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Lithofacies and Sedimentology of the Miocene-Pliocene Ringold Formation, Hanford Site, South-Central Washington

Abstract

The Miocene-Pliocene Ringold Formation is one of the principal stratigraphic units within the suprabasalt "unconfined" aquifer at the Hanford Site in southcentral Washington. Consequently, understanding the geology of the Ringold Formation is necessary for the accurate characterization and modeling of groundwater flow and contaminant transport at Hanford. The Ringold Formation is a complexly interstratified sequence of unconsolidated to semiconsolidated clay, silt, sand, and granule to cobble gravel. Evaluation of borehole geological and geophysical data and outcrops on and adjacent to the Hanford Site suggests that the most accurate method for the study of Ringold sediments is through the use of lithofacies. Six lithofacies are defined using primarily grain size data and borehole geophysical responses. These lithofacies are: 1) mud (M), 2) mud and sand (MS), 3) sand (SS), 4) sand and granule to pebble gravel (SG), 5) granule to pebble gravel (G), and 6) cobble to boulder gravel (CB). Analysis of lithofacies distributions and associations reveal that: 1) coarse-grained lithofacies (CB, G, SG, SS) tend to be concentrated along complexly stacked, elongate fluvial channel tracts that display a high degree of vertical interconnectedness, 2) fine-grained lithofacies (M, MS) tend to occupy relatively stable positions, and 3) individual lithofacies identified at the Hanford Site tend to be discontinuous even over short lateral distances. Based on the analysis of lithofacies distributions and associations more accurate appraisals of the hydrogeology of the Hanford Site are possible.

Introduction

Thousands of tons of radioactive and other hazardous wastes have been introduced into the late Cenozoic sediments on the Hanford Site, Washington, since the late 1940's (PNL, 1986, 1987). The accumulation of these wastes has necessitated a long-term program of groundwater monitoring and geohydrologic characterization of the unconfined aquifer to assess the extent of present and potential future groundwater contamination in this area. The Miocene-Pliocene Ringold Formation is the principal stratigraphic unit within the suprabasalt "unconfined" aquifer; thus, its stratigraphic and sedimentary complexities are important to the characterization of the groundwater flow system. A fundamental parameter in stratigraphic and sedimentary studies are lithofacies (Miall 1977, 1978; Rust 1978).

This paper presents findings from a study of primarily subsurface lithofacies identified in the Ringold Formation on and immediately adjacent to the Hanford Site. The paper reevaluates the five-tiered subdivisions of the Ringold Formation generally used at the Hanford Site (Myers *et al.* 1979; DOE 1988), suggests alternative methods for characterizing these strata, and presents sedimentological interpretations.

Geologic Setting

Suprabasalt terrigenous clastic sediments (Figure 1), including the Ringold Formation, are present throughout much of the central Columbia Plateau in south-central Washington (Grollier and Bingham 1971, 1978; Myers *et al.* 1979; Tallman *et al.* 1979, 1981; Fecht *et al.* 1985). Regionally, the Ringold Formation consists of up to 280 m of interstratified unconsolidated to cemented clay, silt, sand, and granule to cobble-sized gravel deposited in fluvial and lacustrine settings (Newcomb 1958; Bjornstad 1985; Fecht *et al.* 1985; DOE 1988). Exposures of the Ringold Formation are limited because of an extensive Pleistocene-Holocene sedimentary cover and erosion by catastrophic, proglacial Pleistocene floods. However, informative outcrops exist; 1) on the White Bluffs north and east of the Columbia River, 2) in ravines and coulees between Wallula Gap and Moses Lake, Washington, and 3) near prominent anticlinal ridges including Rattlesnake Mountain, the Saddle Mountains, Gable Mountain, and the Frenchman Hills (Figures 2 and 3).

The Ringold Formation at the Hanford Site consists dominantly of sand and granule to cobble-sized gravel with lesser, yet still significant amounts of clay, silt, and sand (Newcomb

Quaternary	Holocene	Holocene surficial deposits
	Pleistocene	unconformity Hanford formation unconformity Early 'Palouse' soil unconformity
Tertiary	Pliocene	Plio-Pleistocene unit unconformity
	Miocene	Ringold Formation unconformity Columbia River Basalt Group

Figure 1. Generalized stratigraphy of the late Cenozoic sediments in the Pasco Basin, southcentral Washington.

1958; Newcomb *et al.* 1972; Myers *et al.* 1979; Tallman *et al.* 1979, 1981; Bjornstad 1984, 1985); it is greater than 50 m thick at most localities and reaches a maximum thickness of 260 m near the center of the Hanford Site. Exposures of the Ringold Formation along the White Bluffs (Figure 3) consist of up to 125 m of interbedded clay, silt, sand, and relatively minor granule to cobble gravel. These exposures generally lie stratigraphically above those Ringold strata described from the Hanford Site.

Ringold Formation strata originally were considered to be Pleistocene-aged (Merriam and Buwalda 1917, Newcomb 1958, Grollier and Bingham 1971, Newcomb *et al.* 1972). However, subsequent paleontologic, paleomagnetic, and palynologic studies have demonstrated a greater age for the Ringold. Gustafson (1973, 1980) and Packer and Johnson (1979) suggested a Miocene to Pliocene age based on paleomagnetic and paleontologic data from Ringold exposures and

drill core, while Leopold and Nickman (1981) determined a Miocene age for the oldest Ringold strata on the basis of pollen samples collected near the base of the Ringold Formation. Fecht *et al.* (1985) established a maximum age of 8.5 Ma for the Ringold Formation from K-Ar whole-rock dating of the underlying Miocene basalt (McKee *et al.* 1977) and a minimum age of 3.4 Ma on the basis of paleomagnetic data and vertebrate fossil evidence.

Previous Studies

All suprabasalt sediments (including strata now assigned to the Ringold Formation) on the central Columbia Plateau and in the eastern foothills of the southern 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 fine-grained terrigenous clastic sediments exposed on the White Bluffs and near Pasco, Washington to a unit they called the Ringold Formation. Culver (1937) later mapped the Ringold Formation across the central Columbia Plateau. Both Merriam and Buwalda (1917) and Culver (1937) restricted their definition of the Ringold Formation to strata exposed at the surface.

The concurrent establishment of the Hanford Site and expansion of nearby irrigated farmland in the early 1940's resulted in numerous test boreholes and production wells that revealed a sequence of buried sediments overlying the Columbia River Basalt Group. A significant proportion of these strata were found to be subsurface extensions of Ringold exposures found on the White Bluffs (Newcomb 1958). As a result, the Ringold Formation was redefined to include all sedimentary strata in the Pasco Basin that overlie the Columbia River Basalt Group and that underlie Pleistocene glaciofluvial deposits (Newcomb 1958).

