DOE/RL-2002-39
Rev. 0

Standardized Stratigraphic Nomenclature for Post-Ringold-Formation Sediments Within the Central Pasco Basin

United States
Department of Energy

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P.O. Box 550, Richland, Washington 99352

EXECUTIVE SUMMARY

A consistent, standardized stratigraphic nomenclature for post-Ringold-Formation (late Pliocene to Quaternary) deposits is needed to support hydrogeologic characterization and performance-assessment modeling at the Hanford Site. Descriptions for post-Ringold sedimentary deposits within the central Pasco Basin have evolved significantly since the first geologic studies of the Hanford Site over 50 years ago. Stratigraphic information has naturally become more refined with additional data and changing interpretations based on dozens of excavations and hundreds of boreholes at Hanford. Unfortunately, much of the stratigraphic nomenclature has been developed for site-specific projects without regard for the regional geologic setting. Because of lithologic heterogeneity within post-Ringold deposits, nomenclature developed for one site-specific area commonly does not correlate with other areas.

This document defines a standardized stratigraphic nomenclature for post-Ringold deposits based on regional stratigraphic and sedimentary facies observations. Sedimentary deposits disconformably overlying the Ringold Formation are differentiated on the basis of grain size, sedimentary structure, color, roundness, sorting, fabric, cementation, and/or relative basalt content. A total of three post-Ringold stratigraphic units are presented: the Cold Creek unit (or CCU) (formerly the Plio-Pleistocene unit), the Hanford formation, and Holocene deposits.

The CCU is divided into five facies within the central Pasco Basin, which developed after regional incision of the Ringold Formation and prior to Ice Age flooding. The CCU facies include the following: (1) fine-grained, laminated to massive (f[lam-msv]); (2) fine- to coarse-grained, calcium-carbonate cemented (f-c[calc]); (3) coarse-grained, multilithic (c[ml]); (4) coarse-grained, angular, basaltic (c[ang-bas]); and (5) coarse-grained, rounded, basaltic (c[rnd-bas]). Environments of deposition for these facies are interpreted as overbank-eolian, calcic paleosol, mainstream alluvial, colluvial, and sidestream alluvial, respectively. The CCU facies may grade laterally and vertically, as well as intercalate with one another.

Pleistocene-age, cataclysmic flood deposits (Hanford formation) are classified into 11 lithofacies (Fm, Fl, Sm, Sr, Sh(f), Sh(c), Sp, St, Gm, Gh, and Gp) based on grain size and sedimentary structure. Various combinations of these facies can be grouped into three facies associations (gravel-dominated [GD], sand-dominated [SD], and interbedded sand- and silt-dominated [ISSD]), which represent deposition within high- to low-energy flood environments, respectively. Within the Hanford formation, these facies associations grade vertically as well as laterally into one another, and occasionally recur within a flood sequence.

Holocene deposits consisting of thin sequences of unconsolidated sediments that have locally accumulated since cataclysmic flooding are divided into the following seven lithofacies: (1) fine-grained, massive, well sorted [f(msv-ws)]; (2) fine-grained, weakly laminated, poorly sorted [f(lam-ps]; (3) medium-grained, cross-bedded, well-sorted [m(xbed-ws)]; (4) coarse-grained, rounded [c(rnd)]; (5) coarse-grained, angular, basaltic ([c(ang-bas)]; (6) coarse- to fine-grained, massive, matrix supported [c-f(msv-ms)]; and (7) tephra (t).

Interpreted depositional environments for these lithofacies are eolian loess, slopewash, eolian dune sand, alluvium, colluvium (i.e., talus), landslide/debris flow, and volcanic ashfall, respectively. Appendix A contains figures and photographs that relate to the information discussed in the text, and Appendix B shows additional outcrop exposures of the Hanford formation within the Pasco Basin.

The U.S. Department of Energy, Richland Operations Office and U.S. Department of Energy, Office of River Protection request that the nomenclature presented herein be used as the standard in all geologic/geohydrologic discussions until such time as a new standard is recognized.

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METRIC CONVERSION CHART

Into Metric Units			Out of Metric Units		
If You Know	*Multiply By*	*To Get*	*If You Know*	*Multiply By*	*To Get*
Length			**Length**		
inches	25.4	millimeters	millimeters	0.039	inches
inches	2.54	centimeters	centimeters	0.394	inches
feet	0.305	meters	meters	3.281	feet
yards	0.914	meters	meters	1.094	yards
miles	1.609	kilometers	kilometers	0.621	miles
Area			**Area**		
sq. inches	6.452	sq. centimeters	sq. centimeters	0.155	sq. inches
sq. feet	0.093	sq. meters	sq. meters	10.76	sq. feet
sq. yards	0.836	sq. meters	sq. meters	1.196	sq. yards
sq. miles	2.6	sq. kilometers	sq. kilometers	0.4	sq. miles
acres	0.405	hectares	hectares	2.47	acres
Mass (weight)			**Mass (weight)**		
ounces	28.35	grams	grams	0.035	ounces
pounds	0.454	kilograms	kilograms	2.205	pounds
ton	0.907	metric ton	metric ton	1.102	ton
Volume			**Volume**		
teaspoons	5	milliliters	milliliters	0.033	fluid ounces
tablespoons	15	milliliters	liters	2.1	pints
fluid ounces	30	milliliters	liters	1.057	quarts
cups	0.24	liters	liters	0.264	gallons
pints	0.47	liters	cubic meters	35.315	cubic feet
quarts	0.95	liters	cubic meters	1.308	cubic yards
gallons	3.8	liters			
cubic feet	0.028	cubic meters			
cubic yards	0.765	cubic meters			
Temperature			**Temperature**		
Fahrenheit	subtract 32, then multiply by 5/9	Celsius	Celsius	multiply by 9/5, then add 32	Fahrenheit
Radioactivity			**Radioactivity**		
picocuries	37	millibecquerel	millibecquerels	0.027	picocuries

ACKNOWLEDGEMENTS

The principal author of this report, Bruce Bjornstad, would like to thank other contributors from the Pacific Northwest National Laboratory, including George Last, Duane Horton, and Steve Reidel. Additional contributors and reviewers included Karl Fecht (BHI), Gary Smith (University of New Mexico), Kevin Lindsey (Kennedy/Jenks Consultants, Inc.), and Dave Myers (CHG). Editorial support was provided by BHI editor Michelle Riffe and programmatic support was supplied by Moses Jarayssi (BHI) and Mike Thompson (DOE/RL).

The nomenclature presented in this report is the results of recommendations made during a multi-organizational Standardized Post-Ringold Formation Stratigraphic Nomenclature Workshop held in Richland, Washington on March 26, 2002. Workshop participants included: Bruce Bjornstad (Chair), Christopher Murray, (Moderator), David Weekes, Kevin Singleton, Mike Thompson, George Last, Kevin Lindsey, Karl Fecht, Gary Smith, Marc Wood, John Silko, Stan Sobczyk, Bruce Williams, Fred Mann, Dave Myers, and Paul Thorne.

1.0 INTRODUCTION

A standardized, stratigraphic nomenclature is needed to support hydrogeologic characterization and modeling. Specifically, this standardized nomenclature is needed for consistent identification and assignment of hydrogeologic properties for stratigraphic units that are modeled across the Hanford Site. While the nomenclature of the formalized Ringold Formation is more straightforward because of facies continuity, the nomenclature for post-Ringold strata is more complex. Subdivision of the Hanford formation, in particular, is problematic because of a general lack of lateral continuity of facies and limited marker beds on which to perform correlation. The result has been an inconsistent and constantly changing nomenclature that lacks regional stratigraphic context. The purpose of this document is (1) to develop a post-Ringold stratigraphy that integrates all aspects of the depositional system, and (2) to present standardized nomenclature that can be applied consistently across the Hanford Site and central Pasco Basin.

Stratigraphic terminology for the suprabasalt sediments within the central Pasco Basin (Figure A-1) has evolved significantly since the 1940s when geologic studies at the Hanford Site first began. Only three post-basalt units were initially identified: recent alluvium, terrace deposits, and the Ringold Formation (Parker and Piper 1949) (Figure A-2).

Since that time, stratigraphic terminology has evolved as characterization of the subsurface became more important to waste-disposal operations and siting studies (Newcomb and Strand 1953; Newcomb 1958; Brown 1959, 1960, 1970; Tallman et al. 1979, 1981; Myers and Price 1979; Webster and Crosby 1982; Bjornstad 1984, 1990; DOE 1984, 1988; Last et al. 1989; Lindsey and Gaylord 1990; Lindsey 1991, 1992, 1995; Lindsey et al. 1992a, 1992b, 1994a, 1994b; Connelly et al. 1992a, 1992b; Slate 1996, 2000; Reidel and Horton 1999; Johnson et al. 1999; Williams et al. 2000; Wood et al. 2000, 2001). These studies, while helping to increase understanding of the geology of the Pasco Basin, have led to differences in interpretation and stratigraphic nomenclature that frequently vary from site to site.

Post-Ringold Formation deposits within the central Pasco Basin are late Pliocene to Holocene in age. Initially, the upper age limit for the fluvial-lacustrine Ringold Formation was assigned as middle to late Pleistocene (Newcomb 1958), but as the level of information increased, it was later recognized as late Pliocene on the basis of fossil evidence (Gustafson 1978), paleomagnetic measurements (DOE 1988), and age dating of tephra (Lindsey 1996). With the general acceptance of an Ice Age flood(s) hypothesis for the Channeled Scabland and associated deposits came the recognition that much of the Hanford Site was covered by a thick blanket of glaciofluvial sediments (i.e., the Hanford formation). It was also recognized that another distinct sequence of sediments lay between the Ringold and glaciofluvial sediments. Various names for this intermediate stratigraphic sequence have included "caliche," "early Palouse soil," "pre-Missoula gravels," and "Plio-Pleistocene unit."

The nomenclature for the oldest suprabasalt sediments of gravel, sand, silt, and clay within the Pasco Basin was previously established as the Miocene to Pliocene Ringold Formation (Newcomb 1958; Myers and Price 1979; Tallman et al. 1979, 1981; DOE 1988;

Delaney et al. 1991; Lindsey 1991, 1992, 1995, 1996; Lindsey et al. 1992a, 1992b, 1994a, 1994b). The fluvial-lacustrine Ringold Formation represents the predominant unit within the saturated zone at the Hanford Site. However, because of the need to understand and model moisture and contaminant movement within the vadose zone, as well as the saturated zone, it is becoming increasingly important to understand the characteristics of the post-Ringold Formation units. This is particularly true for the Ice Age flood deposits, which contain the majority of contaminants from waste disposal operations at Hanford and is the source for most of the groundwater contamination.

This document describes the post-Ringold Formation units and presents a standardized stratigraphic nomenclature based on our current understanding of the regional stratigraphic relationships of these units.

2.0 METHODOLOGY

Appendix A includes the figures that are referenced throughout the following text. The stratigraphic nomenclature proposed in this document is based on a large database consisting of geophysical logs, drill cuttings, and cores from hundreds of boreholes, as well as a number of surface exposures within the central Pasco Basin and vicinity (Appendices A and B). The data provide the basis for understanding heterogeneity and constructing the conceptual geohydrologic model.

Stratigraphic units are identified using a combination of physical and chemical properties. Physical properties useful to differentiate units include geophysical (e.g., natural gamma) response, lithologic variations in grain size, sorting, color, sedimentary fabric, and primary and secondary structures, as well as other bedding characteristics (Table 1). Chemical properties used to distinguish among stratigraphic units include mineralogy, and secondary mineralization and cementation via interaction with groundwater and/or pedogenesis. Useful methods for dating stratigraphic units include tephrochronoloy and paleomagnetism (DOE 1988, Baker et al. 1991).

The most useful criterion used to distinguish sedimentary deposits is grain size. The modified Folk-Wentworth classification scheme (Folk 1968, Wentworth 1922) used at the Hanford Site is shown in Figure A-3. Accordingly, sediments can be classified into one of 17 classes shown in the ternary diagram in Figure A-3.

In addition to reviewing the existing literature related to post-Ringold Formation stratigraphy within the Pasco Basin, the views of employed Hanford geoscientists were solicited in the preparation of this report. This report is the culmination of several review cycles, as well as a workshop focused on post-Ringold Formation stratigraphic nomenclature held in the spring of 2002.

Table 1a. Characteristics of Post-Ringold Formation Units Within the Central Pasco Basin. (2 Pages)

Post-Ringold Unit	Lithofacies or Facies Association	Abbreviation[1]	Epoch	Previously Documented	Principal Lithology (Folk Classification)	Subordinate Lithology (Folk Classification)
Holocene Deposits (HD)	Fine-Grained, Massive, Well-Sorted	f(msv-ws)	Holocene	Baker et al. (1991), Busacca and McDonald (1994)	**Fine sand and silt (sM, mS)**	
	Fine-Grained , Weakly Laminated, Poorly Sorted	f(lam-ps)	Holocene	DOE (1988)	Silty sand to sandy silt with pebbles to cobbles (gmS, gsM, mS, sM, mgS, sgM)	
	Medium-Grained, Cross-Bedded, Well-Sorted	m(xbed-ws)	Holocene	DOE (1988, Figure 1.1-8), Gaylord et al. (1991), Gaylord and Stetler (1994), Smith (1992), Fayer et al. (1999)	**Medium sand (S)**	
	Coarse-Grained , Rounded	c(rnd)	Holocene	DOE (1988, Figure 1.1-8)	Sandy gravel to silty sandy gravel (sG, msG)	Gravelly sand (gS), sand (S), muddy sand (mS), sandy mud (sM)
	Coarse-Grained, Angular, Basaltic	c(ang-bas)	Holocene	DOE (1988)	Gravel, sand, and silt (G, sG, msG, smG)	
	Coarse- to Fine-Grained, Massive, Matrix-Supported	c-f(msv-ms)	Holocene	Shuster and Hays (1984), Lewis (1985), DOE (1988, Figure 1.1-8)	Clay to Gravel (mG, smG, msG, gM, sgM, gsM, mgS, gmS)	
	Tephra	t	Holocene	Wilcox (1965), Smith et al. (1977), Westgate and Evans (1978), Mehringer et al. (1984), Mullineaux (1986), DOE (1988), Baker et al. (1991), Sarna-Wojcicki and Davis (1991)	Silt to fine sand (mS, sM)	
Hanford Formation (HF)	Interbedded Sand- to Silt-Dominated	ISSD	Pleistocene	Touchet beds (Flint 1938, Bretz et al. 1956, Carson et al. 1978, Myers and Price 1979, Waitt 1980, Bjornstad 1980, Tallman et al. 1979, 1981, DOE 1988); slackwater flood facies (Moody 1987;Lindsey et al. 1992b; Connelly et al. 1992a; Last et al. 1989; Smith 1993); silt-dominated flood facies (Lindsey et al. 1992a, 1994b, Connelly et al. 1992a) silty flood facies (Lindsey et al. 1994a), and rhythmite flood facies (Baker et al. 1991)	**Graded beds** of coarse sand (S) to silt (M)	Thin, weakly developed paleosols
	Sand-Dominated	SD	Pleistocene	Transitional sand facies (Reidel et al. 1992, Fecht and Weekes 1996); plane-laminated sand facies (Baker et al. 1991); sand-dominated flood facies (Lindsey et al. 1992a, 1992b, 1994a, 1994b, Connelly et al. 1992a, 1992b)	Fine- to coarse-grained sand (S)	Lenses of pebbly sand (gS), silty fine sand (mS), fine sandy silt (sM); thin, weakly developed paleosols

Table 1a. Characteristics of Post-Ringold Formation Units Within the Central Pasco Basin. (2 Pages)

Post-Ringold Unit	Lithofacies or Facies Association	Abbreviation[1]	Epoch	Previously Documented	Principal Lithology (Folk Classification)	Subordinate Lithology (Folk Classification)
	Gravel-Dominated	GD	Pleistocene	Pasco gravels (Brown 1970; Myers and Price 1979; Tallman et al. 1979, 1981; DOE 1984, 1988), Missoula flood gravels (Webster and Crosby 1982), coarse-grained main-channel flood facies (DOE 1988, Last et al. 1989), coarse-grained flood gravels (Moody 1987, Baker et al. 1991), and gravel-dominated flood facies (Lindsey et al. 1992a, 1992b, 1994b, Connelly et al. 1992a, 1992b)	Sandy gravel (sG) to silty sandy gravel (msG)	Lenses and sheets of pebbly sand (gS); fine- to coarse-grained sand (S)
Cold Creek Unit (CCU)	Fine-Grained, Laminated to Massive	f(lam-msv)	Late Pliocene	Palouse soil (Brown 1959, 1960); early "Palouse" soil (Brown 1970, Tallman et al. 1979, DOE 1988, Bjornstad 1990, Delaney et al. 1991, Lindsey et al. 1992b); stratified fines (Lindsey et al. 1994a); part of the "locally derived subunit" of Plio-Pleistocene unit (Slate 2000); H/PPl(?) (Lindsey et al. 2000, Wood et al. 2001); Hf/PPu(?) (Wood et al. 2000)	Fine sand, silt, and/or clay (S, mS, sM, M)	Thin, weakly developed paleosols
	Coarse- to Fine-Grained, Carbonate-Cemented	c-f(calc)	Late Pliocene	Caliche (Brown 1959); pedogenic calcrete facies (DOE 1988); calcic paleosol (Bjornstad 1990, Lindsey et al. 1992b); calcic sand and gravel (Lindsey et al. 1994a); overbank facies (Slate 1996), and part of the "locally derived subunit" (Lindsey et al. 1994b, Slate 2000) of the Plio-Pleistocene unit	$CaCO_3$ cemented clay, silt, sand, and/or gravel (msG, smG, gmS, mgS, mS, gsM, sgM, gM, sM, M)	Intercalated beds of noncalcareous silt, sand, and gravel (msG, smG, gmS, mgS, mS, gsM, sgM, gM, sM, M)
	Coarse-Grained, Multilithic	c(ml)	Late Pliocene	Pre-Missoula Flood Gravels (Webster and Crosby 1982); Pre-Missoula gravels (Delaney et al. 1991, Lindsey et al. 1992b, Williams et al. 2000); mainstream river gravel (Lindsey et al. 1994); "distantly derived subunit" of Plio-Pleistocene unit (Slate 2000)	Sandy gravel (sG) to silty sandy gravel (msG)	Light gray to white, well sorted, medium- to coarse-grained sand (S) to pebbly sand (gS)
	Coarse-Grained, Angular, Basaltic	c(ang-bas)	Late Pliocene	None	Gravel with sand and silt (G, sG, msG, smG, gS, mgS, gmS)	Calcic soils
	Coarse-Grained, Rounded, Basaltic	c(rnd-bas)	Late Pliocene	Sidestream alluvial facies (DOE 1988), channel facies (Slate 1996), and "locally derived subunit" (Slate 2000) of the Plio-Pleistocene unit	Gravel with sand and silt (sG, msG, smG, gS, mgS, gmS)	Calcic soils

Table 1b. Characteristics of Post-Ringold Formation Units Within the Central Pasco Basin. (2 Pages)

Post-Ringold Unit	Lithofacies or Facies Association	Depositional Process	Depositional Environment/Spatial Distribution	Associated Deposits	Typical Sequence Thickness	Matrix color	% Basalt (Gravel Fraction/Sand Fraction)
Holocene Deposits (HD)	Fine-Grained, Massive, Well-Sorted	Eolian	Loess deposited in upland areas and lee (north) sides of ridges	Ashfall, slopewash	Few meters or less	**Pale brown**	NA/<10
	Fine-Grained, Weakly Laminated, Poorly Sorted	Colluvial	Slopewash development along bases of ridges around basin	Ashfall, loess, landslide, sidestream alluvium	Few meters or less	Pale brown to light gray	100/<10
	Medium-Grained, Cross-Bedded, Well-Sorted	Eolian	Dune sand deposited in high-wind areas in lowlands of central basin	Ashfall, alluvium	Few meters or less	Light to dark gray	NA/5-100
	Coarse-Grained, Rounded	Fluvial	Alluvium deposited along Columbia River and ephemeral sidestream channels	Dune sand, slopewash, ashfall	Few meters or less	Brownish gray to gray	20-40/<10
	Coarse-Grained, Angular, Basaltic	Colluvial	Talus development along bases of steep ridges and ridge flanks	Landslide	Few meters or less	Brown to gray	95-100/50-75
	Coarse- to Fine-Grained, Massive, Matrix-Supported	Mass Wasting	Landslide and debris flow deposits on north sides of some ridges and White Bluffs along Columbia River	Slopewash, talus, dune sand	Tens of meters or less	Variable depending on source of slide	Variable depending on source of slide
	Tephra	Volcanic	Ashfall deposited in topographic depressions and other lowland areas protected from wind and running water	Loess, slopewash, dune sand; fine-grained alluvium	Few centimeters (Glacier Peak) to 1 m (3.3 ft) (Mt. Mazama)	**White to light gray**	0
Hanford Formation (HF)	Interbedded Sand- to Silt-Dominated (ISSD)	Ice-Age Cataclysmic Flood	Slackwater deposition within backflooded tributary valleys and valley margins during Ice Age cataclysmic flooding	Frequently grades downward into facies association SD; ashfall (Mount St. Helens "S"), dune sand, slopewash, loess, and/or weak paleosols may occur at tops of some beds	**Rhythmite sequences** range from 3 to 30 m (9.8 to 98.4 ft)	Brownish gray to light gray	NA/5-30
	Sand-Dominated (SD)	Ice-Age Cataclysmic Flood	Moderate to high-energy flood deposition in areas marginal to high-energy flood currents including southern half of Cold Creek bar	May grade upward into facies association SSD; ashfall, dune sand, loess and/or weak paleosols may occur at tops of some beds	Usually ≥10 m (≥32.8 ft); up to 100 m (328 ft) beneath Cold Creek bar	Brownish gray to olive gray	50-90/30-60

Table 1b. Characteristics of Post-Ringold Formation Units Within the Central Pasco Basin. (2 Pages)

Post-Ringold Unit	Lithofacies or Facies Association	Depositional Process	Depositional Environment/Spatial Distribution	Associated Deposits	Typical Sequence Thickness	Matrix color	% Basalt (Gravel Fraction/Sand Fraction)
	Gravel-Dominated (GD)	Ice-Age Cataclysmic Flood	High-energy flood deposits within and along cataclysmic flood channels	May grade upward or be interbedded with facies association SD	Few meters to tens of meters	Dark gray, brownish gray, to olive gray	50-90/30-60
Cold Creek Unit (CCU)	Fine-Grained, Laminated to Massive	Fluvial and/or Eolian	Fluvial overbank to eolian deposits; mostly limited to beneath 200 West Area	May transition laterally or be interstratified with other Cold Creek unit facies	0 to 15 m (0 to 49.2 ft)	**Buff, pale to dark brown**	NA/<5
	Coarse- to Fine-Grained, Carbonate-Cemented	Calcic Paleosol Sequence	Residual deposits with some localized accumulation representing long period of weathering following downcutting of the Ringold Formation; mostly limited to beneath 200 West Area; thicker and rises toward surface in northern 200 West Area; may be equivalent to caliche cap atop Ringold Formation along White Bluffs	May transition laterally or be interstratified with other Cold Creek unit facies	0 to 15 m (0 to 49.2 ft)	**White to light gray**	25-90/10-75
	Coarse-Grained, Multilithic	Mainstream Fluvial	Alluvial deposits from ancestral Columbia River found in central Pasco Basin near Southeast Anticline and southeast of Gable Gap (?)	May transition laterally or be interstratified with other Cold Creek unit facies	Few meters to tens of meters	Light gray to olive gray, **"whitish" or "bleached" clast coatings**	30-50/≤10
	Coarse-Grained, Angular, Basaltic	Colluvial	Talus and slopewash deposited along ridge flanks around margins of Pasco Basin	May transition laterally or be interstratified with other Cold Creek unit facies	0 to 10 m (0 to 32.8 ft)	**Dark gray to black**	95-100/50-75
	Coarse-Grained, Rounded, Basaltic	Sidestream Fluvial	Alluvial deposits of ephemeral streams feeding into Pasco Basin, including ancestral Cold Creek	May transition laterally or be interstratified with other Cold Creek unit facies	0 to 20 m (0 to 65.6 ft)	**Dark gray to black**	75-100/50-75

