred
Depths on individual geologic logs on the cross sections are in meters below the surface.

Stratigraphic unit abbreviations

PM - pre-Missoula gravel of Plio-Pleistocene interval

EP - early Palouse soil

PP - Plio-Pleistocene unit

UR - upper Ringold, Ringold Formation member of Taylor Flat

E - unit E, Ringold Formation member of Wooded Island

C - unit C, Ringold Formation member of Wooded Island

B - unit B, Ringold Formation member of Wooded Island

D - unit D, Ringold Formation member of Wooded Island

LM - lower mud unit, Ringold Formation member of Wooded Island

A - unit A, Ringold Formation member of Wooded Island

(?) - unit uncertain

P.S. - paleosol, unassigned
Wahluko Syncline

Approximate Location of Cross Section

Vertical exaggeration 24.7X

130' 00'

110' 30'

49' 21'30"
APPENDIX D, ISOPACH AND STRUCTURE CONTOUR DATA FOR THE RINGOLD FORMATION FROM THE HANFORD SITE.

Explanation (all elevations are in feet above sea level)

Borehole # - Borehole designation using Hanford Site well identification terminology
Easting - east coordinate in Washington State Coordinate System (WSC82S)
Northing - north coordinate in Washington State Coordinate System (WSC82S)
Top Bas - Elevation of top of uppermost basalt unit in boring
Top Sub A - Elevation of top of paleosol sequence locally underlying unit A
Iso Sub A - Thickness of paleosol sequence locally underlying unit A
Top A - Elevation of top of unit A
Iso A - Thickness of unit A
Top LM - Top of lower mud unit
Iso LM - Thickness of lower mud unit
Top BD - Top of units B and D combined
Iso BD - Thickness of units B and D combined
Top Sub C - Top of paleosol sequence locally underlying unit C
Iso Sub C - Thickness of paleosol sequence locally underlying unit C
Top C - Top of unit C
Iso C - Thickness of unit C
Top Sub E - Top of paleosol sequence locally underlying unit E
Iso Sub E - Thickness of sequence locally underlying unit E
Top E - Top of unit E
Iso E - Thickness of unit E
Iso C+E - Thickness of units C and E combined, included Sub E interval where it is present
Top UR - Top of upper Ringold (e.g., member of Taylor Flat)
Iso UR - Thickness of upper Ringold (e.g., member of Taylor Flat)
Top PMPP - Top of redefined Plio-Pleistocene interval (including early Palouse)
Iso PMPP - Thickness of redefined Plio-Pleistocene interval (including early Palouse)
Top Hf - Top of Hanford formation
Iso Hf - Thickness of Hanford formation
Iso Eo - Thickness of Holocene eolian and alluvial deposits and backfill
Elev - Surface elevation at the borehole (feet above sea level)
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