The Ringold Formation as defined at the Hanford Site by Newcomb (1958) and Myers *et al.* (1979) is divided into the following five lithostratigraphic units. These are the: 1) gravel-dominated basal unit, 2) interstratified to mixed clay, silt, sand, and local gravel of the lower unit (including the prominent 'blue clays' of geologic drill logs), 3) quartzose gravel of the middle unit, 4) interstratified to mixed clay, silt, and sand of

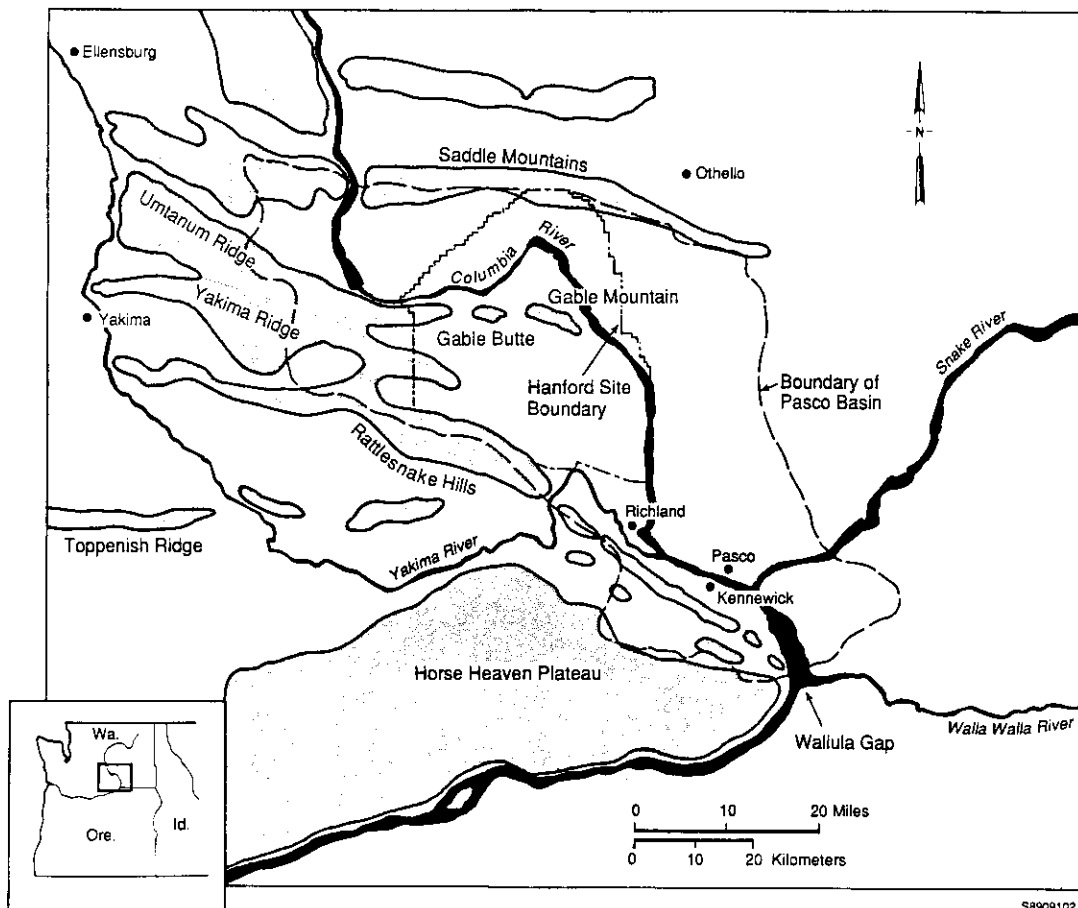


Figure 2. Geographic setting of south-central Washington and location of the Hanford Site.

the upper unit, and 5) locally-derived basaltic gravel of the fanglomerate unit. Only the fanglomerate unit, upper unit, and upper part of the middle unit crop out. Offsite the Ringold Formation has been subdivided on the basis of lithofacies (Grollier and Bingham 1971, 1978). These lithofacies are not the same as those defined in this report.

Methods

Discussion of the Ringold Formation in this paper is largely restricted to subsurface investigations at the Hanford Site (Figures 2 and 3); outcrops on the Hanford Site are uncommon and only occur along the flanks of a few anticlinal ridges. Borehole geologic logs, sediment samples,

and accompanying geophysical data (primarily natural gamma and neutron-neutron logs) from 147 boreholes that extend to basalt were chosen for study. The majority of the sediment samples available from those holes are drill cuttings. Interpretative stratigraphic sections, that are constructed from this joint geologic/geophysical database, form the basis for identification and description of lithofacies and the construction of isolith, isopach, and lithofacies maps. Six lithofacies are defined primarily on the basis of grain size descriptions from geologic drill logs, textural analyses, and to a very limited extent, from borehole geophysical logs, cores, and outcrops. These lithofacies are: 1) mud (M), 2) mud and sand (MS), 3) sand (SS), 4) sand and granule to pebble gravel (SG), 5) granule to pebble gravel

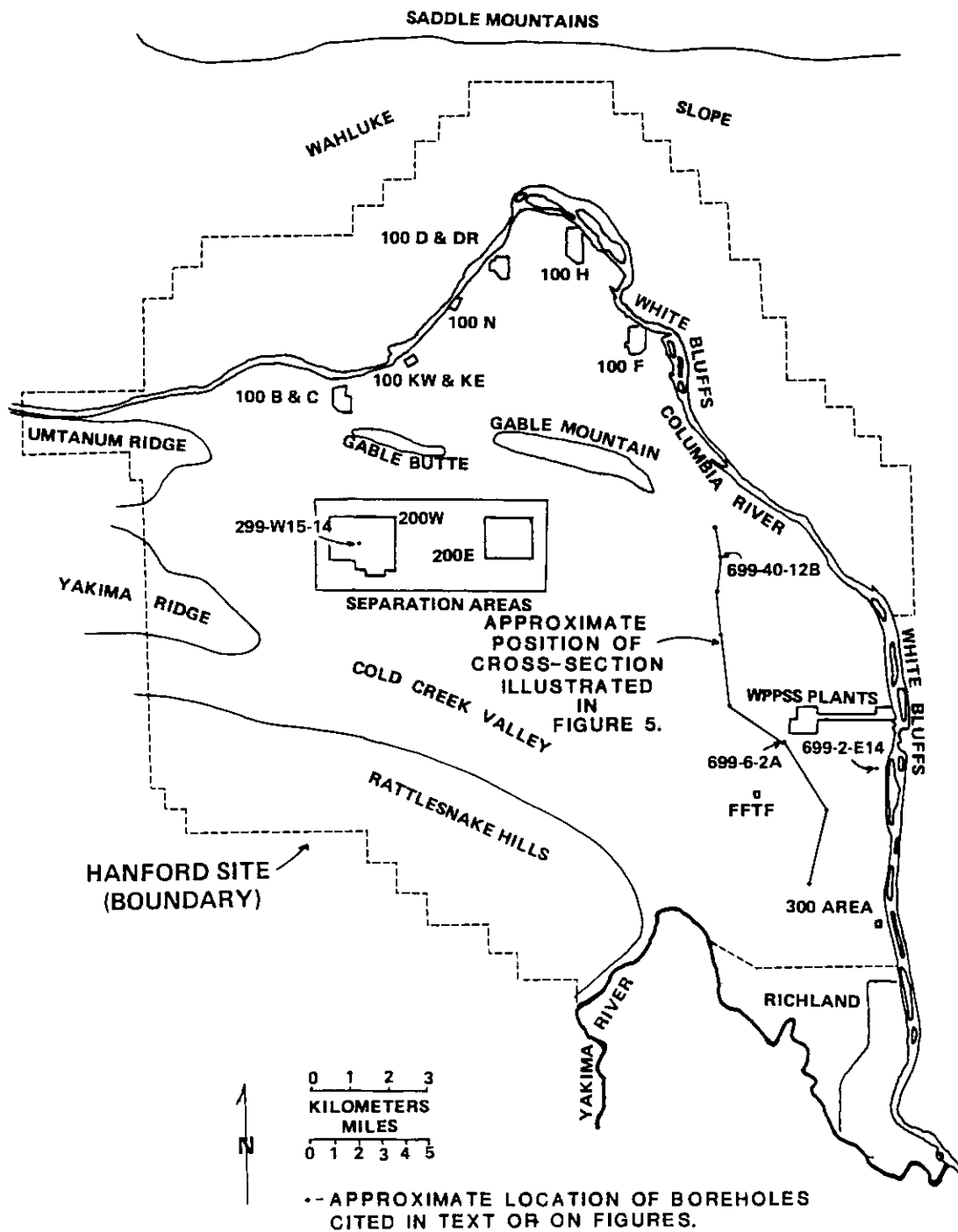


Figure 3. Location map of the Hanford Site modified from Tallman *et al.* (1979).