Table 1c. Characteristics of Post-Ringold Formation Units Within the Central Pasco Basin. (2 Pages)

Post-Ringold Unit	Lithofacies or Facies Association	Gravel Roundness	Sorting	Structure	Calcium Carbonate (wt%)	Fabric
Holocene Deposits (HD)	Fine-Grained, Massive, Well-Sorted	NA	**Moderately to well sorted**	**Massive**	0-10	NA
	Fine-Grained, Weakly Laminated, Poorly Sorted	Angular to subrounded	**Poorly to moderately sorted**	**Weakly laminated/bedded**	0-10	NA
	Medium-Grained, Cross-Bedded, Well-Sorted	NA	**Moderately to well sorted**	**Cross-laminated to cross-bedded**	0-10	NA
	Coarse-Grained, Rounded	**Subrounded to well rounded**	Moderately to well sorted	**Stratified and bedded**	0-5	Clast-supported, imbricated
	Coarse-Grained, Angular, Basaltic	**Angular to subangular**	Poor to moderately sorted	Massive to steeply inclined primary bedding	0-5	Clast- to matrix-supported
	Coarse- to Fine-Grained, Massive, Matrix-Supported	Variable depending on source of slide	Very poor to moderately sorted	**Slumped and rotated blocks; chaotic and irregular bedding in landslides; debris flows are massive and matrix-supported**	Variable depending on source of slide	Clast- to matrix-supported
	Tephra	NA	**Well to very well sorted**	Massive to weakly laminated	0	NA
Hanford Formation (HF)	Interbedded Sand- to Silt-Dominated	NA	Well sorted	Rhythmic graded beds few cm to meter thick, **horizontal to climbing ripple laminations;** generally no cut and fill	2-10	NA
	Sand-Dominated	Subangular to well rounded	Moderate to well sorted	**Low-angle horizontal laminations;** normal and reverse gradations; occasional cut and fill	2-5	NA
	Gravel-Dominated	Subangular to well rounded	Poor to moderately sorted	Horizontal to **large-scale planar-tabular (i.e., foreset) cross-bedding;** cut and fill	2-5	Clast- to matrix-supported; occasional **open work**

Table 1c. Characteristics of Post-Ringold Formation Units Within the Central Pasco Basin. (2 Pages)

Post-Ringold Unit	Lithofacies or Facies Association	Gravel Roundness	Sorting	Structure	Calcium Carbonate (wt%)	Fabric
Cold Creek Unit (CCU)	Fine-Grained, Laminated to Massive	NA	**Well sorted to very well sorted**	Laminated and bedded to massive	5-20	NA
	Coarse- to Fine-Grained, Carbonate-Cemented	Angular to rounded	**Very poor to moderate**	Massive to **platy, bioturbated, rhizoliths**	6-67 (Slate 2000)	Gravel component usually matrix supported; hackly; sometimes "popcorn-like"
	Coarse-Grained, Multilithic	**Subrounded to well rounded**	Well sorted	Stratified and bedded	0-5	Clast-supported, imbricated
	Coarse-Grained, Angular, Basaltic	**Angular to subangular**	Poor to very poor	Massive to steep inclined bedding	0-30	Clast-supported
	Coarse-Grained, Rounded, Basaltic	**Subangular to subrounded**	Poor to moderately sorted	Massive to bedded and laminated	0-30	Clast-supported

NA = not applicable

Table 1d. Characteristics of Post-Ringold Formation Units Within the Central Pasco Basin. (2 Pages)

Post-Ringold Unit	Lithofacies or Facies Association	Induration	Natural-Gamma Response	Other Characteristics	Reference Localities
Holocene Deposits (HD)	Fine-Grained, Massive, Well-Sorted	Weakly to moderately cohesive/compact	NA		Areas above 366 m (1,200 ft) elev. around margins of Pasco Basin, especially on north aspects
	Fine-Grained , Weakly Laminated, Poorly Sorted	Weakly to moderately cohesive/compact	NA		White Bluffs
	Medium-Grained, Cross-Bedded, Well-Sorted	Loose	NA		Dune field west of Ringold Coulee in vicinity of Energy Northwest
	Coarse-Grained , Rounded	Loose	NA		Present Cold Creek, Columbia River, and Yakima River channels
	Coarse-Grained, Angular, Basaltic	Loose	NA	**Gravel-sized clasts almost exclusively basalt**	Talus cones in Wallula Gap
	Coarse- to Fine-Grained, Massive, Matrix-Supported	Weakly to moderately cohesive/compact	NA	**Associated with hummocky surface topography (landslide) or lobate tongues (debris flow)**	Savage Island, Locke Island Landslide complexes (Schuster and Hays 1994)
	Tephra	Loose	NA	**Powdery and gritty texture; occur as distinct thin white bands**	Dry Creek stream gulley
Hanford Formation (HF)	Interbedded Sand- to Silt-Dominated	Weakly to strongly cohesive/compact	Consistently moderate to high	Micaceous, soft sediment deformation along bed contacts, **clastic dikes** common; matrix-supported erratic cobbles and boulders; where exposed **individual beds can be traced laterally for hundreds of meters or more;** infrequent channeling	Kiona Quarry, Burlingame Canyon
	Sand-Dominated	Loose	Consistently low	**"Salt and pepper"-like appearance;** clastic dikes; soft-sediment deformation along bed contacts; where exposed individual beds can be traced laterally for tens of meters or more; localized minor cut and fill channels; occasional rip-up clasts	Mouth of Johnson Creek, U.S. Ecology, ERDF, Transtate Borrow Pit, Pre-Mix Borrow Pit, Locke Island Landslide complex
	Gravel-Dominated	Loose	Consistently very low	**Basaltic; silt coatings** on gravel clasts; laterally discontinuous beds with **ubiquitous cut and fill channels;** unconsolidated, fine-grained, angular **rip-up clasts** common	Kiona Quarry, Mouth of Ringold Coulee, Lower Smith Canyon Borrow Pit, Transtate Borrow Pit

Table 1d. Characteristics of Post-Ringold Formation Units Within the Central Pasco Basin. (2 Pages)

Post-Ringold Unit	Lithofacies or Facies Association	Induration	Natural-Gamma Response	Other Characteristics	Reference Localities
Cold Creek Unit (CCU)	Fine-Grained, Laminated to Massive	Moderately to very strongly cohesive/compact	**Consistently high**	**Micaceous;** weakly to moderately calcareous	Borehole 299-W10-196, 25 to 32 m (82 to 105 ft) bgs (Freeman-Pollard et al. 1994)
	Coarse- to Fine-Grained, Carbonate-Cemented	**Discrete layers and zones of CaCO3 cement;** Stage I-V carbonate development (predominantly Stage III)	**Erratically low to moderate**	**Highly variable and laterally heterogeneous**	Borehole DH-6, 34.5 to 39.7 m (113 to 130 ft) bgs (Lindsey 1995, Slate 2000)
	Coarse-Grained, Multilithic	Loose to compacted and/or cemented	Consistently low to moderate	**Multilithic** gravels; unaltered to slightly altered, locally carbonate cemented	Boreholes 101 (105 to 153 ft bgs); 103 (31 to 56.4 m [100 to 185 ft] below ground surface); and E-1 (41.2 to 61 m [135 to 200 ft] bgs) (Webster and Crosby 1982)
	Coarse-Grained, Angular, Basaltic	Loose to moderately compacted and/or cemented	Consistently low	**Highly basaltic**	Borehole DH-33, 31 to 34.2 m (102 to 112 ft) bgs (Lindsey 1995)
	Coarse-Grained, Rounded, Basaltic	Loose to moderately compacted and/or cemented	Consistently low	**Highly basaltic**	Borehole DH-22, 16.8 to 37 m (55 to 120 ft) bgs (Bjornstad 1984)

NOTE: Diagnostic features in **bold**.
[1] Descriptors: c = coarse-grained; m = medium-grained; f = fine-grained; g = gravel; s = sand; z = silt; (lam) = laminated; (xbed) = cross-bedded; (msv) = massive; (ml) = multilithic; (bas) = basaltic; (calc) = calcium-carbonate cemented; t = tephra; (ang) = angular; (rnd) = rounded; (ws) = well-sorted; (ps) = poorly sorted; (ms) = matrix-supported.
bgs = below ground surface
ERDF = Environmental Restoration Disposal Facility
NA = not applicable

3.0 POST-RINGOLD FORMATION STRATIGRAPHIC UNITS

Basin-filling units younger than the Ringold Formation within the central Pasco Basin include epiclastic to volcaniclastic sediments of the Cold Creek unit (CCU), the Hanford formation, and Holocene deposits. Among the post-Ringold units, the CCU is further subdivided into five lithofacies. The Hanford formation is divided into 11 lithofacies, which group into three facies associations. Holocene deposits are subdivided into seven lithofacies (Table 1). The basin-wide stratigraphic relationships for the CCU and Hanford formation are shown schematically in Figure A-4. Holocene deposits are relatively thin and, therefore, individual facies cannot be shown at the scale of Figure A-4.

A north-south trending geologic cross-section (shown in Figure A-1) further demonstrates the stratigraphic and facies relations for the CCU and Hanford formation across the western Pasco Basin (Figure A-5).

3.1 COLD CREEK UNIT

The Cold Creek unit (CCU) includes the sedimentary sequence that disconformably overlies the Ringold Formation and underlies cataclysmic flood deposits of the Hanford formation. The CCU includes those deposits formerly referred to as the “Plio-Pleistocene unit” and “pre-Missoula Gravels,” as well as the “early Palouse soil” and “caliche layer” within the 200 West Area. The Cold Creek unit is the proposed new name for these deposits. It became apparent that a different name was needed for the Plio-Pleistocene unit because flood deposits of the Hanford formation possibly extend back to the beginning of the Pleistocene Epoch (Bjornstad et al. 2001); thus, these deposits are apparently late Pliocene age. The CCU seems an appropriate name choice because it is independent of age and geographically describes the unit, which is generally confined to the boundaries of the Cold Creek syncline (Tallman et al. 1981) within the west-central Pasco Basin (Figure A-1). The CCU is not to be confused with the “Cold Creek interbed,” which is an informal, now abandoned, name previously used to describe a sedimentary interbed (Ellensburg Formation) that occurs locally between the Esquatzel and Umatilla Members of the Columbia River Basalt Group (DOE 1988).

The CCU represents deposits that accumulated within the central Pasco Basin during the period between about 2 to 3 million years ago, which brackets two significant geologic events. The older event is a regional base-level drop and subsequent incision of the Ringold Formation (Fecht et al. 1987, DOE 1988). Rapid incision is reflected by the abrupt termination and eroded nature of the Ringold Formation top (Brown 1960, DOE 1988). The younger event is the initiation of Ice Age cataclysmic flooding, at the beginning of the Pleistocene, about 1.5 to 2.5 million years ago (Bjornstad et al. 2001). The CCU unconformably overlies the eroded Ringold Formation. During Ringold time, fluvial-lacustrine deposits filled the Pasco Basin up to an elevation of 275 m (900 ft). This former base level is indicated by a calcic paleosol that developed on top of the Ringold Formation along White Bluffs (Fecht et al. 1987). The calcic paleosol atop the White Bluffs is probably equivalent to a similar facies of the CCU discussed below. For reasons still unclear, accumulation of the Ringold Formation ceased abruptly beginning about 3.4 million years ago, during a period of rapid downcutting and incision by the ancestral Columbia-Clearwater-Salmon River system (Fecht et al. 1987, DOE 1988, Reidel et al. 1994). Incision resulted in the removal of up to 200 m (600 ft) of Ringold Formation sediments from the central portion of the Pasco Basin. Following incision, a new local base level was established at approximately the 100-m (300-ft) elevation at Wallula Gap. At this point, significant fluvial erosion ceased, once again permitting aggradation and backfilling to occur locally on the post-Ringold Formation landscape.

Five CCU facies can be differentiated on the basis of grain size, sedimentary structure, sorting, roundness, fabric, and mineralogic composition. The fives facies and interpreted depositional environment are listed in Table 2.

Table 2. Lithofacies of the Cold Creek Unit.

Lithofacies	Symbol	Environment of Deposition
Fine-grained, laminated to massive	CCUf(lam-msv)	Fluvial-overbank and/or eolian
Fine- to coarse-grained, calcium-carbonate cemented	CCUf-c(calc)	Calcic paleosol
Coarse-grained, multilithic	CCUc(ml)	Mainstream alluvium
Coarse-grained, angular, basaltic	CCU c(ang-bas)	Colluvium
Coarse-grained, rounded, basaltic	CCUc(rnd-bas)	Sidestream alluvium

In the abbreviated symbols for these units (second column in Table 2), the first letter(s) after CCU symbolize general grain size; the letter "f" represents fine-grained and the letter "c" represents coarse-grained lithofacies. This is followed by one or more additional modifying terms, which are diagnostic of the facies being described; modifiers may include sedimentary structure, cementation, roundness, and/or composition. Modifiers include "ml" for multilithic, "bas" for basaltic, "calc" for calcereous, "ang" for angular, and "rnd" for rounded. Characteristics of these different lithofacies in Table 2 are more completely described in Table 1, and general facies distribution within the central Pasco Basin is illustrated in Figure A-6.

The CCU appears to be present beneath most of the central Pasco Basin, except where it was locally stripped away during Pleistocene cataclysmic flooding. Locally, Ice Age flooding removed older sediments and scoured into basalt bedrock, particularly through the central Pasco Basin where the floodwaters were the most active. Around the margins of the basin, however, little or no erosion occurred during flooding. This resulted in an area through the central part of the basin that is void of CCU deposits (Figure A-6). Unlike the other sedimentary units within the Pasco Basin, no volcanic ashfall deposits are known, or have yet to be identified, within the CCU.

3.1.1 Coarse-Grained, Multilithic [CCUc(ml)] Lithofacies

Coarse-grained, multilithic facies of the CCU consist of rounded, quartzose to gneissic, clast-supported pebble- to cobble-size gravel with a quartzo-feldspathic sand matrix (Webster and Crosby 1982, Delaney et al. 1991, Slate 2000). More details on the characteristics of this unit are presented in Table 1. Locally, this facies is distinguished from the often similar-appearing gravelly deposits of the Ringold Formation by its whitish or bleached appearance (Lindsey et al. 1994a), less consolidation, and generally less weathered, including lack of yellow cement coatings on gravel clasts (Webster and Crosby 1982) and higher hydraulic transmissivity. The CCUc(ml) facies may also contain a higher percentage of basalt clasts compared to Ringold gravelly facies. The CCUc(ml) facies is generally restricted to the east-central portion of the Pasco Basin, although a few surface exposures are also scattered around the margins of the basin, such as the Yakima Bluffs (Baker et al. 1991, Lindsey et al. 1994a) (Figure A-7).

3.1.1.1 Historical Perspective. The CCUc(ml) facies is equivalent to the “mainstream river gravel” discussed by Lindsey et al. (1994a), and the “distantly derived subunit” of the Plio-Pleistocene unit reported by Slate (2000). The CCUc(ml) facies is also equivalent to what has been referred to as pre-Missoula flood gravels (Figure A-2), originally described in the subsurface south and east of Gable Mountain by Webster and Crosby (1982). However, since this original work, the use of the term “pre-Missoula (flood) gravels” has been inconsistent and ambiguous. The pre-Missoula flood gravels, as originally defined, included older (late Pliocene? to early Pleistocene) flood deposits distinctly different from the underlying fluvial gravels of the Ringold Formation and overlying flood gravels. Webster and Crosby (1982) differentiated the pre-Missoula flood gravels on the basis of a more quartz-feldspar-rich composition (<50% basalt in gravel), as well as better sorting and rounding compared to the overlying flood gravels (>50% basalt in gravel). Compared to the underlying Ringold Formation gravels, the pre-Missoula flood gravels are less altered and weathered and display only thin or no cement and/or weathering rinds. These deposits were interpreted as the earliest deposits from Ice Age floods. However, floodwaters from most (or all) of the early floods impacting the central Pasco Basin were also probably from glacial Lake Missoula, so the name “pre-Missoula” flood gravels appears to be a contradiction.

Since Webster and Crosby’s (1982) original work, the name “pre-Missoula flood gravels” has evolved to “pre-Missoula gravels” (Delaney et al. 1991, Lindsey 1996, Williams et al. 2000), which have taken on a different meaning than was originally intended. More recent studies have interpreted these deposits as fluvial gravels associated with the ancestral Columbia-Snake River system that pre-date the Ice Age floods (Lindsey et al. 1994a). To avoid the cloudy terminology and confusion of the past, we suggest eliminating the term “pre-Missoula (flood) gravels” and recommend using the term “coarse-grained, multilithic facies,” abbreviated as CCUc(ml).

3.1.1.2 Discussion. The CCUc(ml) facies is generally restricted to the east-central portion of the Pasco Basin and is disconformable with the underlying Ringold Formation. The CCUc(ml) facies represent deposition by the ancestral Columbia-Clearwater-Salmon River system, following a period of downcutting into the Ringold Formation and base-level stabilization. Also, during or soon after regional incision, the Snake River was captured by the Columbia River (DOE 1988), which may have contributed detritus to the CCUc(ml) lithofacies. The CCUc(ml) facies may be preserved as a gravel train, which defines the former course of the Columbia River southeastward through Gable Gap (Fecht et al. 1987; Figure A-6). This is indicated by a sequence of coarse-grained, pre-Ice Age flood, "reworked Ringold" deposits that fill a well-defined paleochannel incised into the Ringold Formation (Williams et al. 2000). Narrow through Gable Gap, CCUc(ml) facies widen across the east-central portion of the Hanford Site. The base of the CCU fluvial channel southeast of Gable Gap is at an elevation of approximately 90 m (300 ft), which is consistent with the established local base level for the Pasco Basin at Wallula Gap. In places, some or all the CCUc(ml) facies were subsequently removed during Ice Age flooding.

Possible CCUc(ml) facies at the base of the suprabasalt sequence has recently been recognized in the vicinity of the B-BX-BY waste management area (Wood et al. 2000), which is in the northern portion of Hanford's 200 East Area. Previous studies in this area assigned the entire suprabasalt sequence to the glaciofluvial, Pleistocene-age Hanford formation. However, locally centered over the B Tank Farm is an intervening fine-grained layer (up to 10 m [35 ft] thick) that is composed of predominantly weathered silt and fine sand (designated the Hf/PPu silt layer in Wood et al. [2000], and the H/PP/R?u layer in Lindsey et al. [2001]). Coarse-grained flood deposits of the Hanford formation typically do not contain fine-grained intervals more than 1 m (3.3 ft) thick; therefore, this fine-grained bed is believed to be equivalent to the CCU, with the overlying flood gravels representing the base of the Hanford formation. If this is the case, then the underlying gravels are equivalent to either CCUc(ml) facies, or possibly the Ringold Formation (Lindsey et al. 2001). Away from B Tank Farm, the fine-grained layer is absent and the contact between the CCUc(ml) facies, and the overlying flood gravels is difficult to ascertain without the intervening fine-grained layer. More study needs to be conducted to determine if geochemical signatures exist for the different coarse-grained units to aid in their differentiation.

3.1.2 Coarse- to Fine-Grained, $CaCO_3$-Cemented [CCUc-f(calc)] Lithofacies

The CCUc-f(calc) facies consist of basaltic to quartzitic gravels, sands, silt, and clay that are cemented with one or more layers of secondary, pedogenic $CaCO_3$ (Table 1). The upper boundary is usually sharp and distinct in contrast to the lower boundary, which is commonly gradational and overprinted onto the underlying Ringold Formation within the west-central Pasco Basin. The concentration of $CaCO_3$ within the CCUc-f(calc) facies is generally 20 to 30 wt% but can range from 5 to 70 wt%. Diagnostic features of the CCUc-f(calc) facies include (1) advanced induration, (2) white color, (3) presence of pedogenic structures (e.g., root traces, animal burrows, or soil horizonation), as well as an erratic geophysical log (i.e., natural gamma) response (DOE 1988, Bjornstad 1990).

The overall thickness of the CCUc-f(calc) facies beneath the 200 West Area is highly variable but is generally less than 10 m (30 ft) (Figure A-8). Within the southern part of 200 West Area, the top of the CCUc-f(calc) facies dips to the southwest (Figure A-9) about 1 degree (Wood et al. 2001).

3.1.2.1 Historical Perspective. The CCUc-f(calc) facies in the 200 West Area represents a highly weathered paleosurface that developed unconformably on top of the Ringold Formation (Brown 1959, 1960) following a period of downcutting and degradation within the central Pasco

Basin. Other names used to describe this facies have included "caliche" (Brown 1959) and "calcrete" (DOE 1988) (Figure A-2). The CCUc-f(calc) facies was one of two lithofacies of the Plio-Pleistocene unit reported in DOE (1988).

3.1.2.2 Discussion. Root traces, animal borrows, and other relict soil structures support a pedogenic origin for the $CaCO_3$; however, Slate (1996, 2000) has suggested that some $CaCO_3$ precipitation may be locally associated with paleo-groundwater levels. The $CaCO_3$ commonly forms in arid to semi-arid soils from near-surface evaporation of calcium-bearing meteoric water; soil microbial activity may be a major contributor to $CaCO_3$ precipitation (Ferris et al. 1994).

Calcic soils are classified and subdivided into several morphogenetic stages (Gile et al. 1966; Machette 1985; Rettalack 1988, 1990) (Figure A-10). Characteristic features associated with calcic soil development in the CCUc-f(calc) facies range from a few small calcareous filaments (Stage I) to a meter or more of massive carbonate-plugged horizons with >50 wt% $CaCO_3$ (Stage IV-V). Where no significant aggradation or degradation has occurred, the relative amount of $CaCO_3$ present can provide a rough approximation for the duration of soil development (Slate 1996, 2000). Stage I calcic soils may form in as little as a few tens of thousands of years, while advanced stages of calcic soil development (≥Stage IV) may require a million years or more to develop (Figure A-10). Some examples of surface analogs for calcic soil development in the region, ranging from calcic soil Stage II-V, are presented in Figure A-11. Calcic paleosols of the CCU beneath the 200 West Area are classified as Stage I to V, with Stage III being most common (Slate 2000).

Considerable variability may exist internally within the CCUc-f(calc) facies because of natural heterogeneity inherent in soils and soil-forming processes, which vary under different physical, chemical, and biological conditions (e.g., moisture, grain size, aspect, mineralogy, bioturbation, and microbial activity). An additional complicating factor is that the land surface during late Pliocene time was undergoing changes locally via fluvial and eolian activity, which resulted in variable rates of aggradation, degradation, and soil development (Bjornstad 1984, 1990; DOE 1988; Slate 1996, 2000; Wood et al. 2001). For example, in the southern portion of the 200 West Area, only a single Stage IV-V calcic soil (Figure A-10) is present, may be only 1 m (3.3 ft) or less thick, and developed directly on top of the eroded surface of the Ringold Formation (Figures A-5 and A-12). The $CaCO_3$ overprint is superimposed onto a variety of rock types, including silt, quartz-feldpsar-rich sand and gravel, and locally derived basaltic sand and gravel (Slate 1996, 2000; Lindsey et al. 2000). To the north, on the other hand, up to five separate calcic horizons are present (Slate 1996, 2000) in a sequence up to 15 m (50 ft) thick and mostly developed in post-Ringold fluvial to eolian parent materials (Figure A-5). Multiple, calcic-rich zones are separated by relatively noncalcareous, uncemented sand, silt and locally indigenous, basaltic sand and/or gravel (Bjornstad 1990; Slate 1996, 2000; Wood et al. 2001). Multiple calcic horizons within the CCUc-f(calc) facies indicate that local aggradation occurred periodically between periods of soil development.

Two areas where the land surface did not undergo appreciable aggradation or degradation during CCU time, allowing for the development of a well-developed calic paleosol sequence, were beneath the 200 West Area and on White Bluffs (see Figure A-1). The White Bluffs are an erosional remnant of the late Ringold Formation, preserved under the protective calcified cap, that represents the former base level toward the end of Ringold time. Calcic soil development in these two areas may have begun around the same time, but the White Bluffs calcic paleosol is presently still undergoing pedogenesis (Figure A-13). Development of the calcic paleosol in the 200 West Area, on the other hand, probably terminated abruptly in the late Pliocene, soon after it was deeply buried beneath younger deposits of the CCU, followed by cataclysmic flood deposits of the Hanford formation.