(G), and 6) cobble to boulder gravel (CB). The lithofacies code is loosely based on the set of codes introduced by Miall (1977, 1978) and Rust (1978) for studies in fluvial sedimentology. However, unlike the lithofacies identified by Miall and Rust, Ringold lithofacies are not further subdivided on the basis of primary sedimentary structures. This reflects the small number of intact cores available for study and the lack of clear correlation between drill cuttings and either cored samples or outcrops. This reliance on less than optimum subsurface data as well as the distances between boreholes (usually many hundreds to thousands of feet), limits but does not prohibit identification of the major depositional trends and large-scale architectural elements necessary to reconstruct depositional setting (Miall 1985, 1987).

Lithofacies Description and Interpretation

Lithofacies M: Mud

Lithofacies M (Figure 4) consists of massive to laminated gray, brown, olive, and blue clay and silt. Beds are a few centimeters to tens of meters thick and average less than 10 m thick. Sand comprises up to 10 percent of this lithofacies and occurs as thin (< 30 cm thick) lenticular interbeds and as intermixed grains. Meters-thick paleosols are common in core and surface exposures. Thin (< 10 cm), laterally extensive ash beds are present, but uncommon. Mud lithofacies tend to be discontinuous in the subsurface (Figure 5) and commonly grade down into muddy-sand (MS) and sandy-gravel (SG) lithofacies; they are most commonly overlain by gravel (G) and cobble-boulder (CB) lithofacies.

The fine grain size and generally good sorting indicate that this facies resulted primarily from suspension deposition in standing or slow-moving waters, probably in an overbank and possibly in a backwater swamp or lacustrine setting such as described for similar lithofacies by Miall (1977, 1978). Abundant paleosols indicate periodic subaerial exposure. The laminated clay and silt of this lithofacies have been interpreted as lacustrine (Bjornstad 1985). Thin sand beds are consistent with intermittent tractional transport of ripples and sheet sands (Miall 1977, 1978), probably during flood stage.



Figure 4. Thick laminated to thin bedded mud analogous to the type assigned to facies M. Gradations on Jacob staff are 10 cm.

Lithofacies MS: Mud and Sand

Lithofacies MS (Figure 6) consists of massive to interlaminated gray, brown, olive, and rarely blue clay and/or silt, and sand. Bedding thicknesses range from a few centimeters to less than 10 m. Sand contents range from 10 to 80 percent and average 50 percent. Climbing rippled and normally graded fine-grained sands in sets 20 to 40 cm thick and soft-sediment deformation is common in the lithofacies along the White Bluffs. Meters-thick paleosols are common in core and surface exposures while thin (< 10 cm) ash beds are less common. However, as in lithofacies M, paleosols and ashes are difficult to identify in borehole cuttings. Deposits of lithofacies MS

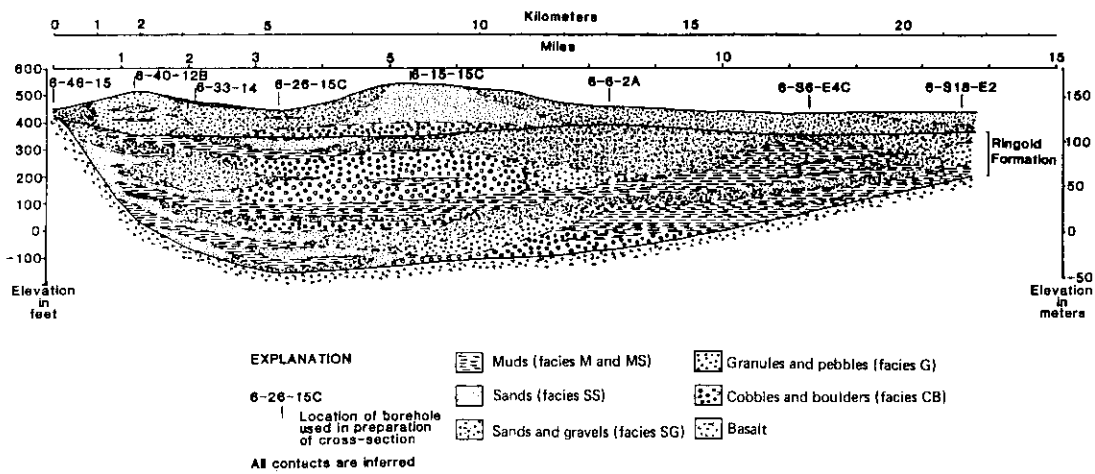


Figure 5. Geologic cross-section showing the marked lateral lithostratigraphic variability of the Ringold Formation. See Figure 3 for location of cross-section.

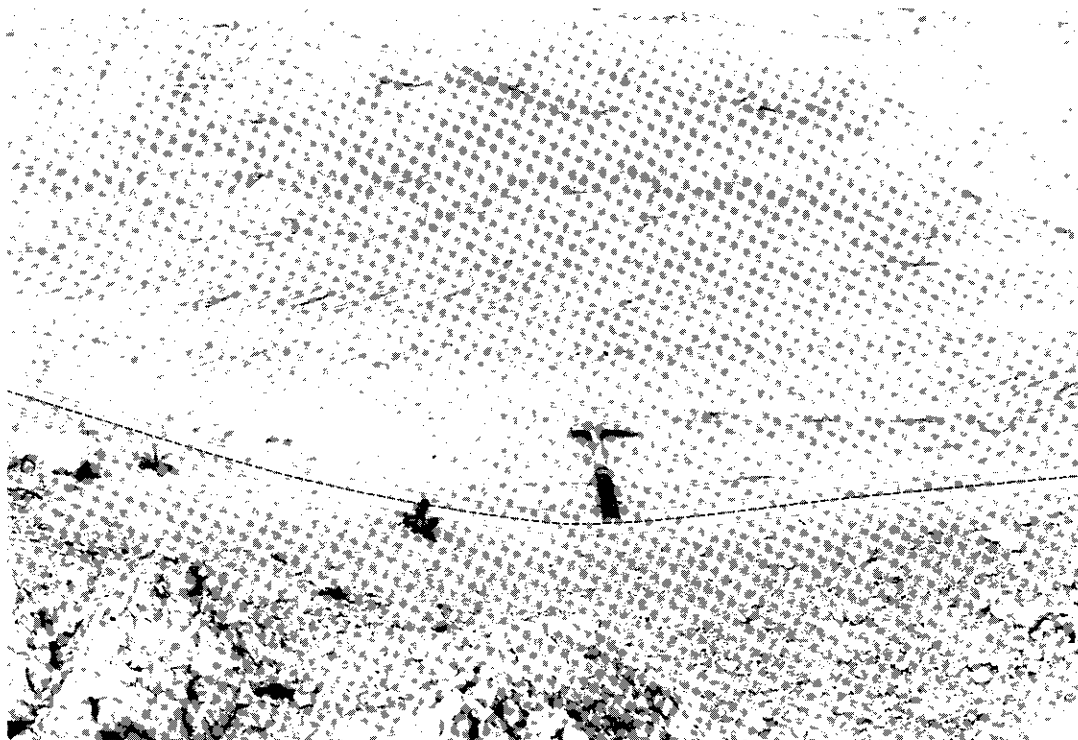


Figure 6. Strata typical of those assigned to facies MS. Dashed line separates sand (above) from mud (below). Note rock hammer for scale.

tend to be discontinuous, generally grade down into sand (S) and sandy-gravel (SG) lithofacies, are gradationally overlain by lithofacies M, and frequently are truncated and overlain by deposits of the gravel (G) and cobble and boulder (CB) lithofacies.

The mixed textural character of lithofacies MS implies that it resulted from episodic input of coarse-grained detritus transported into standing or slow moving waters by intermittent traction and possibly flood currents in an overbank to lacustrine setting. Miall (1977, 1978) and Galloway (1981) ascribe an overbank setting to similar fluviially-derived strata. The relatively high concentration of sand in this lithofacies as compared to that in lithofacies M suggests a more proximal location to stream channeling. Pedogenesis is consistent with a floodplain interpretation (Miall 1977, 1978). However, the presence of soft-sediment deformation indicates periodic rapid accumulation of sediment in deltaic and lacustrine settings.

Lithofacies SS: Sand

Lithofacies SS (Figure 7) consists of sand that is gray, olive, and less commonly, tan and brown, fine to coarse-grained, moderately to poorly sorted, subangular to subrounded, and unconsolidated to weakly cemented. Up to 20 percent of this lithofacies may be composed of mud, granules, and pebbles, most commonly as lenticular interbeds. Sand lithofacies in core and outcrop display massive bedding, plane to horizontal stratification, and planar and trough cross-stratification in 5 cm to 1 m thick tabular sets. Total thicknesses of lithofacies SS are generally < 10 m. Deposits of the sand lithofacies commonly grade upwards into lithofacies M, MS, and SG, and grade downwards into lithofacies SG, G, and CB. Lithofacies SS also sharply truncates lithofacies M and MS and is, in turn, truncated by lithofacies SG, G, and CB. Sand detritus is composed dominantly of quartz, feldspar, and mica grains, and with lesser granitic, basaltic, and gneissic lithic fragments.



Figure 7. Cross-bedded sand analogous to the strata comprising facies SS.

The coarse-grain sizes, and primary sedimentary structures are consistent with migration and aggradation of ripples, sand-waves, and plane beds (Miall 1977, 1978). The discontinuous nature of sand lithofacies suggest a channel-like character for these deposits. Deposition of lithofacies SS is inferred to have been confined to trunk and tributary channels, probably during normal stream flow and during the waning stages of floods when these sediments were deposited atop coarser-grained, gravel-dominated lithofacies.

Lithofacies SG: Sand and Gravel

Lithofacies SG (Figure 8) consists dominantly of gravel that is light to dark gray, poorly sorted, unconsolidated and granule- to pebble-sized. Sand and mud make up less than 50 percent of lithofacies SG and occurs as matrix and in lenses and beds up to 1 m thick. Limited outcrops of apparently analogous SG strata (Figure 8) occur in 1 to 20 m thick beds that exhibit large-scale

trough and planar cross-strata, clast imbrication, meters-wide channel scours, and bar-shaped lenticular bodies. Deposits of the sand and gravel lithofacies commonly are gradationally overlain by lithofacies M and MS, are sharply to gradationally overlain by lithofacies SS, and gradationally overlain and are sharply truncated by lithofacies G and CB. Gravels are composed dominantly of quartzitic, basaltic, granitic, gneissic, and porphyritic volcanic clasts; sands generally are quartzofeldspathic.

Deposits of the SG lithofacies are interpreted as mixed in-channel sediments. Deposition of cross-stratified, stratified, and imbricated gravel-dominated and sand-dominated lenses and beds reflect aggradation of transverse and longitudinal gravel bars and dunes (Miall 1977, 1978). The interstratification of sand and gravel, as well as the incorporation of sand as matrix and lenses is common to braid plain systems that experience widely fluctuating currents (Rust and Koster, 1984). Periodically strong stream currents are

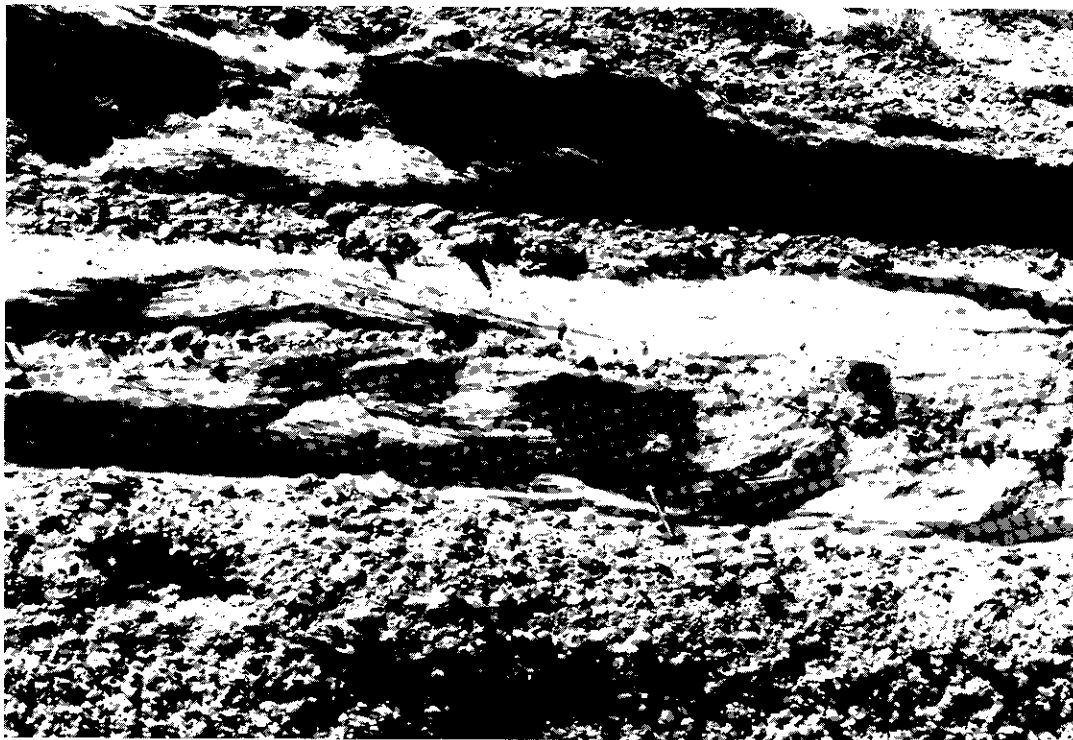


Figure 8. Interbedded crudely stratified granule to pebble gravel and cross-stratified sand analogous to the strata comprising facies SG. Note rock hammer for scale.

implied by concentrations of pebble-sized gravel within this lithofacies.

Lithofacies G: Granule to Pebble Gravel.

Lithofacies G (Figure 9) consists dominantly of clast- and matrix-supported granule and pebble gravel that is light to dark gray, poorly sorted and unconsolidated to poorly cemented. Sand, mud, and cobble-sized gravel comprise less than 20 percent of the lithofacies. Sand and mud occur as both intermixed matrix and as < 50 cm thick lenses; cobbles are present as floating grains. Limited outcrops of analogous strata (Figure 9) display 1 to 10 m thick intervals that exhibit large-scale trough and planar cross-strata, clast imbrication, meters-wide channel scours, and bar-shaped lenticular bodies. Upper and lower bounding surfaces of lithofacies G are sharp to gradational. Gravels are composed of quartzitic, basaltic, granitic, gneissic, and porphyritic volcanic clasts; sands generally are quartzo-feldspathic.