Because the relief on top of CCUc-f(calc) facies in the 200 West Area (Figure A-9) is significantly greater than that of underlying Ringold units, at least some of the relief must be nontectonic (i.e., floodplain sloping toward valley axis) (Wood et al. 2001); although some of the relief on top of the CCUc-f(calc) may be associated with deformation within the Cold Creek syncline. The added relief on top of the CCUc-f(calc) facies probably reflects paleotopography that existed following post-Ringold incision and during the subaerial weathering of the eroded Ringold surface (Slate 1996, 2000). Therefore, it appears that during development of the CCUc-f(calc) facies, the land surface sloped gently southwest, toward the axis of the Cold Creek syncline. This explains the topographic relief on top of the calcic paleosol observed in Figures A-5 and A-9, and is consistent with the general change in thickness and relative amount of carbonate cementation that developed across this paleo-surface. Since the late Pliocene, this paleosurface may have been steepened further by continued long-term downwarping along the north limb of the Cold Creek syncline (DOE 1988).

3.1.3 Coarse-Grained, Rounded, Basaltic [CCUc(rnd-bas)] Lithofacies

A third recognized facies of the CCU is the coarse-grained, rounded, basaltic lithofacies (CCUc[rnd-bas]). This facies consists of weak to well-stratified, dark-colored, subangular to subrounded, clast-supported gravel in a poorly sorted sand to silt matrix (Table 1, Figure A-14). Subordinate calcic soil horizons may be dispersed throughout the CCUc(rnd-bas) facies. A diagnostic feature distinguishing the CCUc(rnd-bas) facies from other gravel-dominated units is the composition of the rounded gravel clasts, which consist of 100% locally derived, dark-colored basalt. This facies is thickest (up to 20 m [65 ft]) south of the 200 West Area (DOE 1988, Slate 2000).

3.1.3.1 Discussion. Historically this unit has been referred to as sidestream alluvial facies of the Plio-Pleistocene unit (DOE 1988) and as a “locally derived subunit” (Slate 2000). The composition (almost purely basalt, stratification, and roundness on gravel clasts) suggests that this unit represents sidestream alluvium, probably from the ephemeral, ancestral Cold Creek (DOE 1988; Slate 1996, 2000). This interpretation is corroborated by the subsurface distribution of the CCUc(rnd-bas) facies, which conforms to a relatively narrow, buried, northwest-southeast trending paleochannel, roughly paralleling the present Cold Creek channel axis (Figure A-6). Locally, topographic relief within this paleochannel at the beginning of the CCU was very high (up to 25 m [80 ft]) (Figure A-5).

3.1.4 Coarse-Grained, Angular, Basaltic [CCUc(ang-bas)] Lithofacies

The CCUc(ang-bas) lithofacies consists of mostly angular, clast-to-matrix supported, basaltic gravel in a poorly sorted mixture of sand and silt, with little or no stratification. Calcic paleosols may be present locally. An example of the CCUc(ang-bas) facies is shown in Figure A-15.

3.1.4.1 Historical Perspective. The CCUc(ang-bas) facies is a new facies designation for the Pasco Basin. In borehole DH-33 (Figure A-6), where the CCU is about 8.5 m (28 ft) thick (Lindsey 1995), the upper 5 m (15 ft) consists of a basaltic cobble gravel, composed of sediments with characteristics of the CCUc(ang-bas) facies (Table 1).

3.1.4.2 Discussion. This facies, composed of mostly angular clasts of basalt, suggests it is locally derived and probably rolled, slid, or crept downslope from immediately adjacent basaltic uplands, primarily under the influence of gravity. Poorly sorted fine-grained sand and silt mixed with angular, basaltic gravel (Figure A-15) is probably derived from eolian or slopewash action that enveloped gravel clasts as they moved downslope. Later, pedogenic $CaCO_3$ may locally cement the deposit together. In the absence of the Hanford formation above the 300-m (1,000-ft) elevation, the CCUc(ang-bas) facies may be difficult to distinguish from younger Pleistocene-age colluvium (discussed in Section 3.3). Below the 300-m (1,000-ft) elevation, the CCUc(ang-bas) facies generally underlies a blanket of Pleistocene slackwater flood deposits of the Hanford formation.

The CCUc(ang-bas) facies is inferred to exist along flanks of ridges that surround the Pasco Basin, but the exact thickness and distribution of this unit is questionable because of limited exposure and borehole information for the basin margins. The CCUc(ang-bas) facies may crop out along stream gullies incised into the flanks of the basalt ridges.

The CCUc(ang-bas) facies may appear similar to the CCUc(rnd-bas) facies because of the high percentage of basalt clasts. However, the CCUc(ang-bas) facies generally lacks stratification. Furthermore, gravel clasts are mostly angular in contrast to the CCUc(rnd-bas) facies, which was reworked by running water, producing a higher degree of sorting, roundness, and stratification.

3.1.5 Fine-Grained, Laminated to Massive [CCUf(lam-msv)] Lithofacies

Cohesive, compact, massive to laminated and stratified fine-grained sand and silt belong to the CCUf(lam-msv) facies of the CCU. This brown- to yellow-colored unit has also been described as micaceous, very well sorted, and moderately to strongly calcareous, with relatively high natural background-gamma activity (Table 1). According to Connelly et al. (1992a), the unit is over 15 m (50 ft) thick in the southern portion of the 200 West Area (Figure A-16).

3.1.5.1 Historical Perspective. This unit was originally described as “Palouse soil” by Brown (1959, 1960), which was reported as being up to 21 m (70 ft) thick. Subsequent work in the 200 West Area further characterized a loess-like unit with minor fine-grained sand as “early Palouse soil” (Brown 1960; Tallman et al. 1979, 1981; Bjornstad 1984, 1990; DOE 1988, Last et al. 1989; Lindsey et al. 1992b, Delaney et al. 1991) (Figure A-2).

3.1.5.2 Discussion. While the CCUf(lam-msv) facies was originally interpreted as an eolian deposit, which was derived from the reworking of the underlying Ringold and/or caliche (Brown 1960), more recent investigations indicate this facies may contain other fine-grained deposits besides eolian silt and fine sand (Lindsey et al. 1994b, 2000). For example, recent studies in the S-SX waste management area (Lindsey et al. 2000, Serne et al. 2002) indicate that the CCUf(lam-msv) facies is composed of mostly intercalated layers of fine sand and silt, with some weakly developed paleosols, which is more characteristic of overbank-type alluvial deposits than eolian deposits (Lindsey et al. 2000). Examples of laminated versus massive structure observed in this facies are shown in Figure A-17.

Locally, within the 200 West Area, the CCUf(lam-msv) facies blankets the CCUc-f(calc) facies. In Figure A-5, these two facies are referred to as upper and lower CCU, respectively, within the 200 West Area. Elsewhere, fine-grained alluvial and/or eolian deposits underlying the Hanford formation are exposed along the Yakima Bluffs in the southern Pasco Basin; older eolian loess is present sporadically elsewhere within the Pasco Basin (Baker et al. 1991).

The CCUf(lam-msv) facies is easily distinguished from the underlying CCUc-f(calc) facies based on a contrast in color, degree of cementation (Figure A-18), and natural gamma activity (e.g., Figure A-12). Furthermore, while the CCUf(lam-msv) facies may be compact and cohesive, it is generally uncemented in contrast to the underlying pedogenically altered and indurated CCUc-f(calc) facies. Even though the CCUf(lam-msv) facies may contain moderate to high concentrations of $CaCO_3$, the carbonate is evenly disseminated as detrital grains. The bulk of the detrital $CaCO_3$ in the CCUf(lam-msv) facies is likely derived from the disintegration and mechanical reworking/redeposition of the underlying CCUc-f(calc) facies (Brown 1960), where discrete $CaCO_3$-rich zones developed diagenetically as a result of pedogenesis, as illustrated in Figure A-10.

The upper contact of the CCU in the 200 West Area is relatively easy to identify in all but the extreme southern portion in the vicinity of the S-SX waste management area. Here, the upper contact is more difficult to distinguish because the texture of the CCUf(lam-msv) facies is similar to the overlying fine-grained flood deposits of the Hanford formation (Johnson et al. 1999, Lindsey et al. 2000). As an example, Lindsey et al. (2000) included everything in borehole 299-W23-19 (Figure A-12) from 38.1 m (125 ft) bgs to the top of the CCUc-f(calc) facies into an "unnamed Hanford formation [?] or Plio-Pleistocene Deposits [?]" because of the uncertainty of the contact with the overlying Hanford formation in this area. However, a distinctive reduction in natural gamma activity on geophysical logs and grain size at about 38.1 m (125 ft) bgs (which was also observed in most other boreholes in this area) likely marks the boundary between the CCU and the overlying Hanford formation.

With one exception, the CCUf(lam-msv) facies appears to be restricted to the 200 West Area. The exception is in the north part of the 200 East Area, where up to 10 m (35 ft) of massive fine sand and silt lies near the bottom of the suprabasalt sequence in the vicinity of the 241-B Tank Farm, which has been described by Wood et al. (2000) as the "Hf/PPu(?) silt layer." Lindsey et al. (2001) also noted similarities of this unit with the CCUf(lam-msv) facies in the 200 West Area.

Some previous investigations (Slate 1996, 2000; Lindsey et al. 2000) in the southern portion of the 200 West Area did not recognize the CCUf(lam-msv) facies as a separate unit, assuming this fine-grained unit was part of the overlying Hanford formation. However, as discussed above, the CCUf(lam-msv) facies clearly stands out in sharp contrast with the overlying, coarser-grained facies of the Hanford formation (Last et al. 1989, Bjornstad 1990, Wood et al. 2001) further north. Regardless of its exact stratigraphic relationship and origin, the CCUf(lam-msv) facies is a distinctive lithostratigraphic unit that plays a significant role in the moisture and contaminant distribution within the vadose zone beneath the 200 West Area.

3.2 HANFORD FORMATION

The name "Hanford formation" was first introduced, informally, by Myers and Price in 1979 to describe Pleistocene catacylsmic flood deposits within the Pasco Basin. Ice Age floods originated from outbursts of glacial Lake Missoula, as well as other ice-dammed lakes (Baker and Bunker 1985) or possible sub-glacial floods (Shaw et al. 1999) associated with the Cordilleran ice sheet (Figure A-19). The Hanford formation includes minor fluvial, colluvial, and/or eolian deposits interbedded with flood deposits. Historically, flood deposits have been recognized and described in the geologic literature since the 1920s (Bretz 1923). Parker and Piper (1949) referred to deposits equivalent to the Hanford formation as "terrace deposits" (Figure A-2). Newcomb and Strand (1953) subsequently identified these as glaciofluvial and fluvial sediments.

Recently, the possibility of converting the Hanford formation into a formalized stratigraphic unit was investigated (Bjornstad et al. 2002). However, it is the consensus that the Hanford formation cannot be formalized as a stratigraphic unit at this time, even though it is a mappable unit, for reasons specified in the International Stratigraphic Guide (Salvador 1994). These reasons include: (1) the Hanford formation as defined is based on a common time period and depositional environment, which are invalid formalization criteria; (2) the Hanford formation is very diverse lithologically (i.e., facies range from bouldery gravels to silts); geologic formations, as defined in the stratigraphic code, should have similar lithologic properties; and (3) there is a lack of complete reference sections with which to define and characterize the Hanford formation. For example, the range of internal variability within the Hanford formation often exceeds that between adjacent stratigraphic units (e.g., CCU and Ringold Formation). At present, therefore, it is recommended that the Hanford formation continue to be used informally to describe cataclysmic flood deposits within the Pasco Basin.

As mentioned above, the Hanford formation consists predominantly of unconsolidated sediments that cover a wide range in grain size, from boulder-size gravel to sand, silty sand, and silt. The sorting ranges from poorly sorted (for gravel facies) to well sorted (for fine sand to silt facies) (Table 1). Traditionally the Hanford formation has been subdivided into three lithofacies (gravel-, sand-, and silt-dominated), which grade into one another, both vertically and laterally (DOE 1988, Baker et al. 1991, Lindsey et al. 1994a). These lithofacies may interfinger with or grade from gravel-dominated to sand-dominated facies, or sand-dominated to silt-dominated facies, but rarely from gravel-dominated to silt-dominated facies.

The silt-dominated facies is stratigraphically equivalent to Touchet Beds, which were formally recognized by Flint (1938). These deposits are named after well-exposed, rhythmically-bedded strata in the Walla Walla Basin (Carson et al. 1978; Bjornstad 1980; Waitt 1980, 1985; Smith 1993). Similar deposits are also reported for the Tucannon Valley (Baker 1973, Waitt 1985; Smith 1993), Yakima Valley (Waitt 1985), the Pasco Basin (Brown 1970, Myers and Price 1979, Tallman et al. 1979, DOE 1984), and elsewhere along the Columbia River Valley (Smith 1993). Beginning in the late 1980s, these deposits began to be called by a variety of other informal names, including slackwater facies (Moody 1987, Lindsey et al. 1992b, Connelly et al. 1992a, Last et al. 1989, Smith 1993), silt-dominated facies (Lindsey et al. 1992a, 1994b; Connelly et al. 1992b), silty facies (Lindsey et al. 1994a), and rhythmite facies (Baker et al. 1991). Silt-dominated facies occur as sequences of rhythmic, graded beds that range from 0.1 to 1 m (0.3 to 3.3 ft) in thickness and are characterized by loose, horizontal- to ripple-laminated, coarse to medium sand, grading up into cohesive fine sand to silt (Table 1). The silt-sized fractions consist predominantly of quartz, feldspar, and mica (Tallman et al. 1979).

Sand-dominated facies of the Hanford formation (Lindsey et al. 1992a, 1992b, 1994a, 1994b; Connelly et al. 1992a, 1992b) consist of relatively thick (≥1 m [≥3.3 ft)), predominantly horizontally laminated, loose, basalt-rich, fine- to coarse-grained sand, sometimes grading upward into a thinner sequences of ripple-laminated fine sand to silt (Table 1). The sand-dominated facies have also been referred to as the transitional sand facies (Reidel et al. 1992, Fecht and Weekes 1996) and the plane-laminated sand facies (Baker et al. 1991). Typically, sand-dominated facies average about 50% mafic (i.e., basalt) and 50% quartz-feldspar (Tallman et al. 1979). This composition gives the Hanford formation its characteristic “salt and pepper” appearance that is frequently noted in drillers’ and geologists’ logs.

The gravel-dominated facies have various names, including Pasco gravels (Brown 1970, Myers and Price 1979, Tallman et al. 1979, 1981, DOE 1984), Missoula flood gravels (Webster and Crosby 1982), coarse-grained main-channel facies (DOE 1988, Last et al. 1989), coarse-grained flood gravels (Moody 1987, Baker et al. 1991), and gravel-dominated facies (Lindsey et al. 1992a, 1992b, 1994b; Connelly et al. 1992a, 1992b). The gravel-dominated facies of the Hanford formation consist of loose, massive, horizontal and large-scale, planar-tabular cross-bedded, poorly sorted mixtures of gravel, sand, and silt. Gravel clasts in flood gravels generally consist of 50% to 75% subangular to subrounded basalt (Tab1e 1).

Below an elevation of approximately 300 m (1,000 ft) within the Pasco Basin, the Hanford formation unconformably overlies the CCU and, where the CCU is eroded, lies directly on the Ringold Formation or Columbia River basalt (Figure A-4).

3.2.1 Timing and Frequency of Ice Age Flooding

Repeated cataclysmic floods stripped away large volumes of Palouse loess, carved deep coulees into the underlying basalt bedrock, and created the Channeled Scabland of eastern Washington (Baker et al. 1991). All floodwater converged upon the Pasco Basin before being funneled through a single, narrow outlet at Wallula Gap. Because of the hydraulic constriction, floodwaters ponded temporarily behind Wallula Gap, forming Lake Lewis (Allison 1933), which locally resulted in thick accumulations of flood deposits upstream within the Pasco Basin (Bjornstad et al. 2001). In general, coarse-grained flood deposits were laid down locally along high-energy flood channels, while finer-grained flood deposits accumulated in backflooded valleys and other slackwater environments along floodpaths (Figures A-19 and A-20).

The first Ice Age floods likely occurred during the early Pleistocene, around 1.5 to 2.5 million years ago (Bjornstad et al. 2001). At least two episodes of pre-Wisconsin cataclysmic flooding, one middle Pleistocene (>130 ka) and one early Pleistocene (>780 ka) are identified from surface exposures based on radiometric age dates, as well as paleomagnetic and pedogenic evidence (Baker et al. 1991, Bjornstad et al. 2001). Physical evidence for pre-Wisconsin cataclysmic floods is limited to a few, isolated, widely distributed localities across southeastern Washington. The evidence for older floods is commonly obscured by erosion or deposition by younger floods and an extensive blanket of Holocene deposits.

As shown in Figure A-21, prior to the late Pleistocene, a dozen or more major glacial advances may have occurred. The timing and frequency of these older glaciations are preserved in the late-Quaternary oxygen-isotope record (Morrison 1991), which indicates nine major glacial-interglacial cycles over the last 800,000 years (through oxygen isotope Stage 20) (Figure A-21). Full glacial conditions, conducive to the generation of cataclysmic floods, prevailed for about two-thirds of this time period (Morrison 1991). Morrison estimates at least 17 complete interglacial-glacial cycles since about 1.77 Ma, and perhaps as many as 44 cycles since the beginning of the Pleistocene (2.58 Ma). If a dozen (or more) floods were associated with each glaciation, as in the case of the late Wisconsin floods (Waitt 1980, 1985), then it is possible that the total number of Ice Age floods for the entire Pleistocene Epoch could number in the hundreds, perhaps exceeding a thousand.

Recently analyzed paleomagnetic data from several boreholes drilled into the Cold Creek flood bar (Figure A-22) provide new insights into the history for older, pre-Wisconsin cataclysmic floods (Bjornstad et al. 2001). Cold Creek bar (Figure A-20), as well as other giant flood bars in the Pasco Basin, represents compound flood bars that developed as floodwaters expanded beyond the confines of basalt uplands in the northern and western parts of the basin (Bretz et al. 1956, DOE 1988).

Much of the flood sequence, up to 100 m (328 ft) thick beneath the bar, appears to be composed of deposits that predate the last magnetic reversal (Brunhes-Matuyama) at 780 ka (Figure A-22). This demonstrates that a significant portion of the bar was established and grew as a result of early Pleistocene floods.

The last large-scale Ice Age cataclysmic flood is estimated at about 13,000 years before present, which is based on a radiometric age associated with Mount St. Helens "set S" tephra that lies near the top of the flood sequence (Mullineaux et al. 1978). As many as 100 separate, cataclysmic Ice Age floods may have occurred during the last glaciation (Waitt 1994); however, the exact frequency and number of floods is contentious (Baker and Bunker 1985).

3.2.2 Mechanics of Ice Age Flooding

Before presenting the revised lithofacies classification system for the Hanford formation, it is first necessary to discuss the mechanics of erosion and deposition that occurred during, as well as between, the Ice Age floods.

Each cataclysmic flood transported massive amounts of sediment, all within a period of a week or less (O'Connor and Baker 1992). Within this turbid column of floodwater was a stratified mixture of sediments being transported by the floods. At the base of the flow, along the sediment-water interface, floodwaters carried everything from gigantic boulders that bounced and rolled along the bottom, to finer-grained particles (gravel to clay) in suspension. Higher in the water column, floodwaters were limited to transporting sand, silt, and clay-sized particles. As a result, deposition of the coarsest flood material (cobbles and boulders), as well as entrained finer-grained sediment, was concentrated to lower elevations along the bases of flood channels. At higher elevations adjacent to the flood channels, floodwaters were starved of coarser material and, thus, yielded principally horizontally laminated sands.

In the Pasco Basin, floods encountered the temporary backwaters behind Wallula Gap (Lake Lewis), slowing the flow and allowing broad sheets of coarser sand to blanket the basin at intermediate elevations around the margins of the basin, including a significant portion of the Cold Creek flood bar (Figure A-23). Thick sequences of flood deposits accumulated within the Pasco Basin due to a decreased gradient coming off the Channeled Scabland, in combination with hydraulic damming behind Wallula Gap. Lake Lewis temporarily rose to an elevation of 380 m (1,250 ft), creating a lake up to 275 m (900 ft) deep (Figure A-24). With increasing elevation and distance from the high-energy flood channels, only finer-grained sand and silt particles were available for deposition. This led to slackwater deposition around the extreme margins of the Pasco Basin and in backflooded valleys, and during standing water as the lake drained. In some slackwater areas, one or more low-energy, graded rhythmites may have accumulated with each flood event. Clay-sized particles are generally absent in the Hanford formation because of the extremely short duration of the floods (5 days or less) (O'Connor and Baker 1992); thus, the smallest particles remained suspended in the floodwater and were flushed out of the basin.

Because of the scale and dynamics of Ice Age floods, the resulting characteristics of the sedimentary deposits are somewhat unique in the geologic record, although finer-grained flood facies have many of the characteristics of the classic Bouma (1962) sequence (Figure A-25). These include rhythmic upward gradations in grain size and sedimentary structure, from horizontally laminated sand to finer-grained ripple to climbing ripple lamination, followed by evenly laminated fine sand and mud (Figure A-25). The formation of Bouma-like sequences signifies rapid accumulation under very turbid conditions and dissipating current energy.

Many late-Wisconsin flood deposits display an overall fining and thinning of beds upsection (see Appendix B). This has been attributed by Waitt (1985) and others as a decrease in the volume of the successive Lake Missoula flood events caused by a thinning ice dam toward the end of the last glaciation.

Clastic dikes are common to the Hanford formation, particularly within sand-dominated and silt-dominated facies. Clastic dikes appear as vertical to subvertical structures that cross-cut normal sedimentary layering (Black 1979, Fecht and Weekes 1996, Fecht et al. 1999). While some dikes appear to have been hydraulically injected from below, others suggest infilling from above. Where clastic dikes intersect the ground surface, networks of interconnecting clastic dikes form polygonal patterned ground (Fecht et al. 1999). Smaller dikelets, sills, and small-scale faults and shears are commonly associated with master dikes that form polygons. Clastic dikes are generally believed to be a type of soft-sediment deformation that occurred during, or soon after, cataclysmic flooding, perhaps induced by seismicity (Fecht et al. 1999).

3.2.3 Lithofacies Associated with the Hanford Formation

The standardized nomenclature defined here uses a facies-model approach to physically classify the Hanford formation, similar to the system presented in Miall (1982) and applied to cataclysmic flood deposits (Bjornstad et al. 1994, 2002). An alternate method for classifying flood deposits, suggested by Smith (1993), identified seven depositional facies, and focused on differentiating flood facies from non-flood facies. The facies-model approach is based on physical characteristics and is independent of the origin. Thus, even though the facies-model approach was developed for fluvial deposits, it may still be used to described deposits from a variety of depositional environments (Bridge 1993), including cataclysmic flood deposits. The facies-model approach seems most appropriate for describing the characteristic textural and structural differences observed in the Hanford formation (Table 3).

A total of 11 textural-structural lithofacies are presented for Ice Age flood deposits and minor interbedded non-flood deposits (Table 3 and Figure A-25). Most facies descriptions for cataclysmic flood deposits discussed in Table 3 are the same as for normal fluvial deposits (i.e., Gp, St, Sp, Sh, Sr, Fl, and Fm), as defined by Miall (1982) and Bridge (1993). Differences to Miall's facies classification include Gm, which was described as massive to crudely and/or horizontally bedded gravel. Table 3 includes only massive gravels in the Gm class; horizontally bedded gravels are assigned to a new lithofacies, Gh, which is not included in the original facies classifications. Another new lithofacies, designated for cataclysmic flood deposits, is massive sand (Sm).

Table 3. Characteristics of Hanford Formation Lithofacies. (2 Pages)

Lithiofacies Code	Grain Size	Sorting	Color	Primary Sedimentary Structure	Fabric/Consistency	Bedding Characteristics	Mineralogy	Depositional Environment	Rate of Development/ Deposition	Degree of Associated Scouring/Erosion	Common Lithofacies Transitions	Facies Association[1]	Other Characteristics
Fm	Silt to fine sand	Poor to moderate	Pale brown to light gray	Massive	None/cohesive	Generally laterally continuous within slackwater beds; discontinuous lenses elsewhere	Predominantly quartzo-feldspathic	Bioturbated slackwater flood deposits and/or inter-flood eolian, fluvial, or slopewash deposits	Slow	None	Fl	ISSD	May have secondary structures such as root traces, animal burrows, weak pedogenic horizonation
Fl	Silt to fine sand	Moderate to well	Pale brown to light gray	Wavy to horizontal laminations	Platy to fissile/cohesive	Generally laterally continuous within slackwater beds; discontinuous lenses elsewhere	Predominantly quartzo-feldspathic	Slackwater flood sedimentation into hydraulically ponded, relatively still water	Slow to moderate	None	Sr	ISSD, SD	Generally fines upward, soft-sediment deformation
Sm	Fine to coarse sand +/- silt	Poor to moderate	Pale brown to light gray	Massive	None/loose to weakly consolidated	Continuous beds to discontinuous lenses	Predominantly quartzo-feldspathic	Bioturbated flood deposits and/or inter-flood eolian, fluvial, or slopewash deposits	Slow to moderate	None	Sr, Fl, Fm	ISSD, SD	May have secondary structures such as root traces, animal burrows, weak pedogenic horizonation
Sr	Silty very fine sand to fine sand	Moderate to well	Pale brown	Ripple cross-lamination to climbing and wavy ripple lamination	Breaks along undulating plates/somewhat cohesive	Generally laterally continuous within slackwater beds; discontinuous lenses elsewhere	Predominantly quartzo-feldspathic, micaceous	Mixture of traction and suspension load under low to moderate flow regime in slackwater environment or waning flood stage	Moderate	None	Sh, St, Sp	ISSD, SD	Upward gradation from ripple cross-lamination to climbing ripples to wavy ripple lamination, abundant visible mica; soft-sediment deformation
Sh(f)	Silty fine to medium sand	Moderate to well	Pale brown	Horizontal to low-angle cross-stratification	Platy/somewhat cohesive	Laterally continuous; locally scoured and filled with coarser lithiofaces	Predominantly quartzo-feldspathic	Super-concentrated plane-bed deposition on top of washed-out, subaqueous dunes away from or above elevation of main flood channels	Rapid	Moderate	Sh(c), Sr	ISSD, SD	
Sh(c)	Medium to coarse sand to pebbly sand	Moderate to well	Gray	Horizontal to low-angle cross-stratification	Granular/loose	Generally laterally continuous in sand-dominated facies, discontinuous lenses in gravel dominated facies	Mixture of quartzo-feldspathic and basaltic sand grains along with a wide variety of other rock fragments	Super-concentrated plane-bed deposition atop washed-out, subaqueous dunes away from or above elevation of main flood channels	Rapid	Moderate	Sh(f), Gm, Gh, Gp	ISSD, SD, GD	Salt and pepper appearance; pebbles usually matrix supported; loose and therefore caves easily; rip-up clasts common
Sp	Medium to coarse sand to pebbly sand	Moderate to well	Gray	High angle planar-tabular cross-stratification	Granular/loose	Discontinuous lenses	Mixture of quartzo-feldspathic and basaltic sand grains along with a wide variety of other rock fragments	Planar-tabular cross-bedded sand deposition associated with straight-crested subaqueous dune migration	Rapid	Moderate to extreme	St, Gm, Gh, Gp	SD, GD	
St	Medium to coarse sand to pebbly sand	Moderate to well	Gray	Trough cross-stratification	Granular/loose	Discontinuous lenses	Mixture of quartzo-feldspathic and basaltic sand grains along with a wide variety of other rock fragments	Trough cross-bedded sand deposition associated with sinuous-crested subaqueous dune migration	Rapid	Moderate to extreme	Sp, Gm, Gh, Gp	SD, GD	
Gm	Silty sandy pebble to boulder gravel	Poor to moderate	Dark gray to dark brownish gray to black	Massive; no contrasts in grain size/sorting	Matrix to clast supported (some open work); no imbrication/ loose to weakly consolidated	Discontinuous lenses	Sand fraction mostly a mixture of quartz, feldspar and basalt; gravel fraction mostly basalt with plutonic and metamorphic clasts along with detrital caliche clasts	Disorganized flood flow and rapid deposition within or near axis of flood channel	Very Rapid	Extreme	Sh, Gh, Gp	SD, GD	Most gravel-sized clasts subangular to subrounded basalt; lesser number of rounded reworked fluvial clasts. Rip-up clasts of semi-consolidated loess, caliche, and/or slackwater flood deposits.

Table 3. Characteristics of Hanford Formation Lithofacies. (2 Pages)

Lithiofacies Code	Grain Size	Sorting	Color	Primary Sedimentary Structure	Fabric/Consistency	Bedding Characteristics	Mineralogy	Depositional Environment	Rate of Development/ Deposition	Degree of Associated Scouring/Erosion	Common Facies Transitions	Facies Association[1]	Other Characteristics
Gh	Silty sandy pebble to boulder gravel	Poor to moderate	Dark gray to dark brownish gray to black	Grain size/sorting variations produce horizontal to subhorizontal bedding	Matrix to clast supported (some open work); weak to moderate imbrication/loose to weakly consolidated	Discontinuous lenses and beds with high degree of lateral as well as vertical heterogeneity; cut and fill common	Sand fraction mostly a mixture of quartz, feldspar and basalt; gravel fraction mostly basalt with plutonic and metamorphic clasts along with detrital caliche clasts	Plane-bed deposition atop washed out subaqueous dunes within or near axis of flood channel	Very Rapid	Extreme	Sh, Gm, Gp	SD, GD	Most gravel-sized clasts subangular to subrounded basalt; lesser number of rounded reworked fluvial clasts. Rip-up clasts of semi-consolidated loess, caliche, and/or slackwater flood deposits.
Gp	Silty sandy pebble to boulder gravel	Poor to moderate	Dark gray to dark brownish gray to black	Planar-tabular, large-scale foreset beds of contrasting grain size/sorting show dip of beds up to 30 degrees	Matrix to clast supported (some open work); weak to moderate imbrication/loose to weakly consolidated	Discontinuous lenses and beds with high degree of lateral as well as vertical heterogeneity; cut and fill common	Sand fraction mostly a mixture of quartz, feldspar and basalt; gravel fraction mostly basalt with plutonic and metamorphic clasts along with detrital caliche clasts	Planar-tabular, large-scale foreset beds deposited on lee sides of migrating giant current ripples within or near axis of flood channel	Very Rapid	Extreme	Sh, Gm, Gh	SD, GD	Most gravel-sized clasts subangular to subrounded basalt; lesser number of rounded reworked fluvial clasts. Rip-up clasts of semi-consolidated loess, caliche, and/or slackwater flood deposits.

[1] Facies associations: ISSD = Interbedded Sand- and-Silt-Dominated, SD = Sand-Dominated, GD = Gravel-Dominated

The range of heterogeneity observed for the Hanford formation is represented in a number of outcrop photomosaics (Appendix B). Most outcrop exposures of flood deposits display two or more of the 11 lithofacies shown in Figure A-25. Exposures rarely occur with just a single lithofacies, or with more than four or five. Finer-grained lithofacies (e.g., Fm, Fl) are not usually associated with turbulent high-energy flood environments that deposit gravel because of the agitated nature of the floodwaters, which do not permit settling of suspended fine-grained silt or clay. In general, coarse-grained lithofacies develop within and proximal to flood channels, while the finer-grained facies are geographically restricted to backflooded and other slackwater environments (Figures A-19 and A-20).

Mineralogical composition of cataclysmic flood deposits also changes vertically within the depositional sequence (Figure A-25). Coarser-grained flood deposits are commonly shades of gray because of the higher basalt content, in contrast to finer-grained strata, which are more quartz-feldspar-rich and appear as shades of brown. This is a direct result of the coarser units being derived from the erosion of the Columbia River Basalt Group, off the Channeled Scabland. Fine-grained flood deposits, however, are derived principally from reworked quartzo-feldspathic deposits of Palouse loess (Busacca and McDonald 1994), and/or other older fluvial or glaciofluvial deposits eroded along the floods path. During flooding, these finer-grained materials remained suspended within the floodwaters, some of which settled out of suspension in slackwater environments during the waning stages of flooding.

3.2.3.1 Gravel-Dominated Lithofacies. Three lithofacies are represented within gravel-dominated strata of the Hanford formation: massive (Gm), horizontally bedded (Gh), and large-scale, planar-tabular (foreset) bedded (Gp). All three facies are dominantly composed of basalt-rich, poorly sorted, silty sandy pebble- to boulder-size gravel (Figure A-26). Roundness on basalt gravel clasts is usually immature (subangular to subrounded) because of relatively recent erosion, transport, and rapid burial of locally derived basaltic detritus. Gravel clasts of other compositions (quartzite, granite, gneiss, and volcanic porphyries) are commonly more rounded as a result of reworking by the floods of older fluvial deposits (e.g., Ringold and Ellensburg Formations). Individual beds of gravel-dominated facies may range from a few centimeters to 3 m (9.8 ft) or more in thickness. Two examples of particularly thick beds of gravel-dominated flood deposits are illustrated in Figures A-27 and B-5b.

Gravel-dominated lithofacies of the Hanford formation are distinguished from the Ringold Formation and the CCU mainstream alluvial (c[ml]) facies by a greater percentage of basalt clasts, with less rounding and poorer sorting for the Hanford formation (Table 1). Associated sedimentary structures are also different; the gravel-dominated facies of the Ringold Formation are more horizontally bedded while the Hanford formation displays large-scale, foreset cross bedding (Gp). The gravel-dominated facies of the Hanford formation are differentiated from CCU sidestream alluvial [c(rnd-bas)] and CCU colluvial [c(ang-bas)] facies by the inclusion of up to 50% nonbasalt clasts.

The three gravel-dominated facies of the Hanford formation (Gm, Gh, and Gp) are texturally and lithologically similar, yet they differ in sedimentary structure. An example of the Gh and Gp facies occurring together is shown in Figure A-27. Flood gravel facies may grade laterally or vertically into discontinuous lenses of the Sh (and less frequently Sp or St) lithofacies (see

Appendix B). Large-scale, planar-tabular, foreset-bedded gravels (Gp) probably represent transport and aggradation of coarse-grained tractive bedload associated with the progradation of high-relief, giant current ripples during cataclysmic flooding. Alternatively, horizontally bedded flood gravels formed during aggradation by low-relief bedforms along the sediment-floodwater interface. In outcrop, it is important to remember that Gp facies may appear as Gh in outcrops where the face is perpendicular to flow direction.

Using the facies-model approach, other characteristics of sedimentary deposits can be added as needed to the facies designation. As an example, differences in sedimentary fabric have been delineated in Figure A-28. Accordingly, flood gravels are classified further by whether they are clast-supported (e.g., Ghc or Gpc) or matrix-supported (e.g., Ghm or Gpm). Within clast-supported flood gravels, the matrix may be filled or partially filled with finer-grained sand and/or silt, or may be absent altogether, which creates an open-work fabric (i.e., Ghco). An open-work fabric, common in flood gravels of the Hanford formation, occurs where the matrices of gravel clasts are void of sediment; an open-work fabric indicates that finer-grained particles remained in suspension temporarily during deposition of the gravel.

3.2.3.2 Sand-Dominated Lithofacies. A total of five lithofacies are recognized for sand-dominated facies of the Hanford formation: trough cross-bedded (St), planar-tabular cross-bedded (Sp), horizontally laminated (Sh), rippled (Sr), and massive (Sm). Examples of these are shown in Figures A-29 and A-30. Sedimentary textures found in facies St, Sp, and Sh all consist of fine to coarse sand, with variable amounts of fine- to very-fine grained, matrix-supported pebbles (Table 3). Rippled sands (Sr), on the other hand, usually consist of well-sorted fine sand to silty sand, while massive sand (Sm) consists of poorly sorted coarse to fine sand with variable amounts of silt.

The sedimentary structures of the sand-dominated lithofacies are also different. Trough cross-bedding (St) and planar-tabular cross-bedding (Sp) form by migrating sinuous-crested versus straight-crested dunes, respectively. Facies Sh, on the other hand, is associated with the lateral migration of very low-relief bedforms. Facies Sh is subdivided further into coarse (Sh[c]) and fine (Sh[f]) subfacies. Because Sh(c) has more coarse sand, which generally contains a higher percentage of basalt, it has a darker appearance than Sh(f) (Figure B-3). The Sh(f) facies, on the other hand, appears as lighter shades of gray or brown because it has more fine sand and silt, which mineralogically consists of mostly light-colored quartz and feldspar (Figure A-31). Occasionally, Sh(c) and Sh(f) lithofacies can be seen together in the same exposure (e.g., Figures B-2 and 3). Individual sand-dominated beds can range from a few centimeters to several meters in thickness.

Grading upward from coarse-grained St, Sp, and/or Sh facies is the finer-grained Sr facies (Figure A-25). Characteristic of this facies is the development of climbing to draping ripple-drift laminations in fine sand to silty fine sand (Figures A-30 and A-32). In higher energy proximal slackwater environments, tops of flood beds may terminate in Sr facies; however, in distal slackwater environments, beds usually grade upward into laminated (Fl) to massive (Fm) silt and sand, frequently accompanied by soft-sediment deformation (Bjornstad 1980). Asymmetric current-ripple laminations preserved in the Sr facies occasionally display evidence for deposition under a dissipating current flow that was initially upvalley and then downvalley (Figure A-30a), associated with filling and then draining of floodwaters within hydraulically dammed lakes. Secondary flood surges are also indicated where multiple Sh-Sr sequences exist (Figures A-30b and A-32).

The Sm lithofacies, where present, may represent a non-flood deposit, such as debris flow (Figure B-29b), slopewash, or eolian depositional events that occurred between floods. Relatively thick layers of facies Sm, along the White Bluffs at the Locke Island Landslide complex (Figure A-33), appear to be eolian deposits that accumulated between floods, in contrast to laminated Sh and Sr lithofacies laid down by moving floodwater. Some of the lack of structure in Sm may also be due to post-depositional bioturbation and pedogenesis (Smith 1993).

3.2.3.3 Fine-Grained Lithofacies. Fine-grained flood facies include laminated (Fl), and massive (Fm) silty fine sand to silt (Table 3). Facies Fl frequently overlies Sr (Figure A-30) and represents the transition between deposition under tractive current versus suspended sediment loads (Figure A-25). Lithofacies Fl may grade upward into massive silt and/or silty fine sand (Fm) in areas that were subaerially exposed and bioturbated, forming weakly developed paleosols, and/or blanketed with eolian loess between flood episodes. Approximately half of the slackwater flood beds reported by Smith (1993) had bioturbated and/or other non-flood deposits indicative of a depositional hiatus between flood-deposited strata. Individual fine-grained beds within the Hanford formation can range from a few centimeters to a meter or more in thickness

3.2.4 Facies Associations of the Hanford Formation

The Hanford formation is separated into three informal facies associations: gravel-dominated (GD), sand-dominated (SD), and interbedded sand- and silt-dominated (ISSD). In general, these facies associations are dominated by either the gravel-, sand-, or fine-grained lithofacies described above. Because individual beds in the Hanford formation can be up to 3 m (9.8 ft) thick, Hanford formation facies associations are assigned to outcrops or sequences with >3 m (>9.8 ft) observed thickness. At a scale of <3 m (<9.8 ft), individual lithofacies may be identifiable, but there may be an insufficient amount of the sequence exposed to make a determination of the overall, broader facies association. Facies association SD is transitional between facies associations GD and ISSD, which represent two end members for flood deposits (Figure A-25).

More than a single facies association is commonly observed in outcrop sequences more than a few meters deep (see Appendix B). Facies associations are differentiated from one another based on the relative percentages of the observed lithofacies identified in Table 3. For example, facies association ISSD typically contains multiple-graded beds of Sr to Fl ±Fm. However, coarser-grained horizontally laminated sand (Sh), which dominates facies association SD, may also be present at the base of some or all rhythmites observed in facies association ISSD, or interbedded with flood gravels in facies association GD. Thus, lithofacies Sh may be found in all three facies associations. A cut-off value of >50% Sh, Sp, St, +/- Sm is used to define a sequence as belonging to facies association SD. Sequences with <50% Sh, Sp, St, +/- Sm and >50% Gp, Gh, +/- Gm fall into facies association GD, and >50% Sr, Fl, and/or Fm would be classified as facies association ISSD. In other words, a flood sequence with >50% Sr ±Fl ±Fm, but <50% of all other lithofacies (including Sh) would be designated part of facies association

ISSD. Alternatively, facies association SD would be composed of >50% Sh ±St ±Sp ± Sm, but <50% of all other lithofacies. A similar approach would be used to distinguish between facies associations GD and SD. Facies association GD would contain >50% Gm ±Gh ±Gp and <50% of all other lithofacies.

Generally, there is a lack of good natural exposures of coarser-grained facies associations GD and SD because of their loose, unconsolidated nature; the best exposures of these deposits occur in recently excavated borrow pits, road cuts, and waste disposal facilities (Appendix B). Facies association ISSD is generally restricted to the margins of the Pasco Basin where there are very few boreholes and even fewer outcrops. For these reasons, relatively little is known about facies association ISSD in the Pasco Basin. The best outcrop exposures of facies association ISSD are located outside the Pasco Basin, in the Walla Walla (Carson et al. 1978, Bjornstad 1980, Waitt 1980, Smith 1993), lower Yakima (Waitt 1985), and Tucannon (Baker 1973, Smith 1993) valleys.

Other notable differences between facies associations include the presence (or absence) of volcanic tephra horizons and clastic dikes. Thin (a few centimeters or less) volcanic marker horizons, particularly the 13,000 ka Mount St. Helens "set S" tephra layer (Mullineaux et al. 1978), are commonly found in outcrops of facies associations SD and ISSD but rarely in facies association GD, apparently because of scouring by subsequent floods, which destroyed the tephra. Clastic dikes, common in facies associations SD and ISSD, also occur much less frequently within facies association GD.

3.2.4.1 Gravel-Dominated Facies Association (GD). Facies association GD was deposited by high-energy floodwaters in, or immediately adjacent to, the main cataclysmic flood channels (Figures A-19 and A-20). Facies association GD consists of >50% gravel-dominated lithofacies (Gp, Gh, or Gm), and <50% all other lithofacies (Figure A-25). The GD deposits appear as relatively continuous sheets within the central Pasco Basin. The upper surface of GD deposits frequently displays an anastomoising channel network (Figures A-20 and A-23), which may include fields of giant current ripples, normally only observable in aerial photographs.

Facies association GD generally consists of poorly sorted, coarse-grained, basaltic sand and pebble- to boulder-size gravel, which may display an open-framework fabric, massive bedding, plane to low-angle bedding, and/or large-scale, planar-tabular, foreset bedding in outcrop (Figures A-27 and A-28). The gravel clasts (dominated by basalt) are usually subangular to subrounded (Figure A-26). Facies association GD sometimes grades vertically, as well as laterally, into facies association SD, but rarely into facies association ISSD (Figures B-2 through B-6). An exception is within Badger Coulee at Kiona Quarry (Figure B-7), where facies association ISSD caps an old flood gravel (GD) and paleosol sequence.

Gravel clasts are dominantly basalt but include other rock types such as volcanic porphyries, granite, quartzite, and gneiss from glaciofluvial reworking of the more quartz-feldspar-rich fluvial facies of the CCU, as well as the Ringold Formation and sedimentary interbeds (Ellensburg Formation) from between flows of Columbia River basalt. The fine pebble-size fractions consist almost entirely of basalt, regardless of location. Rip-up clasts are locally abundant and may be composed of caliche, as well as semi- to unconsolidated, fine-grained

Hanford formation, Palouse loess, Ringold or Ellensburg Formation. Examples of some large, tabular rip-up clasts of Ringold Formation occur at the Transtate borrow pit site (Figures B-2 and B-3).

Erosional unconformities (defined by intercalated finer-grained layers) may represent separate floods, but where fines have been completely eroded during subsequent floods, it is not possible to evaluate the number of floods. Therefore, only a single flood appears to be commonly represented within most sequences of facies association GD. In general, the absence of paleosols or other disconformities within flood-gravel sequences suggests that most or all older flood deposits were stripped away or reworked via erosional scouring by the last (late Pleistocene) flood(s). Occasionally, scour and fill features and gradations within flood-gravel sequences may be present, indicating multiple floods, or flow variations that occurred during a single flood.

3.2.4.1.1 Facies Association GD at 218-E-12B Burial Ground. One of the best exposures for facies association GD is within the northeast corner of the 200 East Area (Figure A-20) at the 218-E-12B Burial Ground (E-12B), a 15-m (49.2-ft)-deep trench, which has been excavated for the disposal of U.S. Navy nuclear submarine reactor core vessels (Lewis et al. 1993, Rhoads et al. 1994). The E-12B Trench is located in an area near where facies association GD transitions into the facies association SD (Figure A-23). The walls of this expansive excavation at one time displayed, in intricate detail, a sequence of gravel, sand, and silt facies that were deposited during the last late-Wisconsin cataclysmic flood(s). A facies analysis, based on a continuous photomosaic along a portion of the the 450-m (1,500-ft) length of the trench, is shown in Figure A-34.

Of particular note is a series of giant current ripples, buried 10 m (30 ft) bgs that developed near the top of a slackwater sequence (Lewis et al. 1993). The ripples, which display an amplitude of 1.8 m (6 ft), are asymmetric and approximately 45 to 60 m (150 to 200 ft) apart (Figure A-35). Current ripples of this magnitude are typical for Ice Age flood deposits reported elsewhere (Baker 1978, Alt 2001). Paleoflow indicators suggest that the ripples were laid down by high-energy flood currents moving from west to east along the northern edge of the Cold Creek flood bar (Figure A-20). Apparently, Sr ±Fl facies filled the troughs on the lee sides of giant-ripple crests during waning stages of flooding. This fine-grained sequence is continuous across the entire excavation (140 m by 450 m [460 ft by 1,500 ft]), although the thickness varies from about 10 cm (3.9 in.) at ripple crests to about 100 cm (39.4 in.) in the troughs (Figure A-35).

3.2.4.1.2 Facies Association GD at Transtate Borrow Pit. Another relatively deep (>15-m [>49.2-ft]) exposure displaying facies association GD is the Transtate borrow pit, located north of Pasco (Figure A-20). Several beds of gravel-dominated facies (Gp, Gh, and/or Gm), separated by thinner beds of horizontally laminated sand (Sh) (Figure B-2), are preserved in the Transtate site. Where gravel-dominated facies are proportionately greater than the sand-dominated facies, as in the lower portion of the sequence, it is designated as facies association GD. However, where the Sh facies is dominant, as in the upper few meters of the sequence (Figure B-3), this portion is designated as facies association SD.

Two features characteristic of flood deposits in the Pasco Basin are found at the Transtate site. One feature is a soft-sediment deformation in the form of huge flame structures atop some of the finer-grained Sh beds (Figure B-2), indicative of rapid sediment loading under saturated conditions. The other feature consists of large, weakly consolidated, tabular to slightly rounded rip-up clasts (Figures B-2 and B-3) derived from erosion of the nearby Ringold Formation and followed by rapid erosion and transport, perhaps while still frozen, before being quickly buried with other flood materials.

3.2.4.2 Sand-Dominated Facies Association (SD). Facies association SD consists of sequences at least several meters thick, composed of ≥50% sand lithofacies (Sh, St, Sp, and/or Sm) and <50% all other lithofacies. Finer-grained lithofacies (Fl and Fm) are generally thin to absent in facies association SD either because of (1) erosion and stripping away of fine-grained deposits associated with subsequent floods, and/or (2) fine-grained sand, silt, and clay remained suspended in the turbulent floodwater, never having an opportunity to settle out before being flushed out of the basin.

Natural exposures of facies association SD are scarce because of the normally very loose nature of the sand lithofacies. The best exposures of facies association SD within the Pasco Basin occur in a road cut near the mouth of Johnson Creek (Figure A-36) and at waste disposal excavations at the ERDF and the U.S. Ecology's landfill (Figure A-20). Sequences of facies association SD also exists at the Pre-Mix (Figure B-6), Transtate (Figure B-3), and Ringold Coulee (Figure B-4) exposures further east within the basin (Figure A-20). Facies association SD is also well exposed in cliffs along the Locke Island Landslide Complex (Figure A-33).