Deposits of lithofacies G are interpreted as in-channel sediments. Deposition of cross-stratified, stratified, and imbricated gravel-dominated beds reflect aggradation of transverse and longitudinal gravel bars and in-channel dunes (Miall 1977, 1978; Rust 1978). The interstratification of sand and gravel as well as the incorporation of sand and mud as matrix material and lenses is common to braid plain systems that experience widely fluctuating currents (Rust and Koster 1984). However, the concentration of granules and pebbles in this lithofacies attest to either consistently stronger currents, or a more limited and gravel-dominated source than is inferred for the SG lithofacies.

Lithofacies CB: Cobble and Boulder

Lithofacies CB (Figure 9) consists of lenses and beds of cobbles and boulders that are light to dark gray, massive to crudely stratified, matrix to clast-supported, poorly sorted, and unconsolidated to poorly cemented. The cobble and

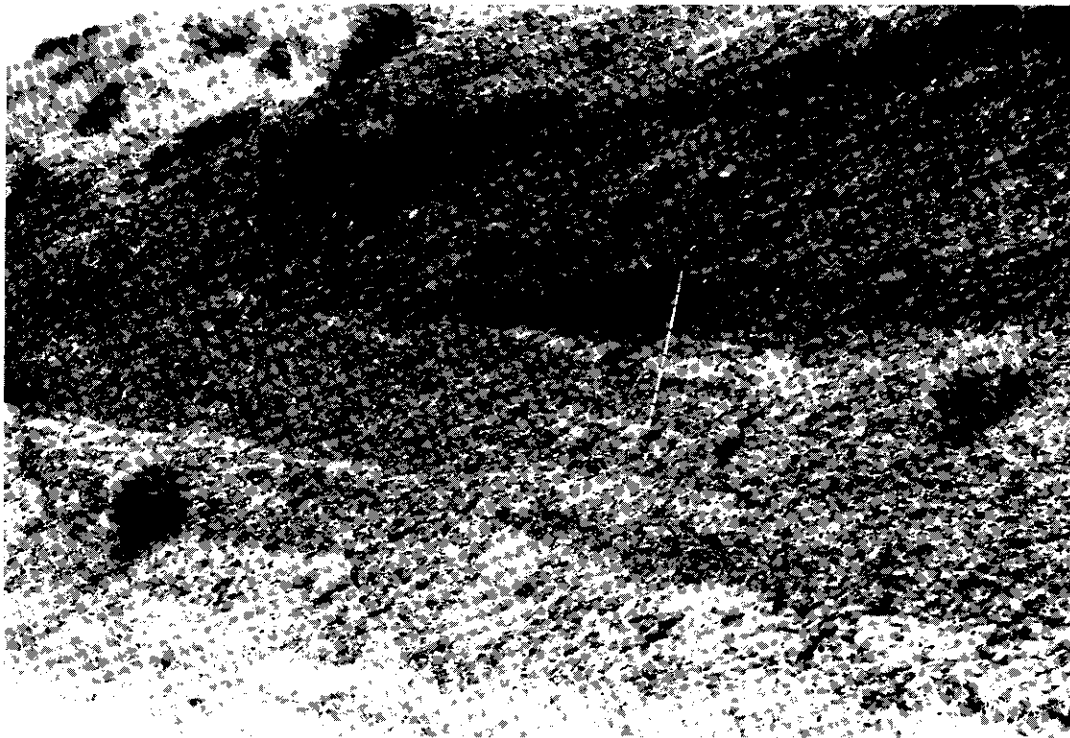


Figure 9. Crudely stratified granule to pebble gravel of the type typical of strata comprising facies G interstratified with cobble and boulder gravel typical of facies CB. Gradations on Jacob staff are 10 cm.

boulder content exceeds 20 percent. Sand, mud, and granule to pebble-sized gravel can comprise up to 80 percent of the lithofacies and may occur as both matrix and as less than 1 m thick interstratified lenses and beds. Strata assigned to lithofacies CB form sequences 0.5 to 5 m thick. Lithofacies CB overlies sharply truncated surfaces and is overlain gradationally by lithofacies SG and G and rarely by lithofacies M and MS.

Deposits of lithofacies CB are interpreted as in-channel and outwash sediments deposited during major floods. Matrix-supported cobble- and boulder-dominated lithofacies deposits commonly reflect mass transport and deposition as debris flow deposits (Bull 1972; Miall 1977, 1978). Clast-supported cobble and boulder gravel probably reflect tractional transport during aggradation of longitudinal bars (Miall 1977, 1978; Rust 1978).

Lithofacies Associations, Sedimentary Architecture, and Environments of Deposition

The architectural arrangement of lithofacies in the Ringold Formation on the Hanford Site is a complexly interstratified sequence of fluvial deposits composed of two principal lithofacies associations: coarse-grained channel deposits and fine-grained overbank and/or backswamp-lacustrine deposits. These sediments were deposited by both the ancestral Columbia and Salmon-Clearwater River systems as they crossed the Pasco Basin (Fecht *et al.* 1985). Fluvial deposits on the Hanford Site are stratigraphically complex and were subjected to numerous episodes of fluvial incision and pedogenesis. The intercalation and gradation between lithofacies seen in cross-sections and stratigraphic sections (Figures 5 and 10) are not easily reconciled by any existing lithofacies models (e.g., Rust and Koster 1984, Walker and Cant 1984, Collinson 1986).

Deposits of the coarse-grained channel lithofacies association are composed of lithofacies SS, SG, G, CB, and subordinate M and MS lithofacies. The abundance of coarse-grained lithofacies and the relative scarcity of mud-dominated lithofacies in this association suggest that deposition occurred primarily in a bedload-dominated stream system (see Schumm 1976, Galloway 1981). Deposits of this lithofacies association

commonly display fining and coarsening upwards sequences that are less than 30 m thick (Figure 9). The fining-upwards sequences identified in our work are generally an order of magnitude thinner and much less continuous than those described by Webster and Crosby (1982).

Mapping the total thickness of coarse-grained lithofacies SS, SG, G, and CB in the Ringold Formation indicates that these lithofacies are concentrated in elongate trends (Figure 11). These coarse-grained lithofacies trends probably reflect multiple stacking of channel tracts that resulted from one or all of the following factors: 1) focusing of stream flow between Gable Mountain in the north and Yakima Ridge and Rattlesnake Mountain in the south, 2) lateral restriction of stream flow by highly cohesive mud-dominated overbank areas, and 3) structural controls. A high degree of vertical interconnectedness of such coarse-grained lithofacies is a common result of such channel stacking (Bridge and Leeder 1979).

The fine-grained overbank lithofacies association is composed of lithofacies M, MS, and subordinate SS. Deposits of this association commonly occur in highly dissected local sequences up to 50 m thick (Figure 5) and as relatively thin lenses and tongues. The fine-grained character and pedogenic alteration of lithofacies within this association support an overbank and/or backswamp-lacustrine interpretation.

The concentration of fine-grained lithofacies M and MS in relatively thick, but localized sequences (Figure 5) indicates that areas of fine-grained overbank deposition were stable for relatively long periods of time. Possible causes for such persistent deposition include: 1) restriction of depositional environments to structural lows and 2) the rapid accumulation of cohesive overbank muds. Thin lenses of lithofacies M and MS that intertongue with the coarser-grained lithofacies are common locally and are interpreted to reflect areas influenced by channel processes.