Generally, facies association SD formed at higher elevations where floodwaters were starved of gravel and/or adjacent to main flood channelways during the dissipating stages of flooding, or perhaps as crevasse splay-like deposits proximal to overflowing flood channels. Hanford formation facies association SD is the predominant facies beneath the sizable Cold Creek flood bar (Figures A-20 and A-22). In the 200 Areas, where much of Hanford's wastes are stored, is where the flood deposits reached their maximum thickness (up to 100 m [328 ft]) within the Pasco Basin (Figure A-23). Core samples of facies association SD from Cold Creek bar are shown in Figure A-37.

Reverse grading (Figures A-29 and A-38) is common between strata in facies association SD and has previously been reported (Bjornstad 1980, Moody 1987, Smith 1993, Fecht and Weekes 1996) as an indication of pulsations or surges during flooding. Therefore, caution is advised when attempting to interpret the number of individual flood events represented in a sand-dominated flood sequence.

3.2.4.2.1 Facies Association SD Exposed in Cold Creek Flood Bar. The largest and best exposures for facies association SD in the Pasco Basin are present within two recent man-made excavations within Cold Creek flood bar (Figure A-23). The two 15-m (50-ft)-deep excavations are the U.S. Ecology's low-level radioactive solid waste disposal facility (Bergeron et al. 1987, Smith 1993), and the ERDF (Weekes et al. 1995, Fecht and Weekes 1996). Stratigraphic correlation between the two sites is corroborated based on the Mount St. Helens "set S" tephra (13,000 ka) that is present at both locations.

Smith (1993), working at the U.S. Ecology landfill (Figure B-1), identified a total of 22 flood beds, with an average bed thickness of about 0.4 m (1.3 ft). Smith (1993) interpreted 11 separate floods, based on the number of individual beds with either eolian deposits and/or soil development at the top of beds. Mount St. Helens "set S" ash couplet is present about 10 beds from the top of the sequence (Figure B-1a). Most beds can be traced laterally for hundreds of meters along the walls of the U.S. Ecology excavation. One exception is a cut-and-fill scour, located toward the base of the section in Figure B-1a.

At ERDF, like the U.S. Ecology landfill, many of the individual beds can be traced laterally across the entire excavation (Fecht and Weekes 1996). Individual flood beds range from less than 0.3 m (1 ft) to greater than 1.8 m (6 ft), and average about 1 m (3 ft). The bases of the horizontally laminated sand beds (Sh), which make up the bulk of the beds, are typically sharp and distinct and grade upward into discontinuous layers of finer-grained sand (Sr) and silt layers (Fl ±Fm) capping some beds (Figure A-38a). Reverse grading is present within and between some beds. Most silt lenses are bioturbated with root casts and animal burrows filled with similar material as the host, and with $CaCO_3$. The coarse sands are composed of 40% to 70% basalt, 30% to 60% quartz/feldspar, and traces of mica and caliche clasts. A thin layer of coarser flood gravels (Gh) is present near the top of the flood sequence and clastic dikes are common (Fecht and Weekes 1996).

3.2.4.2.2 Facies Association SD Exposed at Johnson Creek. In a road cut located near the mouth of Johnson Creek (Figure A-19), an exposed sequence, 3 to 6 m (9.8 to 19.7 ft) high and 100 m (328 ft) long, was deposited during the last Ice Age flood(s). The sequence consists of mostly trough cross-bedded sands and pebbly sands (St), with lesser amounts of horizontally laminated coarse- (Sh) and ripple-laminated fine sands (Sr) (Figures A-29 and A-36). Portions of the sequence are bioturbated with root casts and animal burrows. At least 90% of the coarser sand particles are composed of basalt. A few clastic dikes are also present. The abundance of trough cross-bedded sands may be the result of swirling eddy currents that developed in this side valley immediately adjacent to high-energy flow associated with cataclysmic floods moving down the main channel of the Columbia River.

3.2.4.2.3 Facies Association SD Exposed Along White Bluffs at Locke Island Landslide Complex. A well-exposed sequence of facies association SD is present along the White Bluffs in an area of active landsliding (Figure A-33). Facies association SD appears to fill a paleochannel that is incised about 20 m (65.6 ft) into the Ringold Formation (Figure A-23). The base of the buried channel lies at about the 180-m (590-ft) elevation, or about 65 m (213.3 ft) above the present level of the nearby Columbia River. Within this fill, are preserved as many as 9 relatively thick (up to several meters) "rhythmites," grading from horizontally laminated coarse- to fine-grained sand (Sh) and rippled fine sands (Sr) at the base to mostly massive, fine- to coarse-grained sand (Sm) at the tops of individual beds. The Sh/Sr beds, which display soft-sediment deformation and rip-up clasts, represent flood-laid beds. The intervening light-colored, poorly sorted Sm beds, which show signs of bioturbation, are interpreted as eolian deposits that developed via the reworking by wind of the underlying Ringold Formation; a similar process appears to be continuing today (Figure A-33a). No clastic dikes were observed in the flood sequence.

This flood sequence demonstrates that rhythmite formation is not limited to finer-grained facies along valley margins or backflooded valleys, but may also develop locally under the right conditions toward the interior of the basin. The trend of the paleochannel, which is transverse to the movement of Ice Age floodwaters in this area (Figure A-23), suggests that it is probably not associated with Pleistocene cataclysmic flooding, but instead an old tributary of the Columbia River that existed prior to Ice Age flooding. The ancestral Palouse River is a strong possibility.

3.2.4.3 Interbedded Sand- and Silt-Dominated Facies Association [ISSD]. This facies association was first formally described by Flint (1938) as "buff- to cream-colored silt and sand with erratic stones," upstream of the Columbia Gorge and the Walla Walla Valley. Facies association ISSD consists of ≥50% Sr, Fl, and/or Fm lithofacies and <50% other lithofacies (Figure A-25). Perhaps the best exposure of facies association ISSD is Burlingame Canyon in the Walla Walla Valley, east of the Pasco Basin, where up to 40 well-developed rhythmites are exposed (Figure A-39). Overall, beds become thicker and coarser with depth, whereby the ratio of sand (Sh and Sr) to fine-grained (Fl and Fm) lithofacies increases with depth. Facies association ISSD characteristically consists of graded beds of sand and silt, otherwise known as "rhythmites" (Carson et al. 1978, Bjornstad 1980, Waitt 1980, DOE 1988, Smith 1993). Individual rhythmites range from a few centimeters to a meter in thickness (Baker et al. 1991, Smith 1993), and when exposed in outcrop, they can be traced laterally for hundreds of meters or more.

Slackwater deposits of facies association ISSD are most prevalent around the margins of the Pasco Basin and up backflooded tributary valleys along the flood's route (Figures A-19, A-20, and A-23). Occasional pebble- to boulder-sized clasts, other than basalt found floating within the fine-grained matrix of facies association ISSD, most likely represent ice-rafted erratics that floated in on icebergs (Figure A-24).

Facies association ISSD provides a record of the occurrence of many floods. In slackwater environments, the erosive power of the floods was diminished, resulting in little or no erosion during (and between) flood events. While minor erosion may occur associated with localized scouring along the bases of some beds, the upper portions of rhythmites are predominantly composed of silt that settled out of suspension and covered backflooded areas with a relatively continuous blanket of fine-grained sediment. The cohesive and compact silt caps that mantle most ISSD rhythmites further protected the underlying beds from erosion during subsequent floods.

3.2.5 Discussion

In the Pasco Basin, where the thickest accumulations of flood deposits exist, typically more than one facies association of the Hanford formation is represented in a vertical section. Multiple facies associations of the Hanford formation are common, based both on borehole studies (Figure A-40), as well as in some deeper surface exposures (Appendix B). For example, at lower elevations within the central Pasco Basin, facies associations SD generally overlies GD. This relationship exists at the Transtate borrow pit (Figure B-3), Ringold Coulee (Figure B-4), the lower Smith Canyon (Figure B-5), and Pre-Mix (Figure B-6) locations. Transition from facies associations GD to SD at these locations suggest that perhaps the last flood(s) were smaller and less energetic than earlier floods.

In the Pasco Basin, vertical changes in flood sequences may also be the result of floodwaters entering the basin at different times via at least three different flood routes (i.e., Snake River, Channeled Scabland, and Columbia Valley) (see Figure A-19). As an example, a high-energy proximal flood locality for floods coming down Esquatzel Coulee off the Channeled Scabland (e.g., the Transtate borrow pit site) (Figures B-2 and B-3) might be a distal flood environment for later floods coming down the Columbia River Valley after the retreat of the Okanogan Lobe of the Cordilleran Ice Sheet.

Elsewhere, along the southern margin of the Pasco Basin at Kiona Quarry, facies association GD is overlain by ISSD, separated by a thick calcic paleosol sequence (Figure B-7). One explanation for the flood gravel sequence at the base of the Kiona Quarry is that higher-energy floodwaters initially ran down the ancestral Yakima River valley via Badger Coulee (Fecht et al. 1987). Later, after Badger Coulee became choked with up to 30 m (98.4 ft) of flood deposits, the Yakima River was diverted northward through the saddle between Red Mountain and Rattlesnake Mountain (see Figure A-20). Only after the diversion of the Yakima River did Badger Coulee become an area for slackwater flood sedimentation resulting in deposition of the ISSD sequence.

Typically there is at least one transition from facies association SD to GD in the vicinity of the 200 Areas, and in some cases there are multiple GD/SD sequences (Figures A-5, A-22, and A-40). On a gross scale, most of the northern portion of the 200 Areas is blanketed with facies association GD, underlain by a relatively thick sequence of facies association SD deposits; however, considerable internal complexity and heterogeneity exist at a finer scale. While some fine-grained sand to silt layers are present, these represent only a small fraction of the total volume, and therefore facies association ISSD is not represented in the immediate vicinity of the 200 Areas. Facies association ISSD is present, however, in more distal flood environments that existed south of the 200 Areas (e.g., see Figures A-5, A-20, and A-23).

In summary, multiple GD/SD sequences are the result of the complex hydrodynamics during flooding set up by constant changes in the volume, direction, and velocity of floodwaters over time and space. For this reason, correlations of individual beds or flood events cannot be performed with any confidence, except where volcanic marker horizons are present or where the magnetostratigraphy is well constrained. Generally, because of a greater preservation potential within the finer-grained flood deposits, more confidence is associated with correlation of facies associations SD and ISSD around the margins of the basin than coarse-grained flood deposits (GD) in the center of the basin.

3.3 HOLOCENE DEPOSITS

Holocene surficial deposits of silt, sand, and gravel up to 5 m (16 ft) thick are locally present within the Pasco Basin. Below about the 300-m (1,000-ft) elevation, these deposits overlie Pleistocene cataclysmic flood deposits of the Hanford formation. Above 300 m (1,000 ft), these deposits generally lie on top of Columbia River basalt. Because of their relatively young geologic age, Holocene deposits are generally unweathered and unconsolidated.

Characteristics of the Holocene deposits are identified in Table 1. Similar to the CCU, Holocene deposits are described first on the basis of grain size, followed by one or more descriptive modifiers, which are diagnostic of the lithofacies being described; modifiers include sorting, roundness, sedimentary structure, fabric, and/or basalt content. Accordingly, seven lithofacies are identified for the Holocene deposits (Table 4).

Table 4. Lithofacies of the Holocene Deposits Within the Pasco Basin.

Lithofacies	Symbol	Environment of Deposition
Fine-grained, massive, well-sorted	HDf(msv-ws)	Eolian loess
Fine-grained, weakly laminated, poorly sorted	HDf(lam-ps)	Slopewash (colluvium)
Medium-grained, cross-bedded, well-sorted	HDm(xbed-ws)	Eolian dune sand
Coarse-grained, rounded	HDc(rnd)	Alluvium
Coarse-grained, angular, basaltic	HDc(ang-bas)	Talus (colluvium)
Coarse- to fine-grained, massive, matrix-supported	HDc-f(msv-ms)	Landslide/debris flow
Tephra	HDt	Volcanic ashfall

Holocene deposits derive from a variety of depositional environments including eolian, alluvial, colluvial, landslide, and occasional volcanic ashfall activity, which post-date the last Ice Age cataclysmic flood about 13,000 years before present.

Eolian deposits include loess and dune sand. Loess is a massive, somewhat cohesive, pale brown, fine sand and silt that develops in the uplands around the margins of the Pasco Basin, especially on lee (north) aspects. Dune sand, which consists of loose, well-sorted, cross-stratified fine to medium sand, is restricted to the central portion of the basin where strong winds are best organized (Figure A-41). Two principal wind directions, west-southwest and west-northwest, are effective at transporting sand through the central basin; the predominant wind direction varies from one part of the basin to another (DOE 1988). Much of the east-central Pasco Basin is blanketed by Holocene dune sand, expressed on the surface as a series of longitudinal northeast trending dunes (Gaylord et al. 1991, Fayer et al. 1999). Most dunes are stabilized but are easily reactivated after fire or other disturbances. Reactivation can occur in isolated dune "blowouts," or over entire regions. Two areas with regionally active dune movement are a large dune field located west of Ringold Coulee, and the western Hanford Site after the wildfire in the summer of 2000. Dune sand is primarily derived from reworked flood deposits (i.e., Hanford formation). Holocene loess and dune sand are differentiated from older eolian deposits (e.g., CCUf(lam-msv) facies, Fm and Sm facies of the Hanford formation) by a combination of stratigraphic position (i.e., overlies cataclysmic flood deposits) and general lack of weathering.

Coarse-grained, angular, basaltic gravel with or without a massive, poorly sorted, sand to silt matrix, which occurs along steep to gentle upland slopes, is colluvium (Table 1). The coarse-grained fraction is sometimes referred to as “talus” and the fine-grained fraction as “slopewash” (Table 4). Colluvium, a type of mass wastage deposit, is derived from the slow, continuous downslope movement of sedimentary particles that commonly collect at the base of these slopes, primarily under the influence of gravity and/or unconcentrated surface runoff (i.e., sheetwash). Holocene colluvium may be differentiated from older colluvium (e.g., CCUc(ang-bas) facies) by a combination of stratigraphic position (i.e., overlies cataclysmic flood deposits) and general lack of weathering.

Isolated, large blocks of disturbed or chaotically bedded sediment and/or bedrock, along with massive, very poorly sorted, matrix-supported gravel, represent landslides (Figure A-41) and debris flow deposits, respectively. Landslides and debris flows are another type of mass wastage deposit that form as a result of rapid, in-mass movement downslope strictly under the influence of gravity. In the Pasco Basin, landslides and debris flows are intimately associated with one another. Landslides create large backward-rotated blocks, and debris flows frequently move further downslope beyond these blocks as a result of liquefaction that may develop during landslide events.

Two types of landslides represented in Figure A-41 include (1) landslides that occurred prehistorically along steep north-facing basaltic ridges of the Pasco Basin, perhaps associated with the rapid drop in water level and dewatering following Ice Age floods; and (2) landslides along the White Bluffs within the weak Ringold Formation as a result of undercutting by the Columbia River and/or instability caused by percolating irrigation water upslope of the bluffs (Schuster and Hays 1984).

Stratified gravel, sand, and silt deposited near the surface along stream valleys make up alluvial deposits (Figure A-41). Thicknesses are usually only a few meters or less. Alluvial fans are also present locally, especially along the bases of steeper north-facing ridges. Alluvial fans are associated with a decrease in stream gradient where ephemeral streams flow off steep ridges onto the gentler valley terrain. Sediment transport within ephemeral alluvial channels probably only occurs sporadically during periods of high-precipitation and/or rapid snow melt.

Another type of sedimentary deposit that can occur within or between other Holocene deposits is tephra, derived from Cascade volcanic eruptions (Wilcox 1965, Sarna-Wojcicki and Davis 1991). Holocene tephra deposits in the Pasco Basin are loose, light-colored, gritty, powdery, fine-grained, and found only sporadically. Two Holocene-age volcanic ashfall layers are present locally within the Pasco Basin (DOE 1988, Baker et al. 1991). One is the 6,800-year-old Mount Mazama ash, and the other is from eruption(s) of Glacier Peak (Westgate and Evans 1978), dated at 11,200 years before present (Mehringer et al. 1984). Mazama ash is much thicker (up to 1 m [3.3 ft]) and has a “pinkish” cast compared to the much thinner (a few centimeters or less), almost pure white Glacier Peak tephra, which commonly occurs as a couplet.

4.0 CONCLUSIONS

A consistent, standardized stratigraphic nomenclature for post-Ringold (late Pliocene to Quaternary) deposits has been presented in this document to support hydrogeologic characterization and performance assessment modeling at the Hanford Site. Standardized terminology was presented based on sedimentary facies observed on a more regional scale (i.e., central Pasco Basin) than has been presented in the past.

A total of three post-Ringold units are proposed: the CCU (formerly the Plio-Pleistocene unit), the Hanford formation, and Holocene deposits. The CCU developed following Ringold incision (3.4 Ma) and prior to Ice Age flooding, which began 1.5 to 2.5 million years ago. Five lithofacies of the CCU are differentiated on the basis of grain size, sedimentary structure, sorting, roundness, cementation, and relative basalt content. These facies consist of: (1) coarse-grained multilithic [c(ml)]; (2) coarse- to fine-grained $CaCO_3$-cemented [c-f(calc)]; (3) coarse-grained rounded, basaltic [c(rnd-bas)]; (4) coarse-grained, angular, basaltic [c(ang-bas)]; and (5) fine-grained, laminated to massive [f(lam-msv)]; interpreted as mainstream alluvial, calcic paleosol, sidestream alluvial, colluvial, and overbank-eolian environments, respectively.

Pleistocene-age, cataclysmic flood and inter-flood deposits (Hanford formation) consist of 11 distinct lithofacies: Fm, Fl, Sm, Sr, Sh(f), Sh(c), Sp, St, Gm, Gh, and Gp. These lithofacies are differentiated on the basis of textural and structural characteristics. The lithofacies occur together into three general groupings, namely gravel-dominated (GD), sand-dominated (SD), and interbedded sand- and silt-dominated (ISSD) facies associations. Commonly, these facies associations intercalate with, and grade laterally as well as vertically into each other. The type of facies association(s) present is a function of elevation, as well as distance with respect to high-energy flood channels. Flood deposits are generally restricted to elevations below 380 m (1,250 ft) within the central Pasco Basin. Slackwater flood facies (i.e., SD and ISSD) around the margins of the basin exhibit more lateral continuity compared to coarser-grained, high-energy flood deposits (GD) located toward the center of the basin.

Holocene deposits consist of relatively thin sequences (a few meters or less) of unconsolidated, fine- to coarse-grained sediments. Similar to the CCU, these deposits are differentiated on the basis of grain size, sedimentary structure, sorting, roundness, fabric, and relative basalt content. A total of seven lithofacies are recognized as follows: (1) fine-grained, massive, well sorted [f(msv-ws)]; (2) fine-grained, weakly laminated, poorly sorted [f(lam-ps]; (3) medium-grained, cross-bedded, well-sorted [m(xbed-ws)]; (4) coarse-grained, rounded [c(rnd)]; (5) coarse-grained, angular, basaltic ([c(ang-bas)]; (6) coarse- to fine-grained, massive, matrix supported [c-f(msv-ms)]; and (7) tephra (t).

Interpreted depositional environments for these lithofacies are eolian loess, slopewash, eolian dune sand, alluvium, colluvium (i.e., talus), landslide/debris flow, and volcanic ashfall, respectively. Some of these lithofacies, including coarse-grained, rounded [c(rnd)] and coarse-grained, angular, basaltic ([c(ang-bas)], are similar to those of the CCU but are differentiated on the basis of stratigraphic position and degree of weathering/cementation.

The U.S. Department of Energy, Richland Operations Office, and the U.S. Department of Energy, Office of River Protection request the nomenclature presented herein be used as the standard in all geologic/geohydrologic discussions until such time as a new standard is recognized. The standardized stratigraphic nomenclature presented herein should be revisited periodically and updated as needed to reflect new data and interpretations in the conceptual geohydrologic model for the central Pasco Basin.

5.0 REFERENCES

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APPENDIX A

FIGURES AND PHOTOS

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FIGURES

Figure A-1. Location Map Showing Central Pasco Basin.

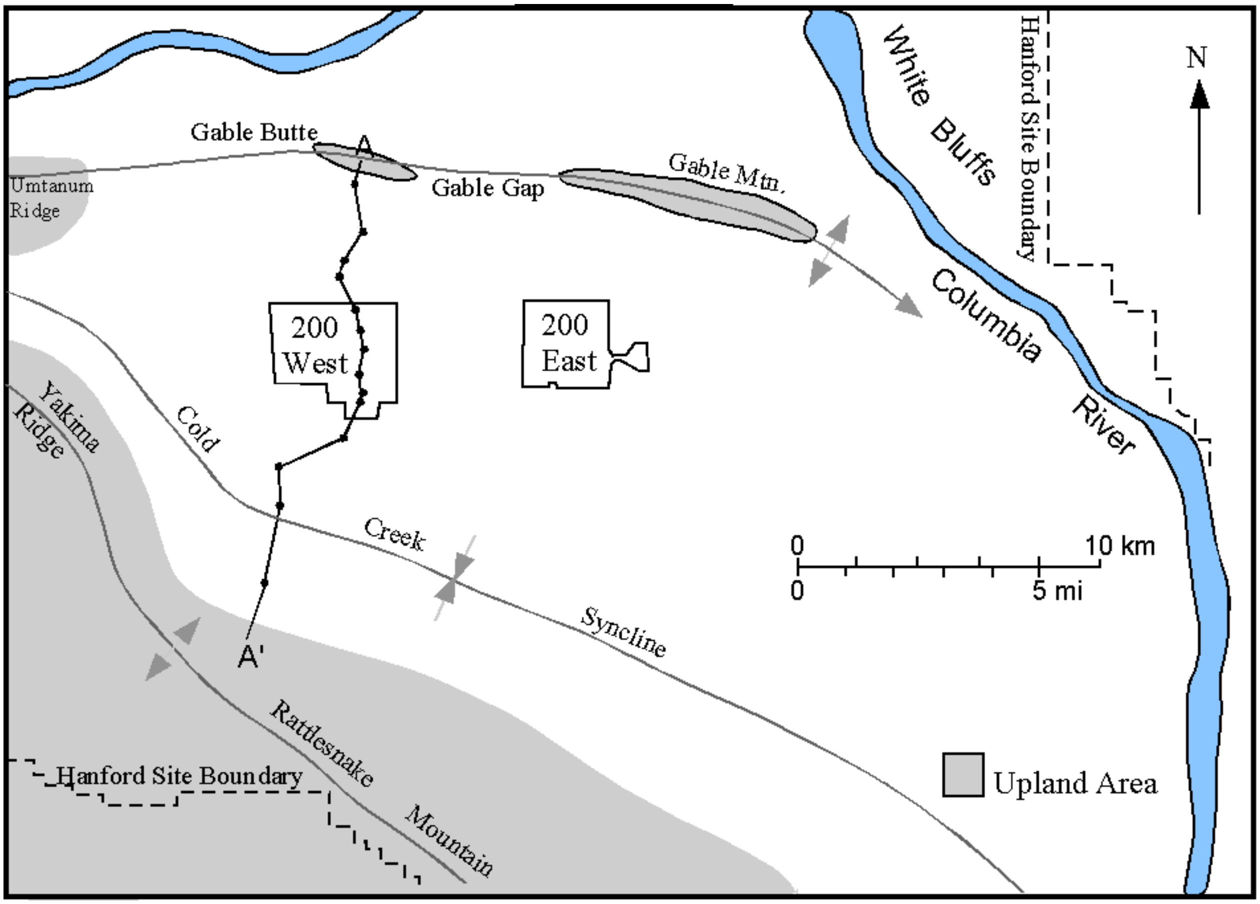
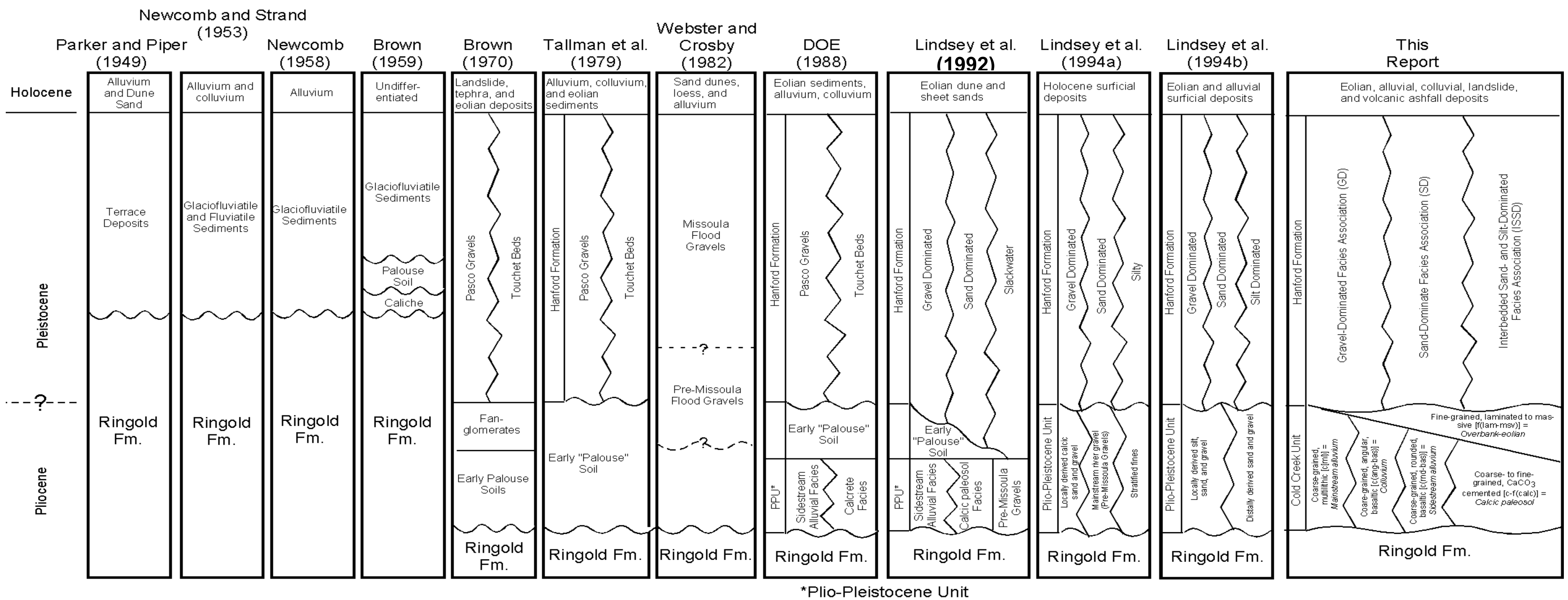


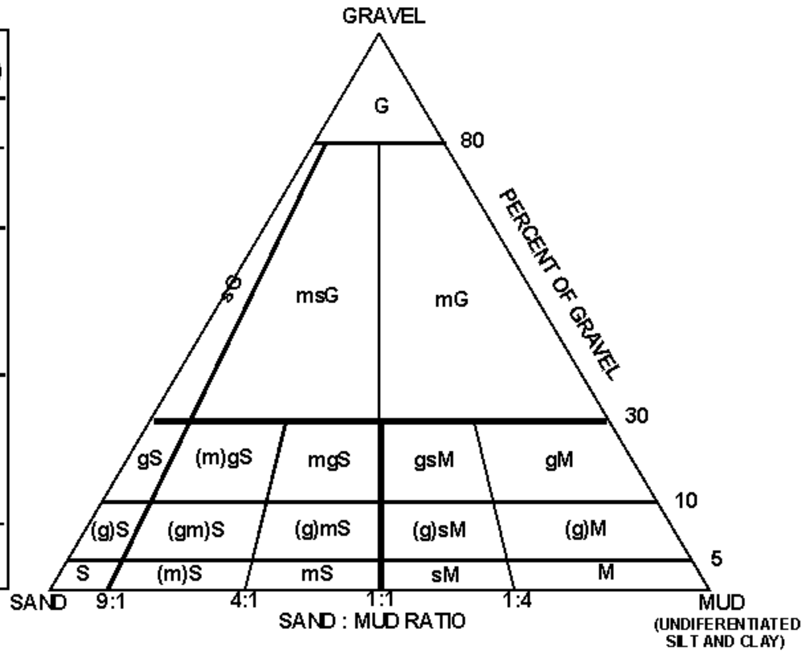
Figure A-2. Evolution of Post-Ringold Stratigraphic Nomenclature Within Central Pasco Basin.



*Plio-Pleistocene Unit

Figure A-3. Sediment Classification Scheme and Grain-Size Nomenclature.[a,b]

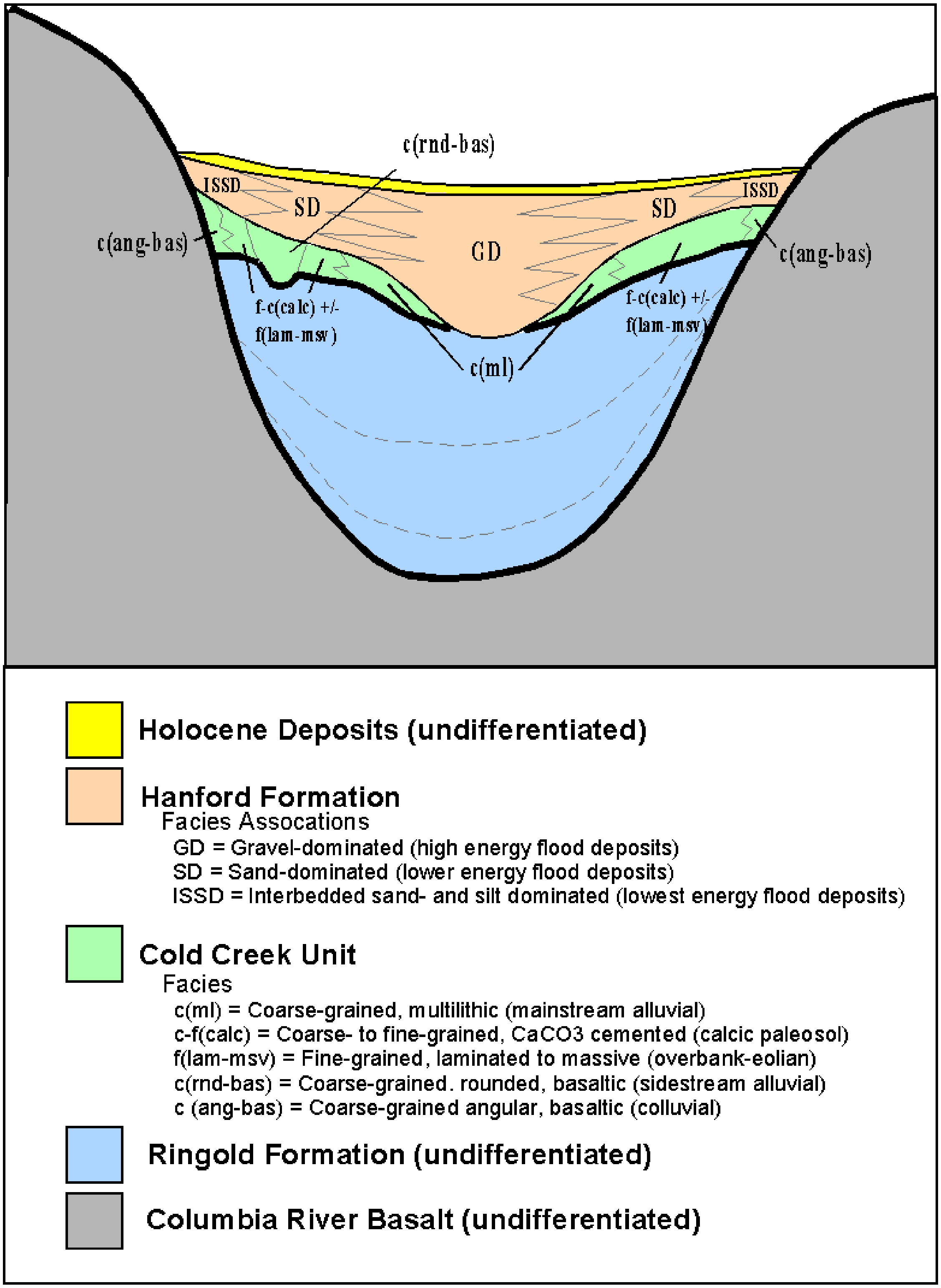
PARTICLE DESIGNATION			PARTICLE DIAM. (MM)
GRAVEL	BOULDER		>256
	COBBLE	LARGE	256-128
		SMALL	128-64
	PEBBLE	VERY COARSE	64 - 32
		COARSE	32 - 16
		MEDIUM	16 - 8
		FINE	8 - 4
		VERY FINE	4 - 2
SAND		VERY COARSE	2 - 1
		COARSE	1 - 1/2
		MEDIUM	1/2 - 1/4
		FINE	1/4 - 1/8
		VERY FINE	1/8 - 1/16
MUD		SILT & CLAY	<1/16



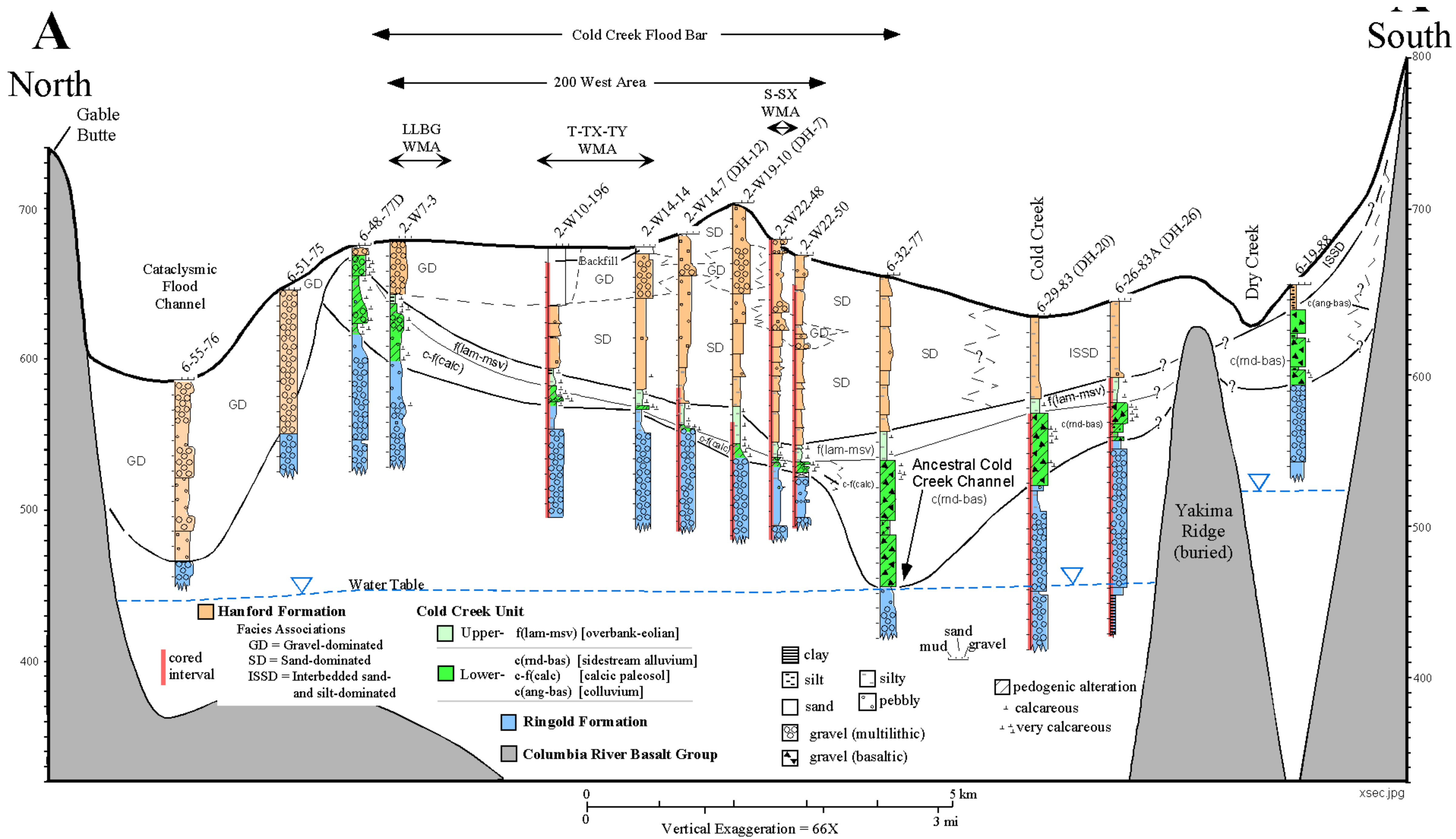
[a] Sediment classification scheme modified from Folk (1968), and grain-size nomenclature modified from Wentworth (1922).

[b] The term "mud" is a general term used in stratigraphy to include all particles smaller than sand (i.e., clay- and silt-sized particles).

Figure A-4. Generalized Stratigraphic Relationships Among Post-Ringold Units for Central Pasco Basin.



Section (A-A') Within Western Pasco Basin.[a]



[a] See Figure A-1 for cross-section location. Note the dramatic lateral facies changes that occur within the Cold Creek unit and Hanford formation. Holocene deposits are generally less than 1 m (3.3 ft) in thickness and, therefore, are not shown in this figure.

Figure A-6. Facies Distribution for Cold Creek Unit Within the Central Pasco Basin.

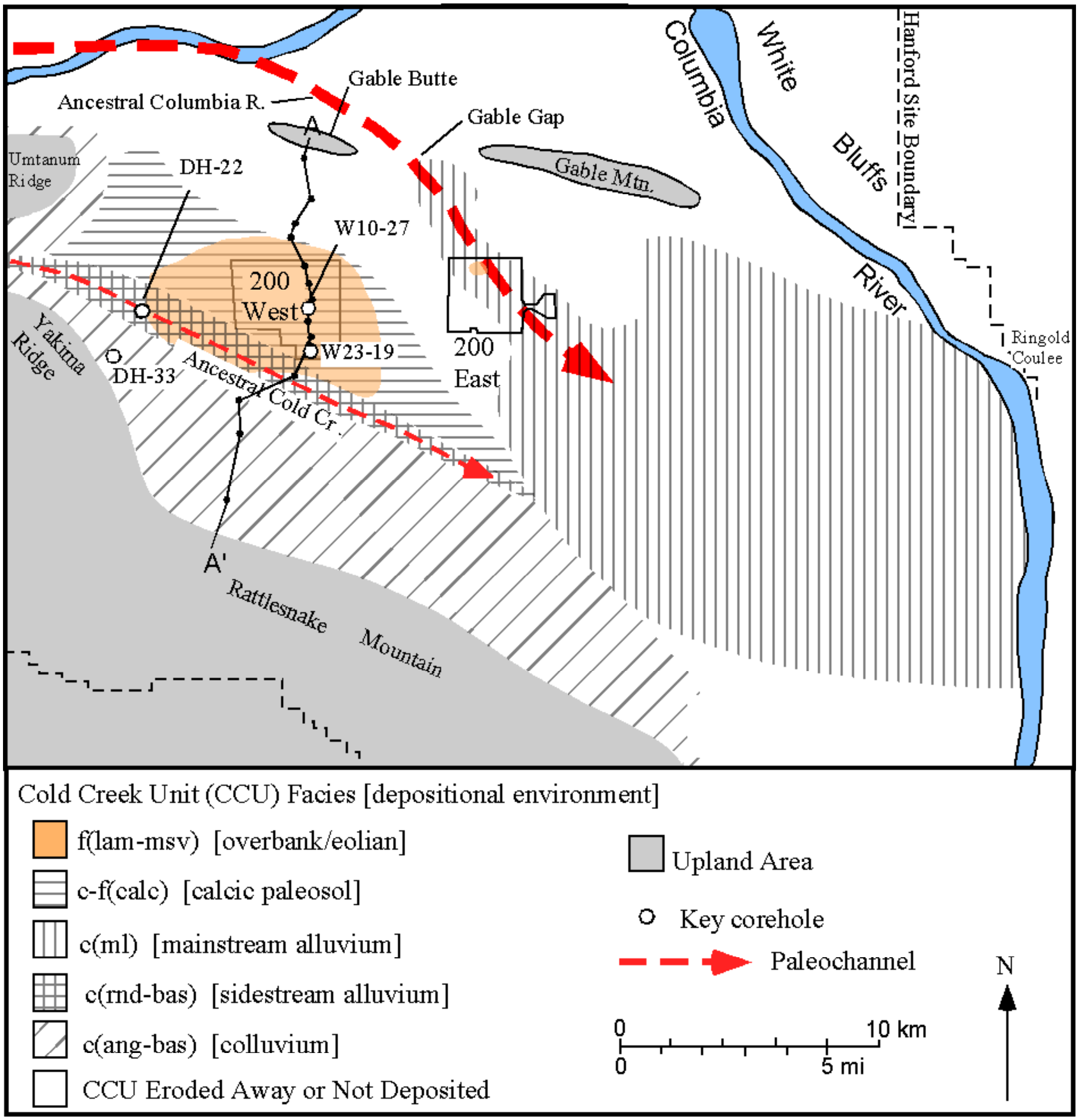
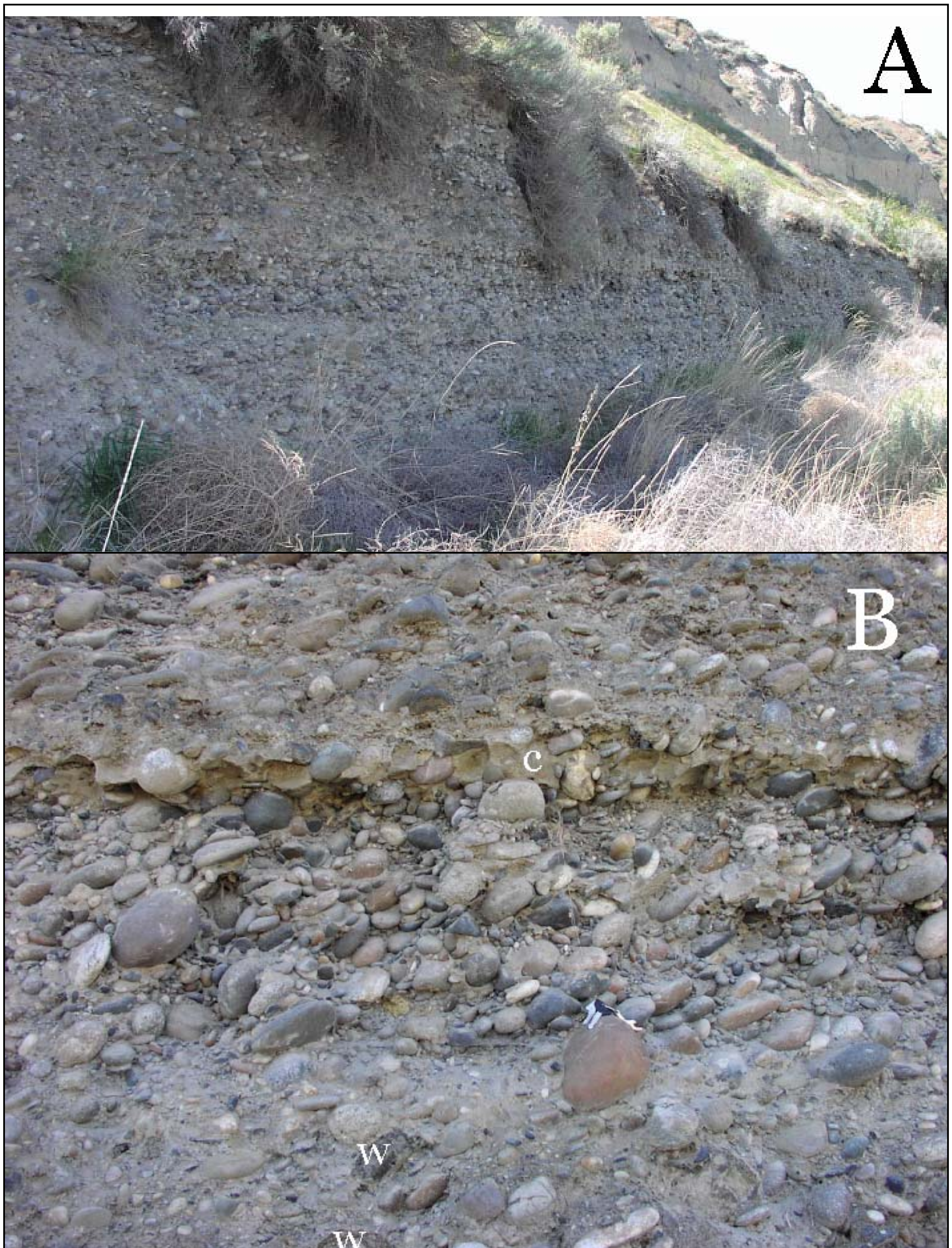


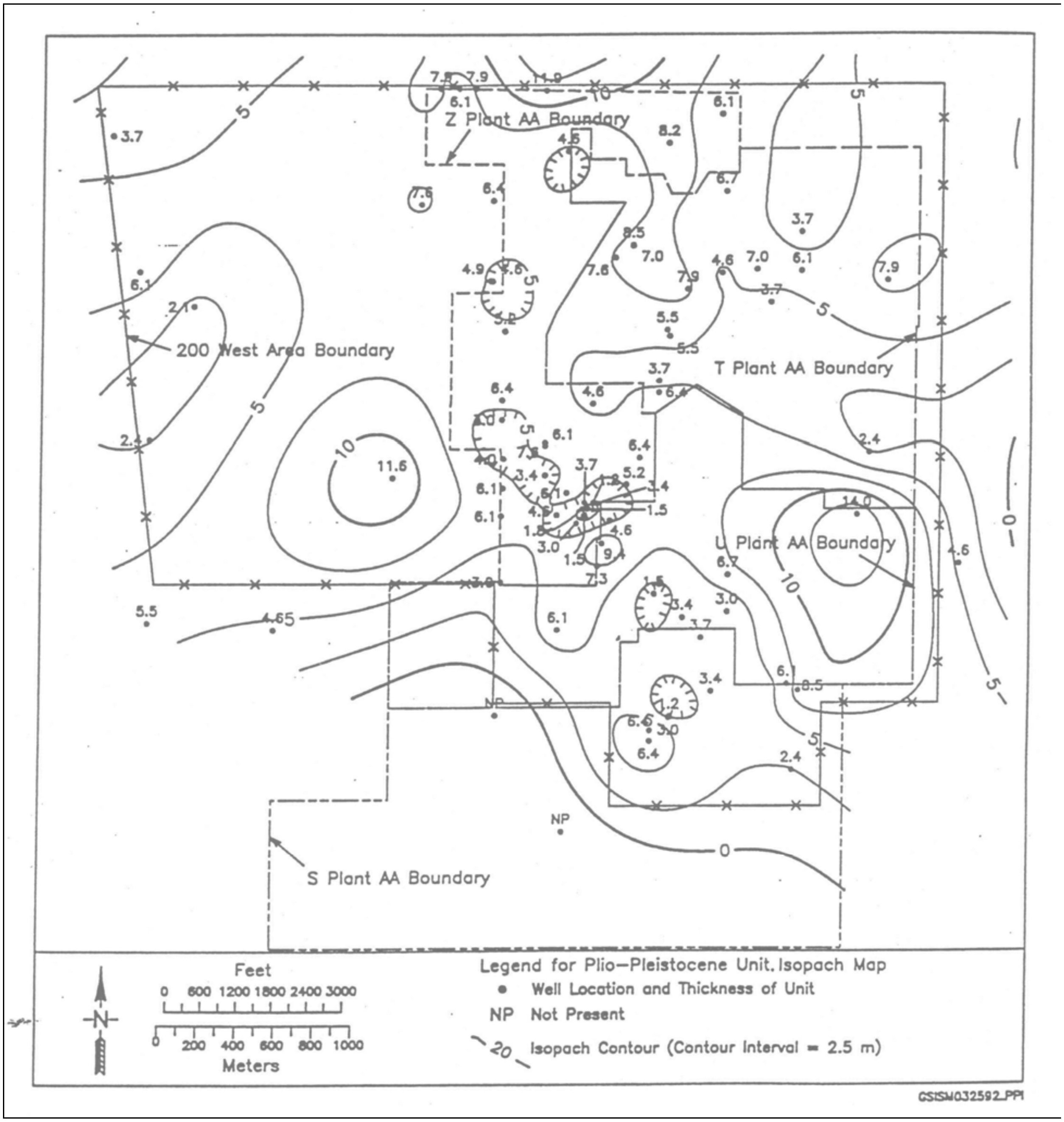
Figure A-7. Coarse-Grained Multilithic Lithofacies (CCUc[ml]) of Cold Creek Unit at Yakima Bluffs.[a,b]



[a] The notations in the figure indicate the following: (A) shows the horizontal bedding with more resistant $CaCO_3$ cemented layers. (B) shows a close-up of rounded, clast-supported, sandy, pebble to cobble gravel with local $CaCO_3$ cemented layer (C). Only a small percentage of the basalt clasts have significant weathering rinds (W). (Car keys are shown for purpose of scale.)