Discussion

Stratigraphic trends common to the Ringold Formation are not easily integrated into the generally used Ringold stratigraphic model (Myers *et al.* 1979, DOE 1988) because of the high degree of lateral and vertical variability of the component lithofacies of this unit. For example, where

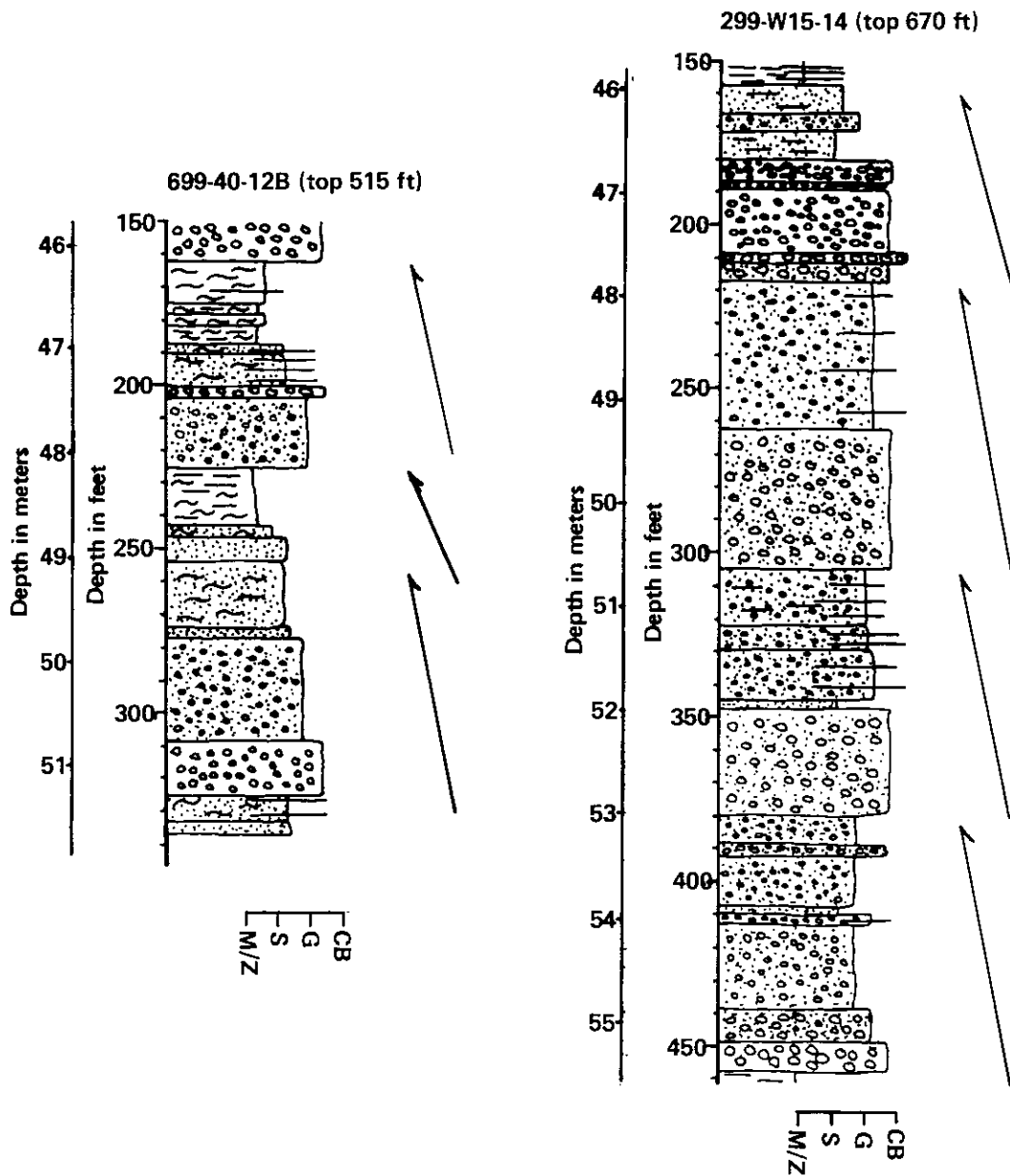


Figure 10. Fining-upwards fluvial sequences typical of those seen throughout the Ringold Formation. See Figure 12 for key to symbols.

multiple mud-dominated intervals are separated by thick, coarse-grained lithofacies (Figure 12), it is difficult, if not impossible, to determine the stratigraphic position of the lower mud-dominated unit. This problem is compounded further where strata typically assigned to the mud-dominated lower unit of Myers *et al.* (1979)

grade into and intertongue with coarse-grained strata containing numerous fine-grained interbeds (Figure 5). In cases where fine-grained strata are absent (Figure 13), it often is not possible to differentiate between the gravels of the basal and middle units of the Ringold Formation.