[b] Interpreted depositional environment is mainstream alluvium.

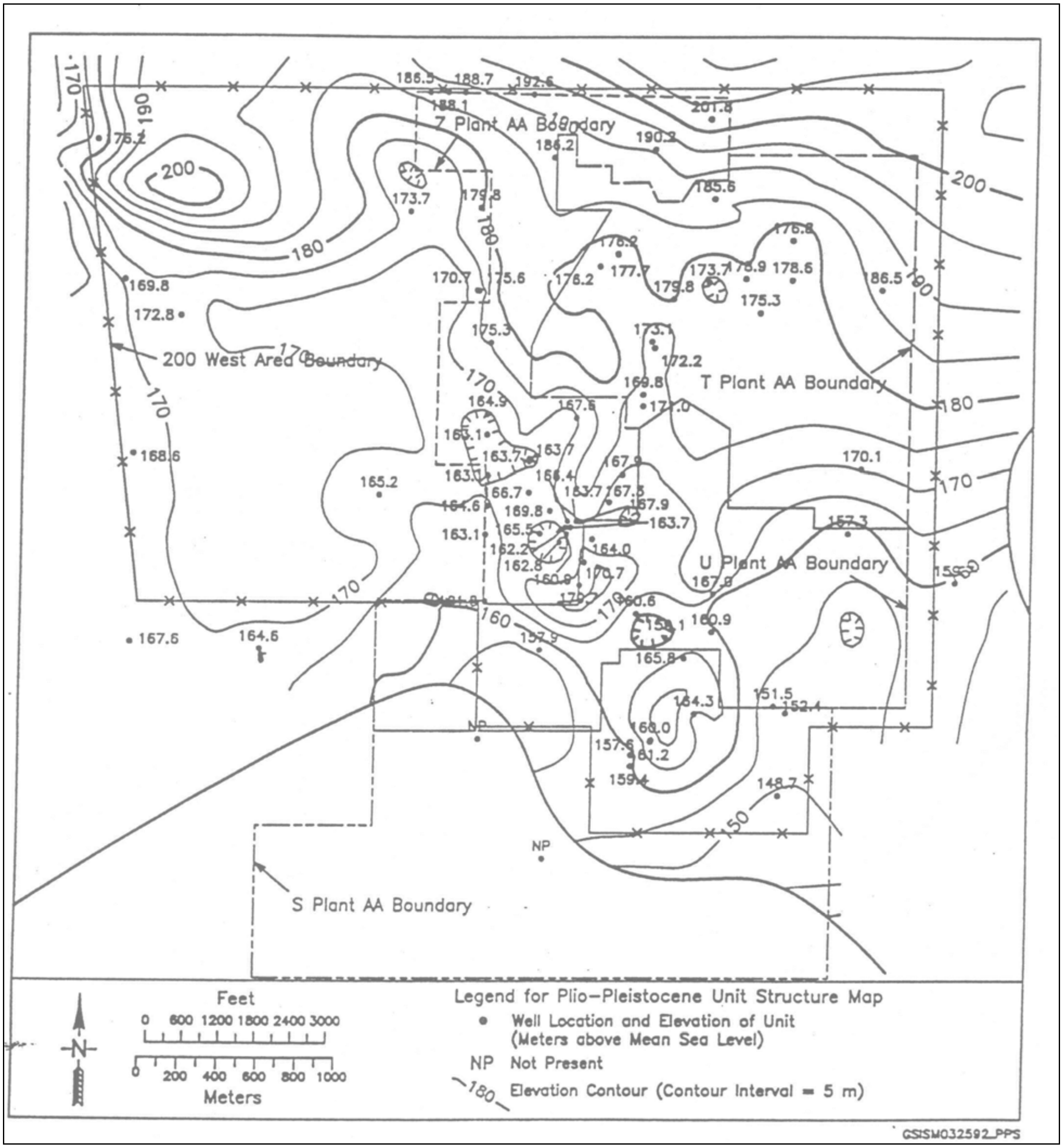
Figure A-8. Isopach Map of the CCUc-f(calc) Lithofacies in Vicinity of 200 West Area.[a]



Source: Connelly et al. 1992.

[a] The CCUc-f(calc) facies is equivalent to what has been traditionally referred to as the Plio-Pleistocene unit.

Figure A-9. Contour Map of Top of CCUc-f(calc) Lithofacies in Vicinity of 200 West Area.



Source: Connelly et al. 1992.

Figure A-10. Morphogenetic Stages of Pedogenic $CaCO_3$ Development in Fine- vs. Coarse-Grained Soils.

Calcic Soil Development in Gravelly versus Fine-Grained Soils

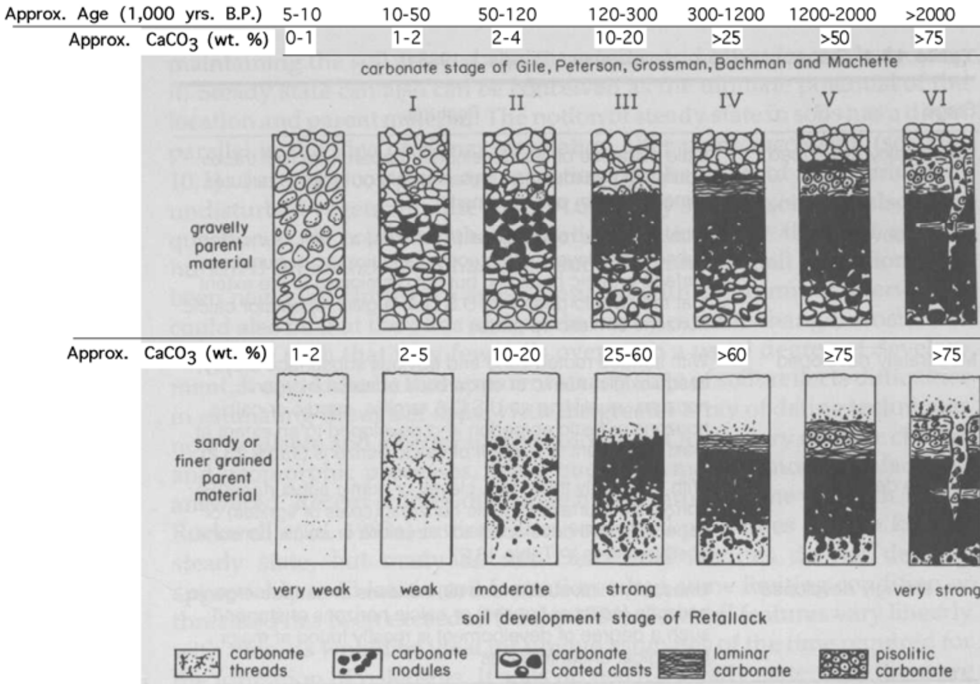


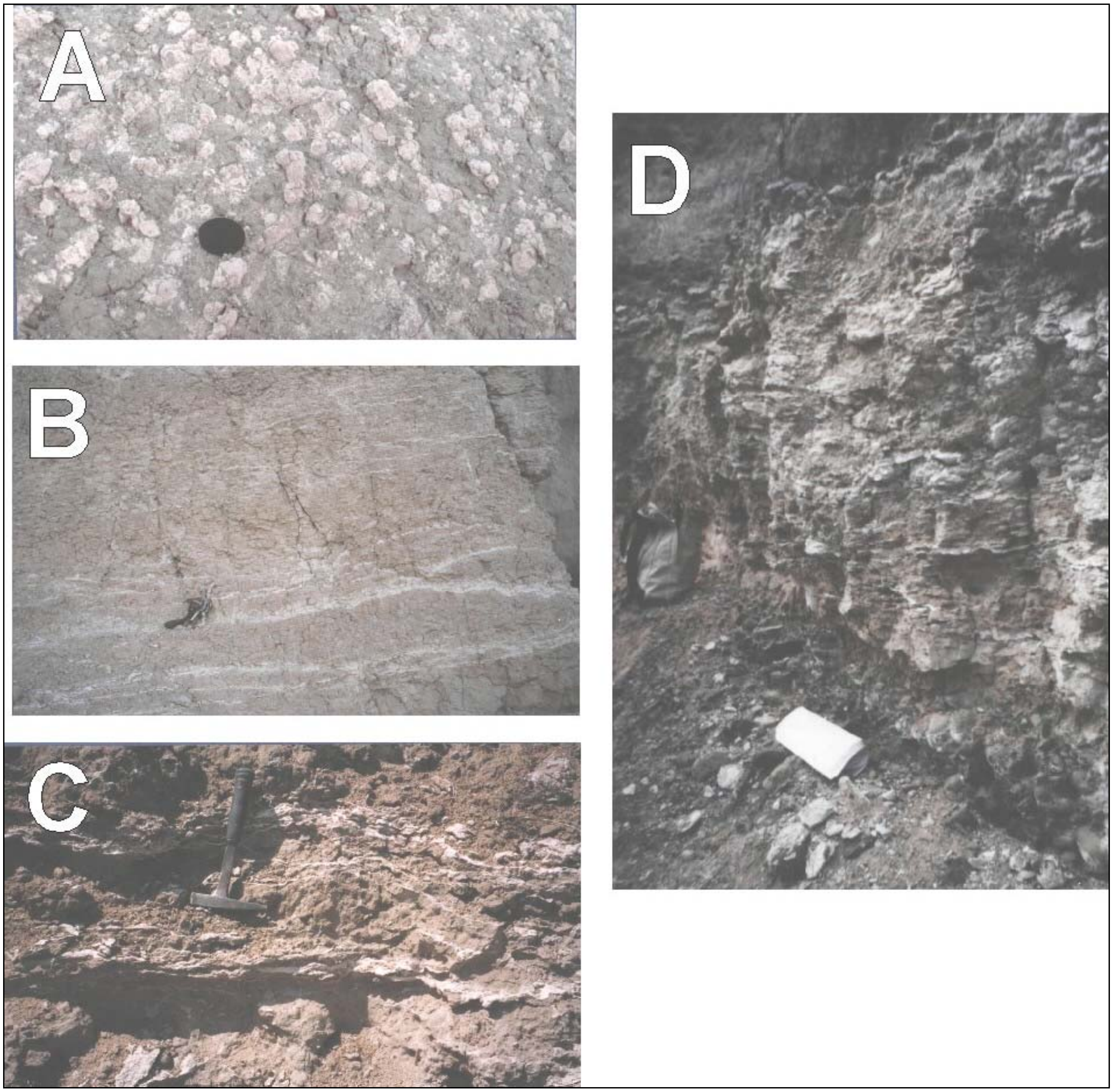
Figure 13.3 Stages of the morphology of carbonate accumulations in soils formed on gravelly and on sandy or finer grained alluvium (modified from Gile *et al.* 1966 and Machette 1985, with permission of Williams & Wilkens Co. and the Geological Society of America).

Table 13.2 Stages of carbonate accumulation in paleosols (from Machette 1985)

Stage	Paleosols developed in gravel	Paleosols developed in sand, silt or clay
I	Thin discontinuous coatings of carbonate on underside of clasts	Dispersed powdery and filamentous carbonate
II	Continuous coating all around and in some cases between clasts: additional discontinuous carbonate outside main horizon	Few to common carbonate nodules and veinlets with powdery and filamentous carbonate in places between nodules
III	Carbonate forming a continuous layer enveloping clasts: less pervasive carbonate outside main horizon	Carbonate forming a continuous layer formed by coalescing nodules: isolated nodules and powdery carbonate outside main horizon
IV	Upper part of solid carbonate layer with a weakly developed platy or lamellar structure capping less pervasively calcareous parts of the profile	
V	Platy or lamellar cap to the carbonate layer strongly expressed: in places brecciated and with pisolites of carbonate	
VI	Brecciation and recementation as well as pisoliths common in association with the lamellar upper layer	

Source: Modified after Rettalack (1990).

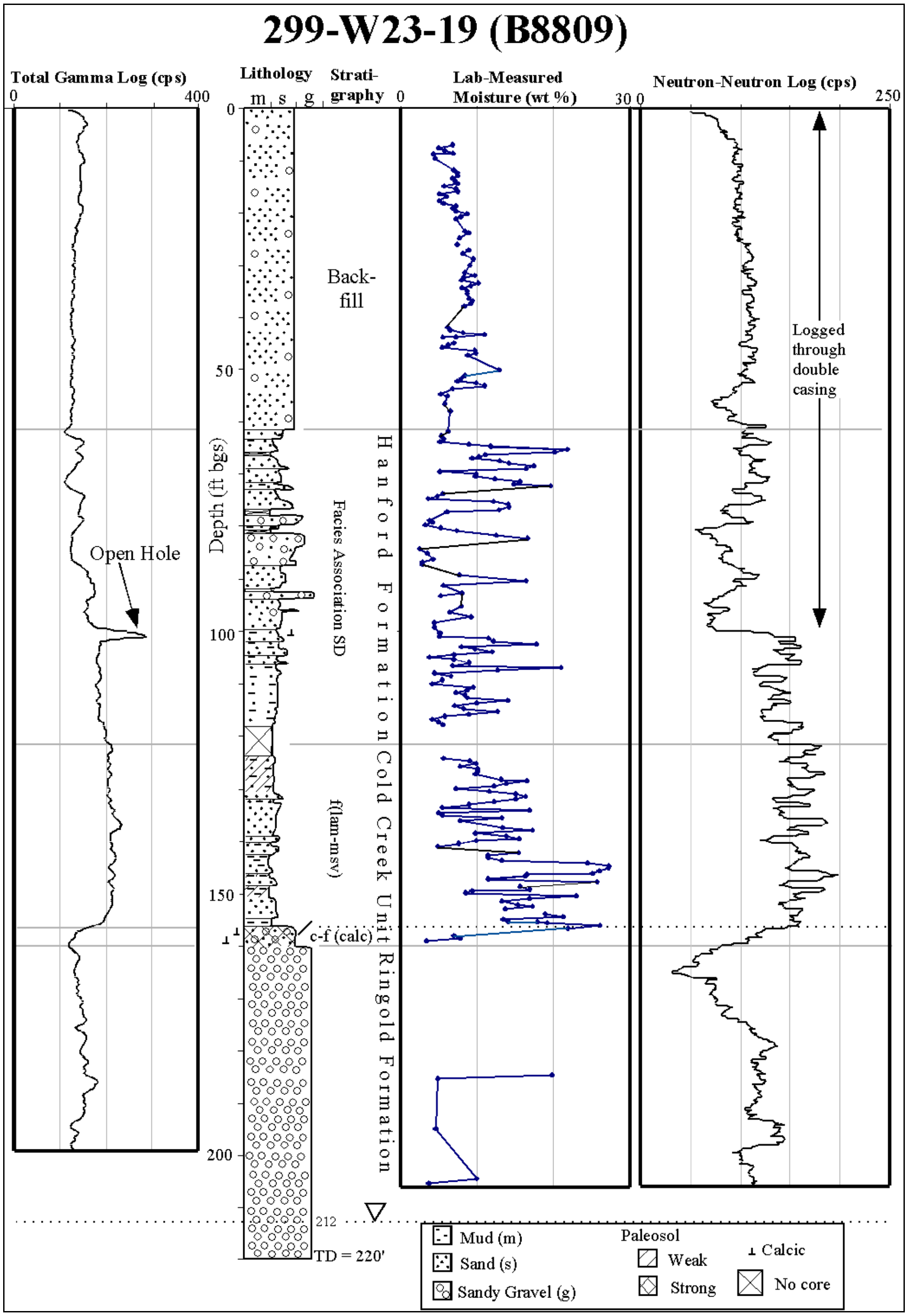
Figure A-11. Surface Analogs for $CaCO_3$ Cemented (c-f[calc]) Lithofacies of Cold Creek Unit.[a,b]



[a] (A) shows light-colored, pedogenic, calcium-carbonate nodules in fine-grained matrix (Stage II-III). (B) and (C) show subhorizontal $CaCO_3$ stringers and veinlets in fine-grained matrix (Stage II-III). (A) and (B) are from the Ringold Formation member of Savage Island, White Bluffs. (C) is from the pedogenically altered loess of the Palouse Formation near Kahlotus, Washington. (D) shows thick (1-m [3.3-ft]) zone of platy to laminar $CaCO_3$ forming a true petrocalcic zone where most pore spaces are completely plugged with secondary $CaCO_3$ (Stage IV-V). From paleosol overlying early Pleistocene cataclysmic flood gravels at Old Maid Coulee (Bjornstad et al. 2001).

[b] Interpreted depositional environment is calcic paleosol (i.e., buried calcareous soil horizons).

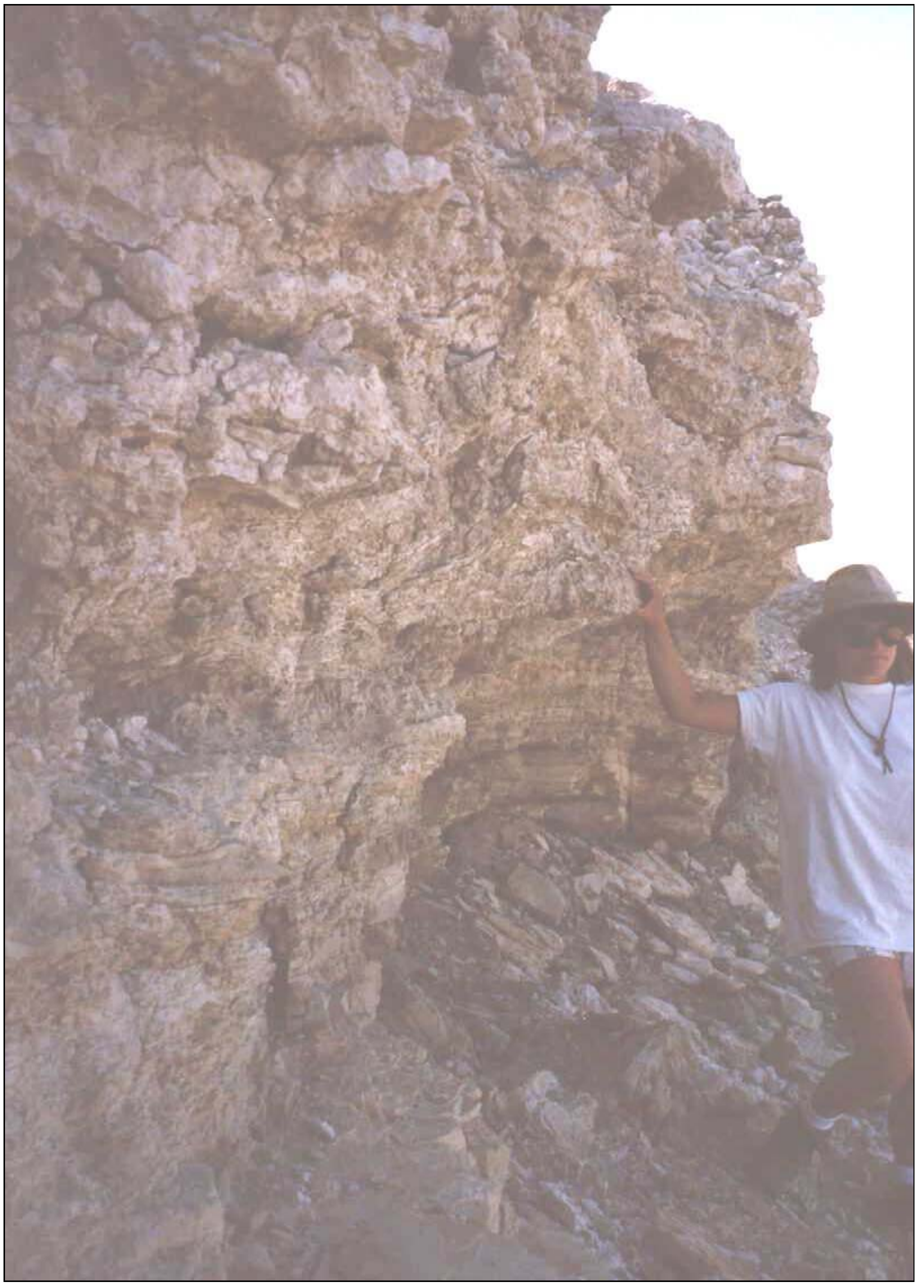
Figure A-12. Lithologic and Geophysical Logs for Borehole 299-W23-19.[a]



Source: Modified after Serne et al. 2002.

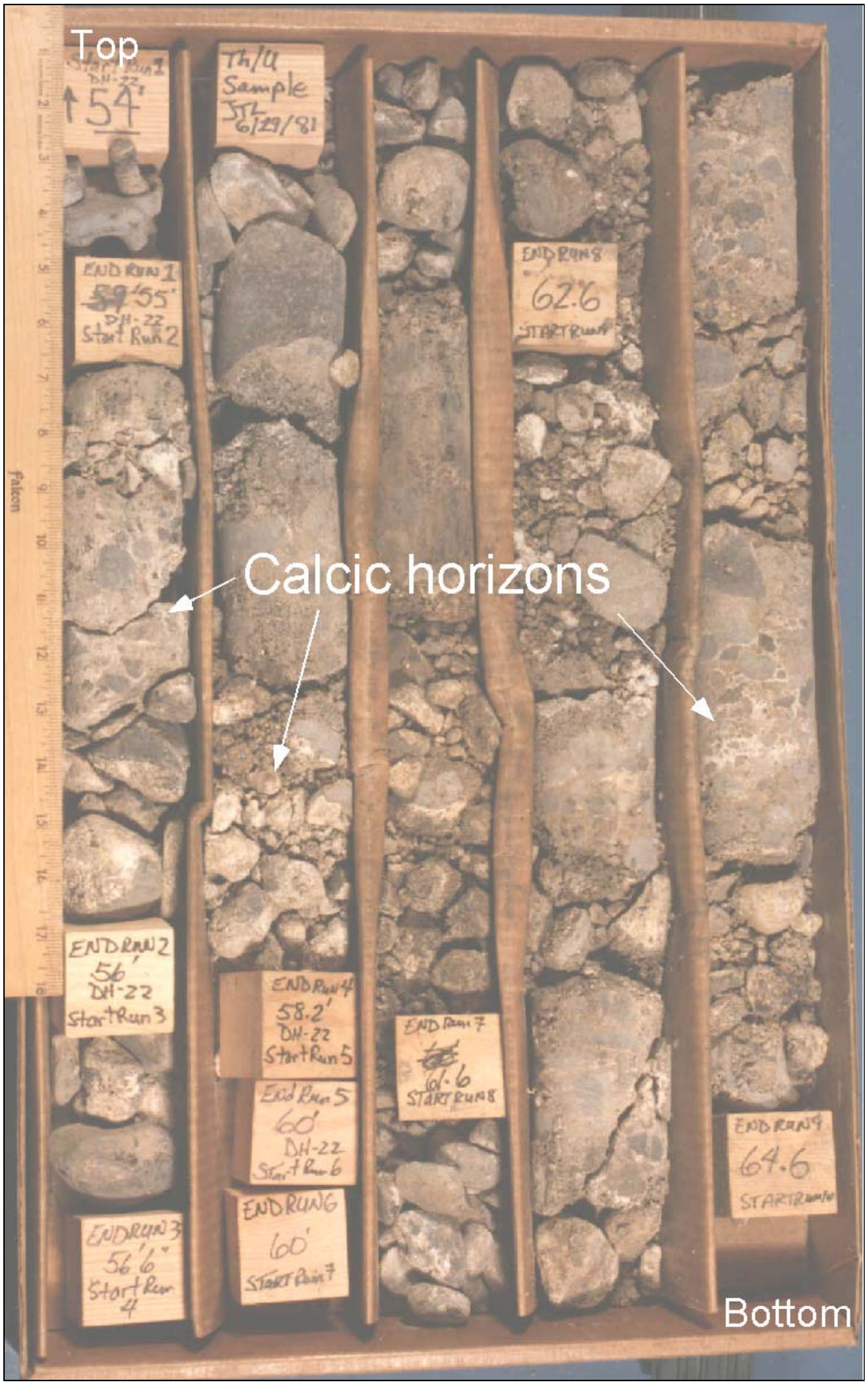
[a] Within the southern 200 West Area, the CCUc-f(calc) facies is preserved only as a single, thin (1.2-m [4-ft]) calcic paleosol sequence, which developed directly on gravels of the Ringold Formation at about the 48.2-m (158-ft) depth in this borehole.