It is generally accepted that syndepositional

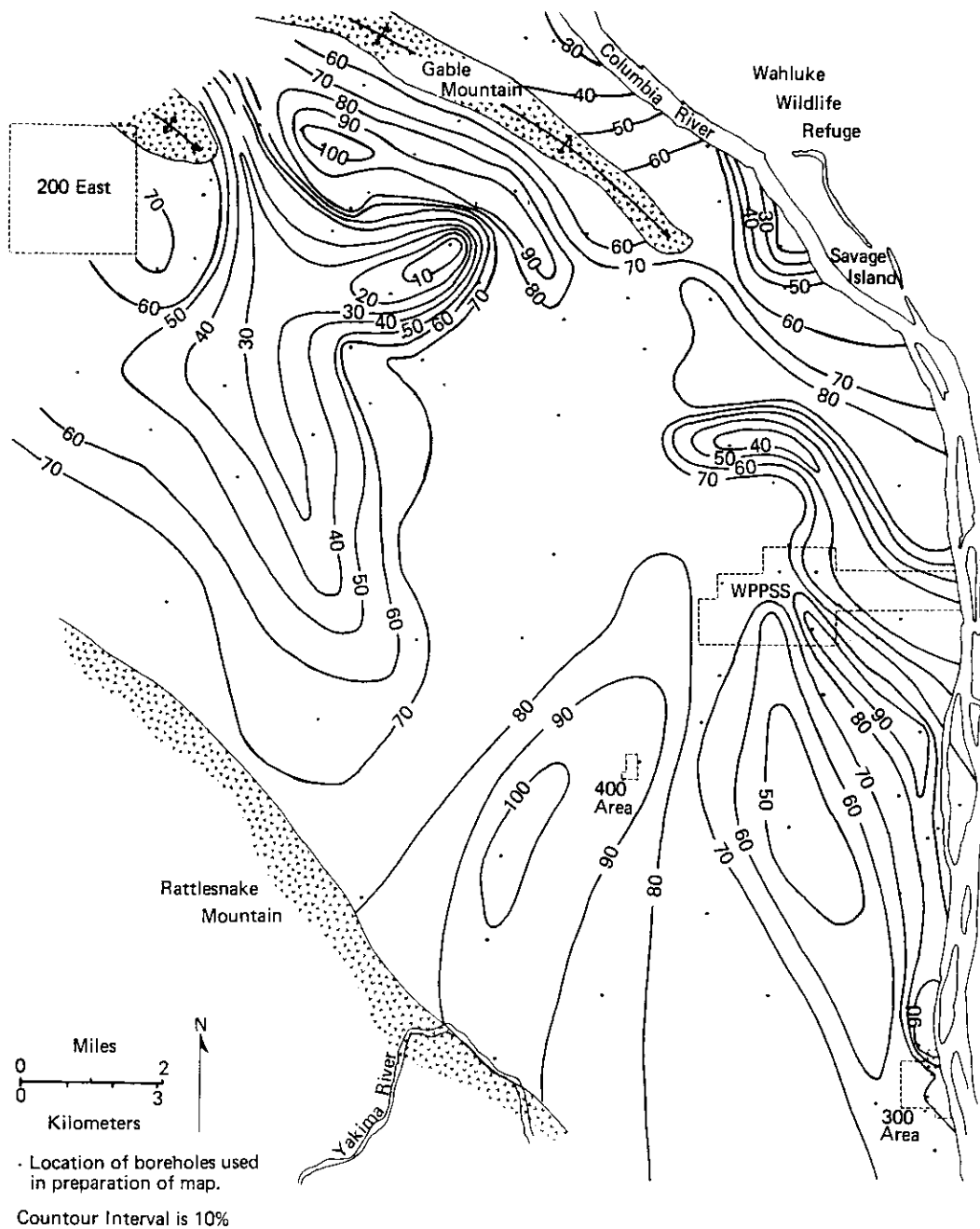


Figure 11. Map illustrating the distribution of coarse facies (SS, SG, G, and CB) in the Ringold Formation south of Gable Mountain. Contours indicate percent of coarse facies.

subsidence of the Pasco Basin influenced the position of fluvial depositional systems during accumulation of the Ringold Formation (Tallman *et al.* 1979, 1981; Reidel and Fecht 1981;

Bjornstad 1985; Fecht *et al.* 1985; DOE 1988). For example, strata generally thicken into structural lows where subsidence and associated sedimentation are interpreted to have been more

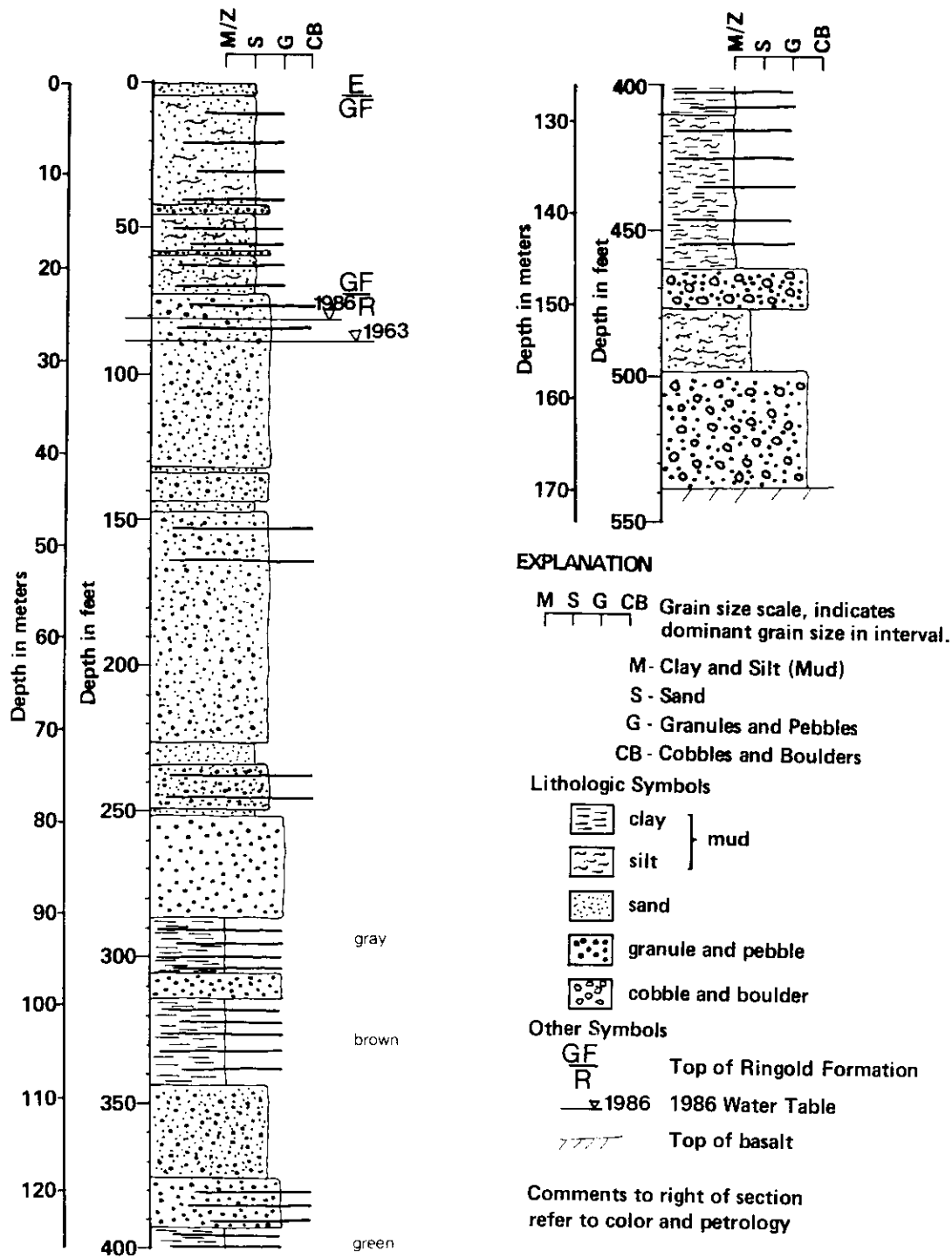


Figure 12. Geologic section of borehole 699-6-2A. This section shows a case where several mud-dominated facies are separated by thick gravelly strata.

distribution also was controlled by the migration of depositional environments within the fluvial system.

Conclusions

Analysis of existing subsurface geologic and geophysical data reveals that the five-tiered Ringold Formation stratigraphy as currently used at the Hanford Site may lead to erroneous interpretations of the distribution, architectural arrangement, and ultimately, geohydrologic properties of the Ringold Formation. In particular, the marked lenticularity and variability of Ringold strata, the relative lack of continuous marker horizons, and the gradational and ambiguous nature of unit contacts all hinder strict application of the generally accepted Ringold formation lithostratigraphic model (Myers *et al.* 1979, DOE 1988) to the Ringold Formation on the Site. An alternate method for the characterization of Ringold Formation strata has been suggested.

Six broad categories of lithofacies were defined primarily on the basis of grain size descriptions from geologic drill logs, textural analyses, and to a limited extent, on borehole geophysical logs, cores, and outcrops. These are: 1) mud (M), 2) mud and sand (MS), 3) sand (SS), 4) sand and granule to pebble gravel (SG), 5) granule to pebble gravel (G), and 6) cobble to boulder gravel (CB). These lithofacies aid in portraying the variability of sedimentary packages or elements, interpretation of depositional and erosional systems, and evaluation of hydrologic properties. The architectural arrangement of lithofacies in

the Ringold Formation on the Hanford Site reveals a complexly stacked sequence of fluvial deposits composed of two principal lithofacies associations: coarse-grained channel deposits and fine-grained overbank and/or backswamp-lacustrine deposits. Coarse-grained channel deposits are concentrated along relatively elongate tracts reflecting multiple-stacking of bedload-dominated stream channel tracts. Overbank and/or backswamp-lacustrine deposits are concentrated in a few localized areas that escaped extensive stream channel incision for sedimentologic and structural reasons.

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Literature Cited

- Bjornstad, B. N. 1984. Suprabasalt stratigraphy within and adjacent to the Reference Repository Location. Rockwell Hanford Operations Report SD-BWI-DP-039. 6 p.
- _____. 1985. Late Cenozoic stratigraphy and tectonic evolution within a subsiding basin, south-central Washington (abs. with program). *Geol. Soc. Amer. (Abst.)* 17:7:524.
- Bridge, J. S., and M. R. Leeder, 1979. A simulation model of alluvial stratigraphy. *Sedimentology*. 26:617-644.
- Bull, W. B. 1972. Recognition of alluvial-fan deposits in the stratigraphic record. *In* J. K. Rigby and W. K. Hamblin (eds.), *Recognition of Ancient Sedimentary Environments*. Society of Economic Paleontologists and Mineralogists Special Publication 16. Pp. 63-83.
- Collinson, J. D. 1986. Alluvial sediments. *In* H. G. Reading (ed.), *Sedimentary Environments and Facies*. Blackwell Scientific Publications, Oxford. Pp. 20-62.
- Culver, H. E. 1937. Extensions of the Ringold Formation. *Northw. Sci.* 11:3:57-60.
- DOE. 1988. Consultation Draft, Site Characterization Plan, Reference Repository Location, Hanford Site, Washington. U.S. Department of Energy Report DOE/RW-0164, 8 vols.
- Fecht, K. R., S. P. Reidel, and A. M. Tallman. 1985. Paleodrainage of the Columbia River system on the Columbia Plateau of Washington State: A summary. Rockwell Hanford Operations Report RHO-BW-SA-318P. 55 p.
- Galloway, W. E. 1981. Depositional architecture of Cenozoic Gulf Coastal Plain fluvial systems. *In* F. G. Ethridge and R. M. Flores (eds.), *Recent and ancient nonmarine environments: models for exploration*. Houston Geological Society, Houston. Pp. 127-155.

- Grolier, M. J., and J. W. Bingham. 1971. Geologic map and sections of parts of Grant, Adams, and Franklin Counties, Washington. U.S. Geological Survey Miscellaneous Geologic Investigations Series Map 1-589, 6 sheets, 1:62500.
- _____. 1978. Geology of parts of Grants, Adams, and Franklin Counties, east-central Washington. Washington Division of Geology and Earth Resources Bulletin 71. 91 p.
- Gustafson, E. P. 1973. The vertebrate fauna of the late Pliocene Ringold Formation, south-central Washington. University of Washington, Seattle. Ph.D. Dissertation. 164 p.
- _____. 1985. Soricids (Mammalia, Insectivora) from the Blufftop Local Fauna, Blanco Ringold Formation of central Washington, and the correlation of Ringold Formation faunas. *J. Vert. Paleont.* 5:88-92.
- Leopold, E. B., and R. Nickmann. 1981. A late Miocene pollen and spore flora from the Hanford Reservation, eastern Washington. *Golder Associates, Kirkland.* 23 p.
- McKee, E. H., D. A. Swanson, and T. L. Wright. 1977. Duration and volume of Columbia River Basalt volcanism: Washington, Oregon, and Idaho. *Geol. Soc. Amer. (Abst.)* 9:4:463-464.
- Merriam, J. C., and J. P. Buwalda. 1917. Age of the strata referred to the Ellensburg formation in the White Bluffs of the Columbia River. *Univ. Calif. Bull. Geol. Sci.* 10:255-266.
- Miall, A. D. 1977. A review of the braided river depositional environment. *Earth Sci. Rev.* 13:1-62.
- _____. 1978. Lithofacies types and vertical profile models in braided river deposits: A summary, *In* A. D. Miall (ed.), *Fluvial Sedimentology*. Can. Soc. Pet. Geol. Memoir 5. Pp. 597-604.
- _____. 1985. Architectural-element analysis: A new method of facies analysis applied to fluvial deposits. *Earth Sci. Rev.* 22:261-308.
- _____. 1987. Recent developments in the study of fluvial facies models, *In* F. G. Ethridge, R. M. Flores, and M. D. Harvey (eds.), *Recent Developments in Fluvial Sedimentology*. Society of Economic Paleontologists and Mineralogists Special Publication 39. Pp. 1-9.
- Myers, C. W., S. M. Price, J. A. Caggiano, M. P. Cochran, W. H. Czimer, N. J. Davidson, R. C. Edwards, K. R. Fecht, G. E. Holmes, M. G. Jones, J. R. Kunk, R. D. Landon, R. K. Ledgerwood, J. T. Lillie, P. E. Long, T. H. Mitchell, E. H. Price, S. P. Reidel, and Tallman, A. M. 1979. Geologic studies of the Columbia Plateau: A status report. Rockwell Hanford Operations Report RHO-BWI-ST-4.
- Newcomb, R. C. 1958. Ringold Formation of Pleistocene age in the type of locality, the White Bluffs, Washington. *Amer. J. Sci.* 256:328-340.
- Newcomb, R. C., J. R. Strand, and F. J. Frank. 1972. Geology and groundwater characteristics of the Hanford Reservation of the Atomic Energy Commission, Washington. U.S. Geological Survey Professional Paper 717. 78 p.
- PNL. 1986. Environmental monitoring at Hanford for 1986. Battelle, Pacific Northwest Laboratory Report PNL-6120. Richland.
- _____. 1987. Environmental monitoring at Hanford for 1987. Battelle, Pacific Northwest Laboratory Report PNL-6145. Richland.
- Packer, D. R., and J. M. Johnson. 1979. A preliminary investigation of the magnetostratigraphy of the Ringold Formation. Rockwell Hanford Operations Report RHO-BWI-C-46. 48 p.
- Reidel, S. P., and K. R. Fecht. 1981. Wanapum and Saddle Mountains Basalts of the Cold Creek Syncline Area. *In* C. W. Myers and S. M. Price (eds.), *Subsurface Geology of the Cold Creek Syncline*. Rockwell Hanford Operations Report RHO-BWI-ST-14. 45 p.
- Rust, B. R. 1978. A classification of alluvial channel systems, *In* A. D. Miall (ed.), *Fluvial Sedimentology*. Can. Soc. Pet. Geol. Memoir 5. Pp. 187-198.
- Rust, B. R., and E. H. Koster. 1984. Coarse alluvial deposits. *In* R. G. Walker (ed.), *Facies Models*, 2nd ed. Geoscience Canada Reprint Series 1. Pp. 53-70.
- Schumm, S. A. 1976. *The Fluvial System*. Wiley-Interscience, New York.
- Smith, G. O. 1901. Geology and water resources of a portion of Yakima County, Washington. U.S. Geological Survey Water-Supply Paper 55. 68 p.
- Tallman, A. M., K. R. Fecht, M. C. Marratt, and G. V. Last. 1979. Geology of the Separations Areas, Hanford Site, south-central Washington. Rockwell Hanford Operations Report RHO-ST-23. 132 p.
- Tallman, A. M., J. T. Lillie, and K. R. Fecht. 1981. Suprabasalt sediments of the Cold Creek Syncline Area. *In* C. W. Myers and S. M. Price (eds.), *Subsurface Geology of the Cold Creek Syncline*. Rockwell Hanford Operations Report RHO-BWI-ST-14. 28 p.
- Walker, R. G., and D. J. Cant. 1984. Sandy fluvial systems. *In* R. G. Walker (ed.), *Facies Models*, 2nd ed. Geoscience Canada, Reprint Series 1. Pp. 71-90.
- Webster, G. D., and J. W. Crosby. 1982. Stratigraphic investigation of the Skagit/Hanford Nuclear Project. *In* Skagit/Hanford Nuclear Project Preliminary Safety Analysis Report. Puget Sound Power and Light Company. 5:appendix 2R:35.

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