Figure A-13. Stage V-VI Calcic Paleosol on Top of White Bluffs.[a]



[a] Erosional escarpment exposes petrocalcic horizon at the 275-m (900-ft) elevation. Paleosol is overprinted onto the lacustrine facies (informal member of Savage Island) of the Ringold Formation. This calcic paleosol is probably equivalent to the CCUc-f(calc) facies beneath the 200 West Area.

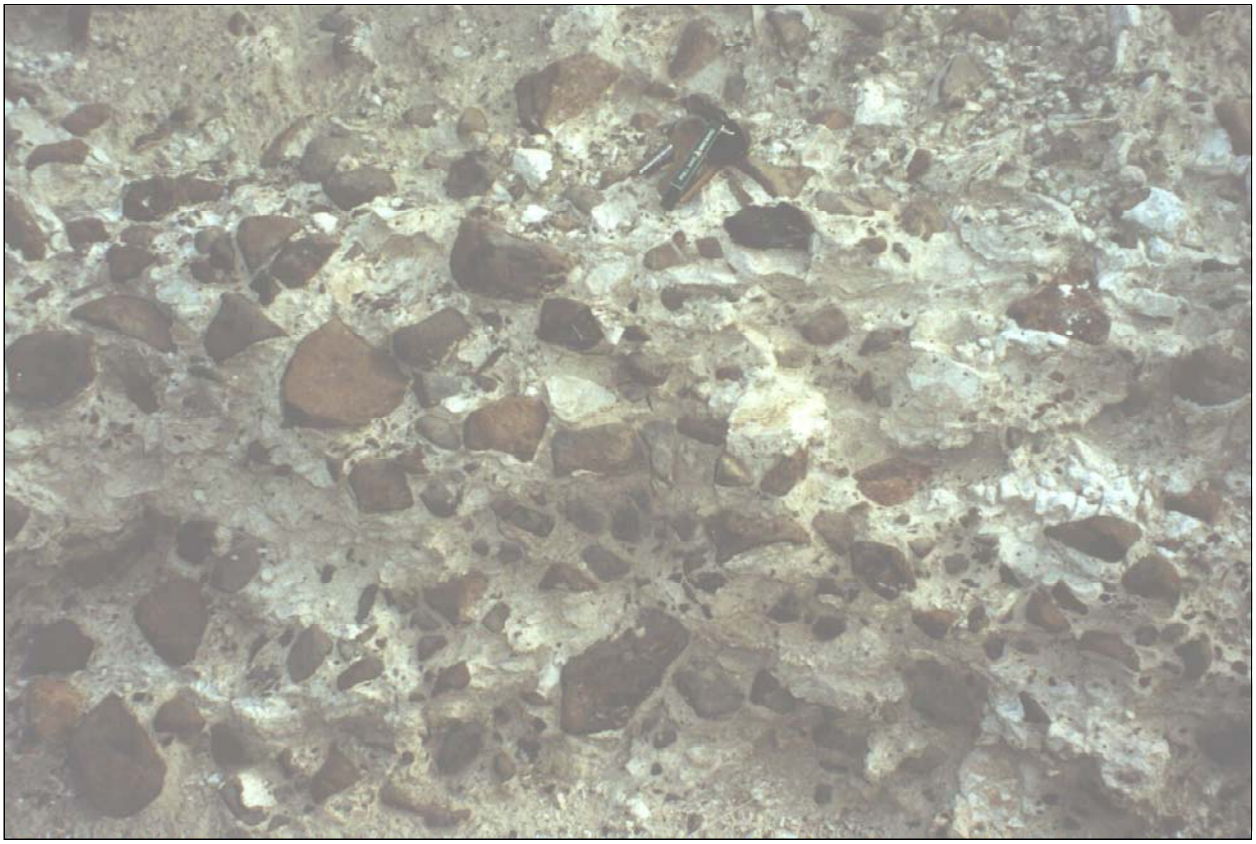
Figure A-14. Coarse-Grained, Rounded, Basaltic (c[rnd-bas]) Lithofacies of Cold Creek Unit.[a,b]



[a] Represented is a 3-m (10-ft) interval from borehole DH-22 (depth interval of 16.5 to 19.5 m [54 to 64 ft]). See Figure A-6 for borehole location.

[b] Interpreted depositional environment is sidestream alluvium.

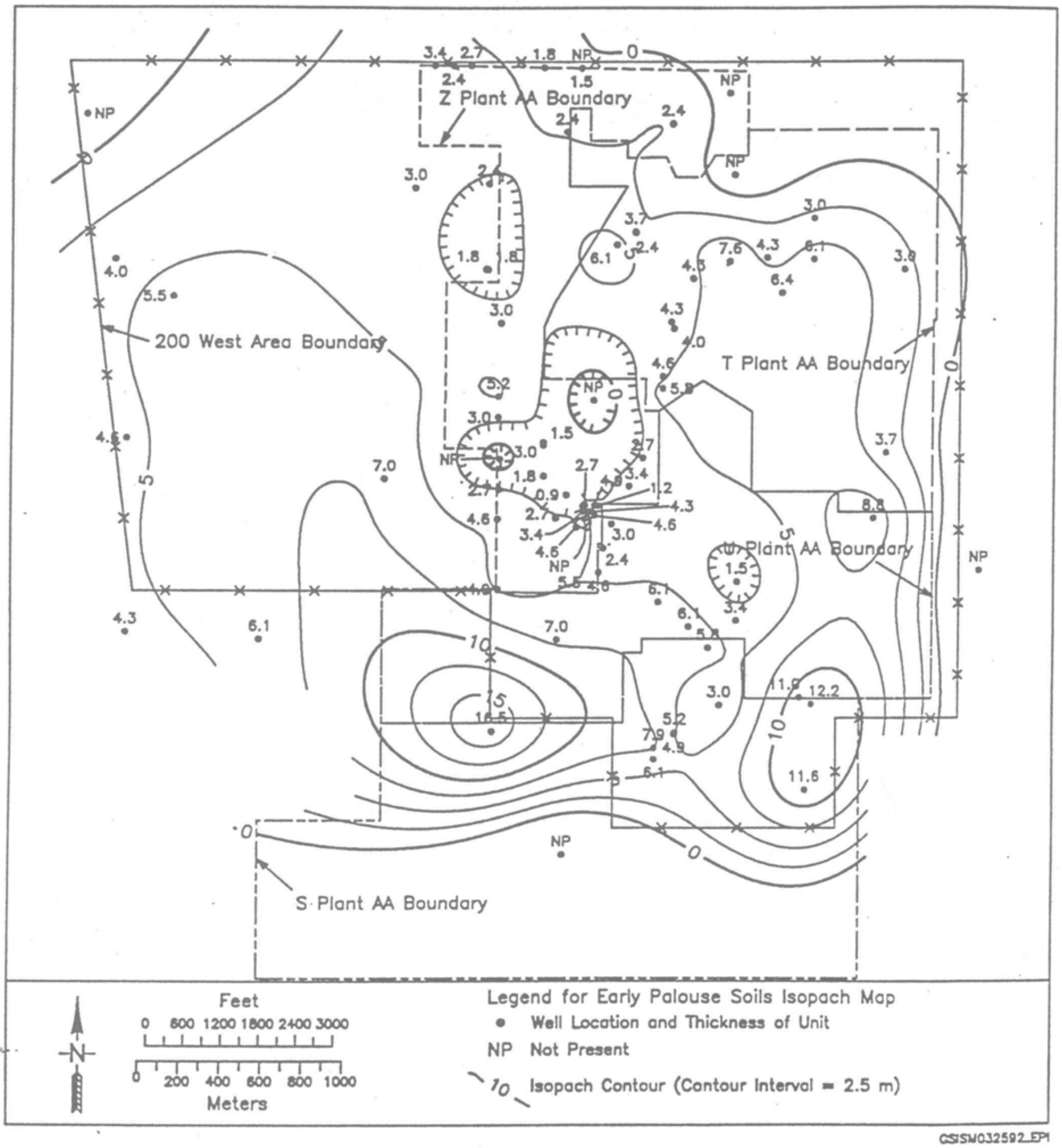
Figure A-15. Coarse-Grained, Angular, Basaltic (c[ang-bas]) Lithofacies of Cold Creek Unit.[a,b]



[a] Shown is massively bedded, angular, matrix-supported, basaltic gravel mixed with sand and silt and cemented with $CaCO_3$. Exposed along the flanks of Badger Mountain within the southern Pasco Basin (SW1/4 Sec. 35, T.9N., R.28E.). (Keys are shown for purpose of scale.)

[b] Interpreted depositional environment is colluvium.

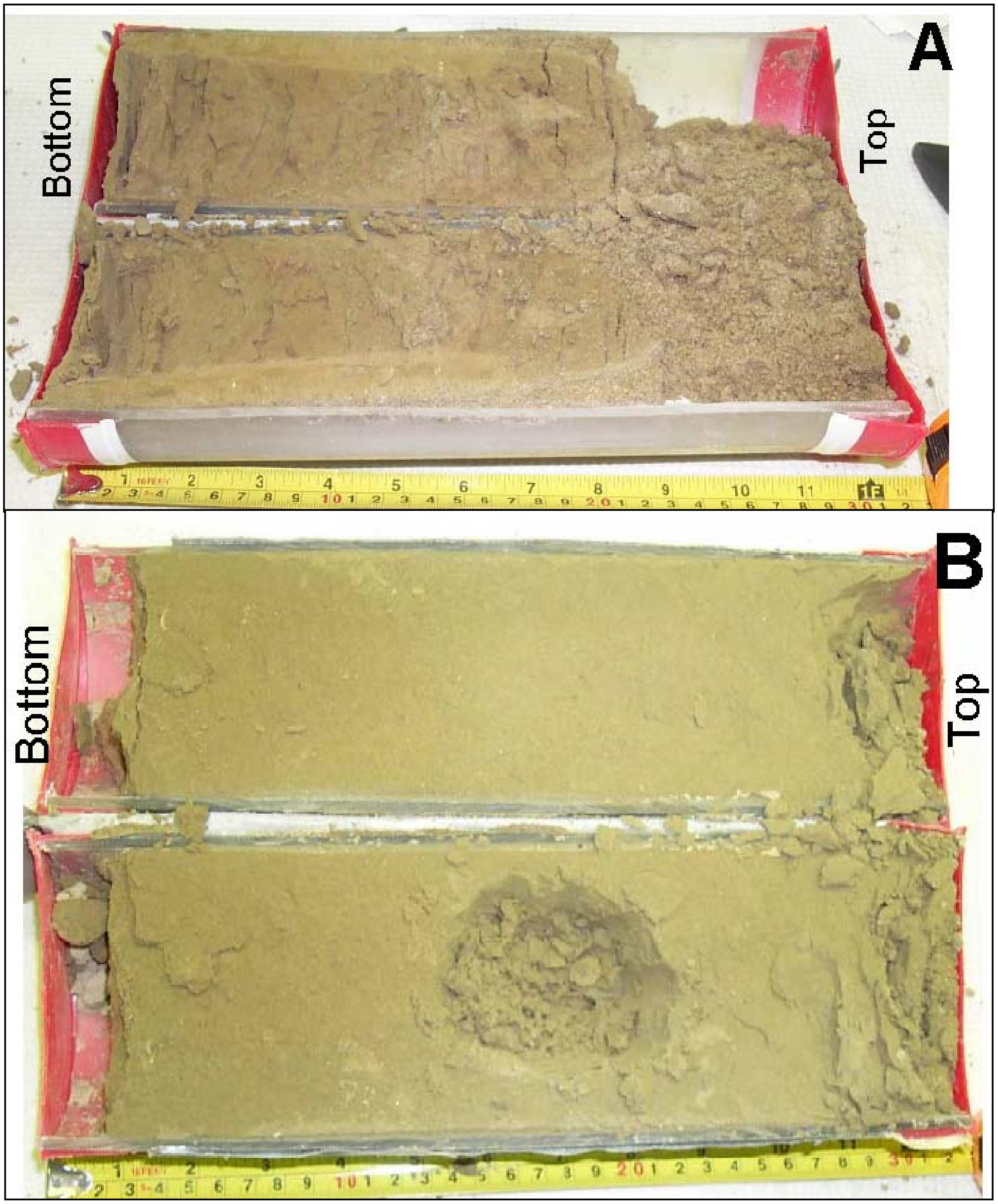
Figure A-16. Isopach Map of CCUf(lam-msv) Facies in Vicinity of 200 West Area.[a]



Source: Connelly et al. 1992.

[a] This facies is equivalent to early "Palouse" soil and interpreted to be associated with either fluvial overbank and/or eolian depositional environments.

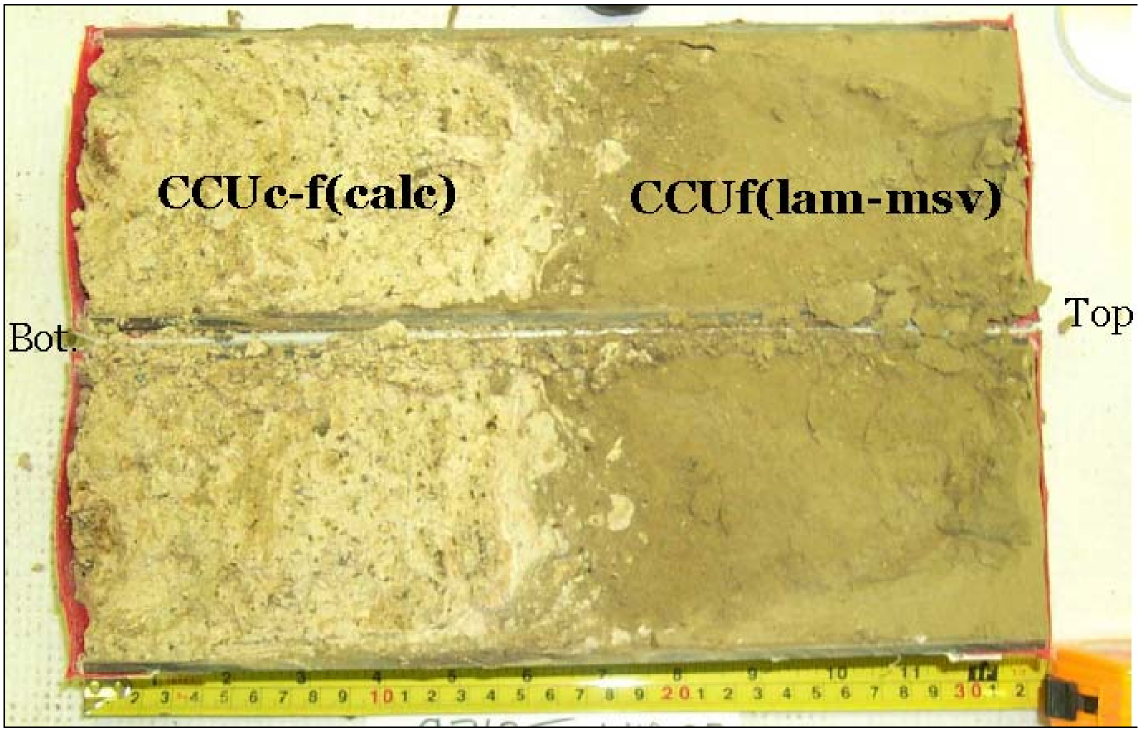
Figure A-17. Examples of CCUf(lam-msv) Facies from Borehole 299-W10-27 Core Samples.[a, b]



[a] As shown on the figure, (A) indicates interbedded and laminated fine sand and silt (depth of 27.8 to 28 m [91 to 92 ft]), which is interpreted as a fluvial overbank type deposit. (B) indicates massive, homogeneous fine sand and silt (depth of 29.3 to 29.6 m [96 to 97 ft]), which is likely an eolian deposit.

[b] See Figure A-6 for borehole location.

Figure A-18. Contact Between Lower (c-f[calc]) and Upper (f[lam-msv]) Cold Creek Unit, Borehole 299-W10-27 (29.7- to 30-m [97.5- to 98.5-ft] depth).[a, b]



[a] This sharp contact is typical of that observed between these two facies beneath most of the 200 West Area.

[b] See Figure A-6 for borehole location.

Figure A-19. Geographic Elements of Ice Age Cataclysmic Flooding from Glacial Lake Missoula.

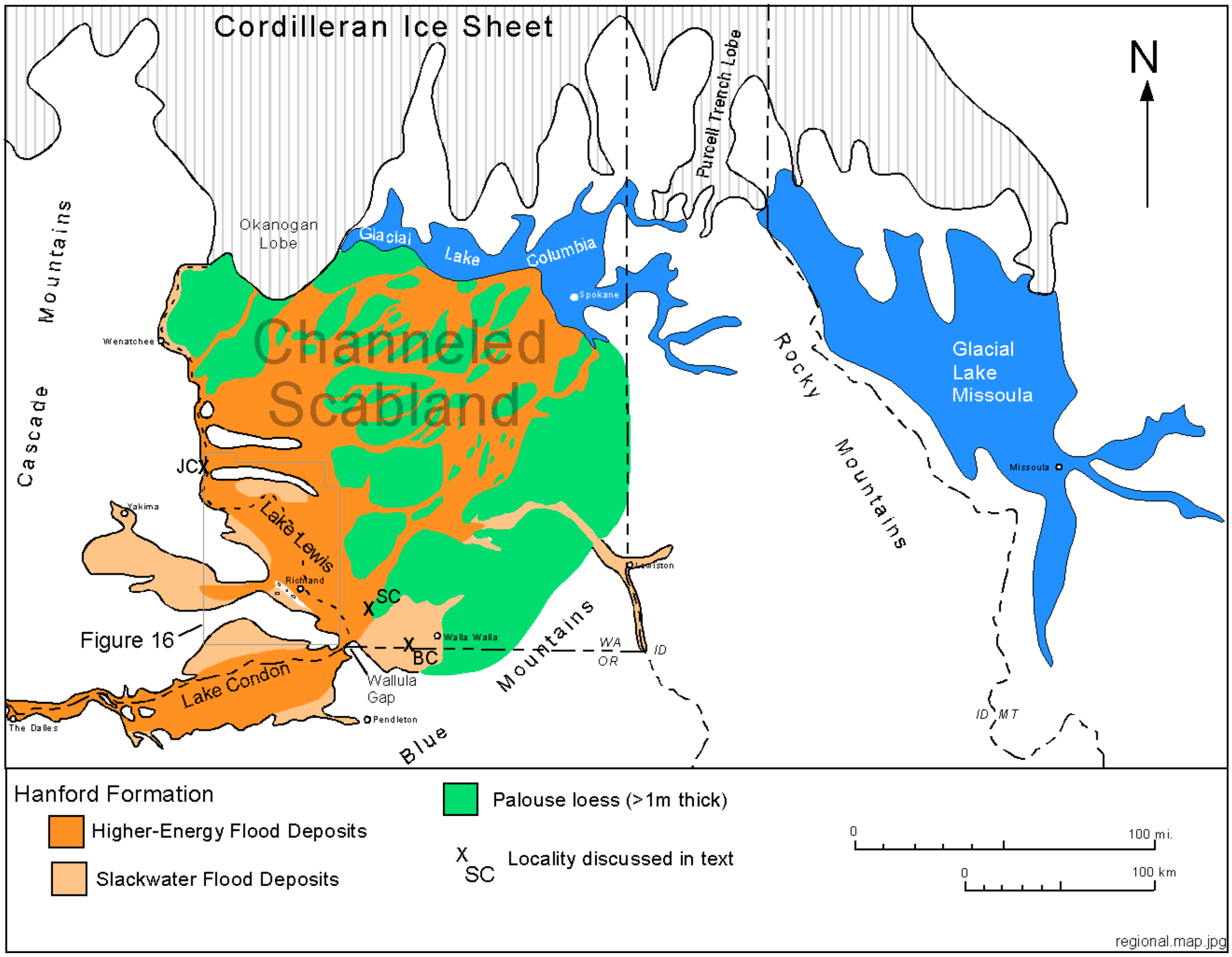
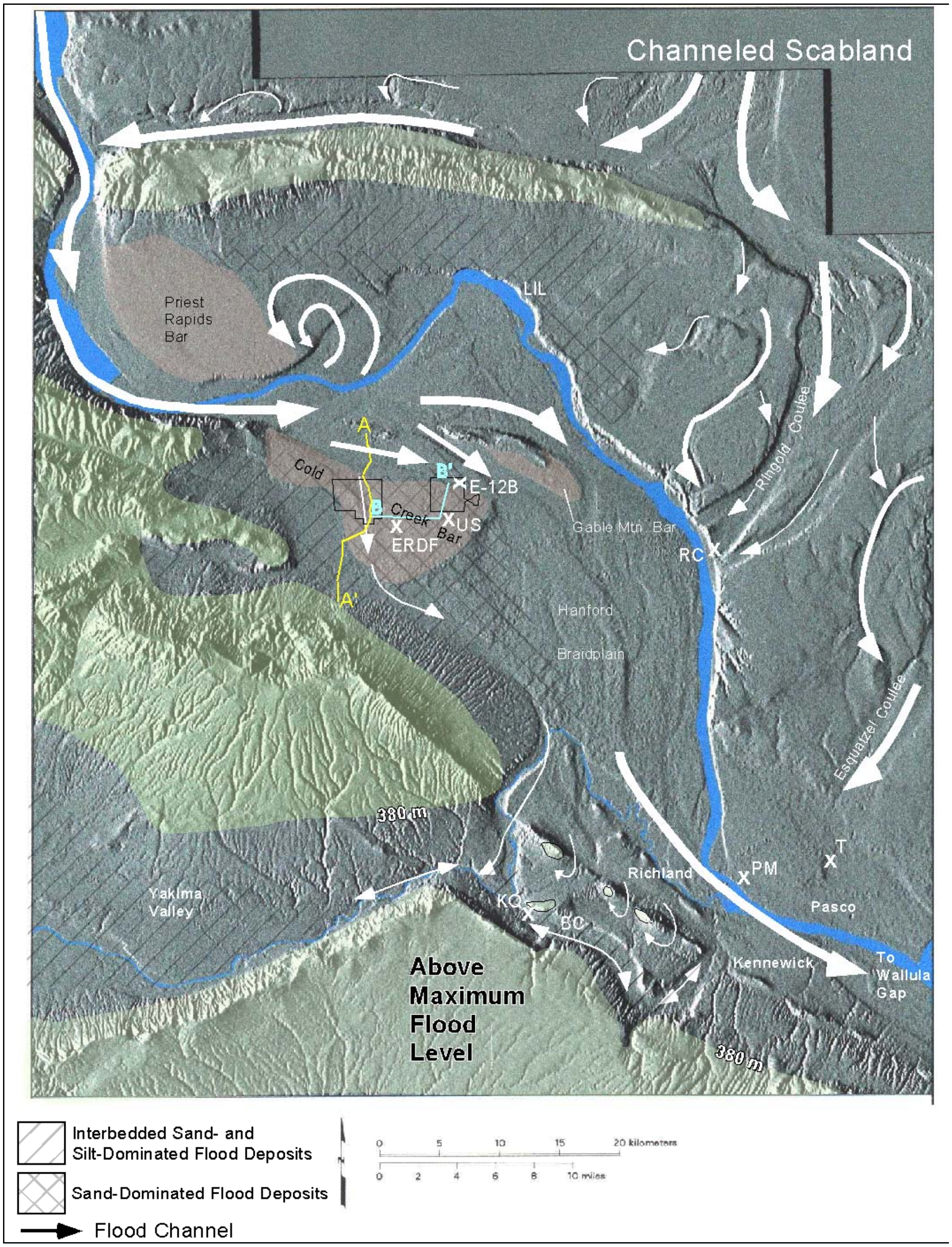
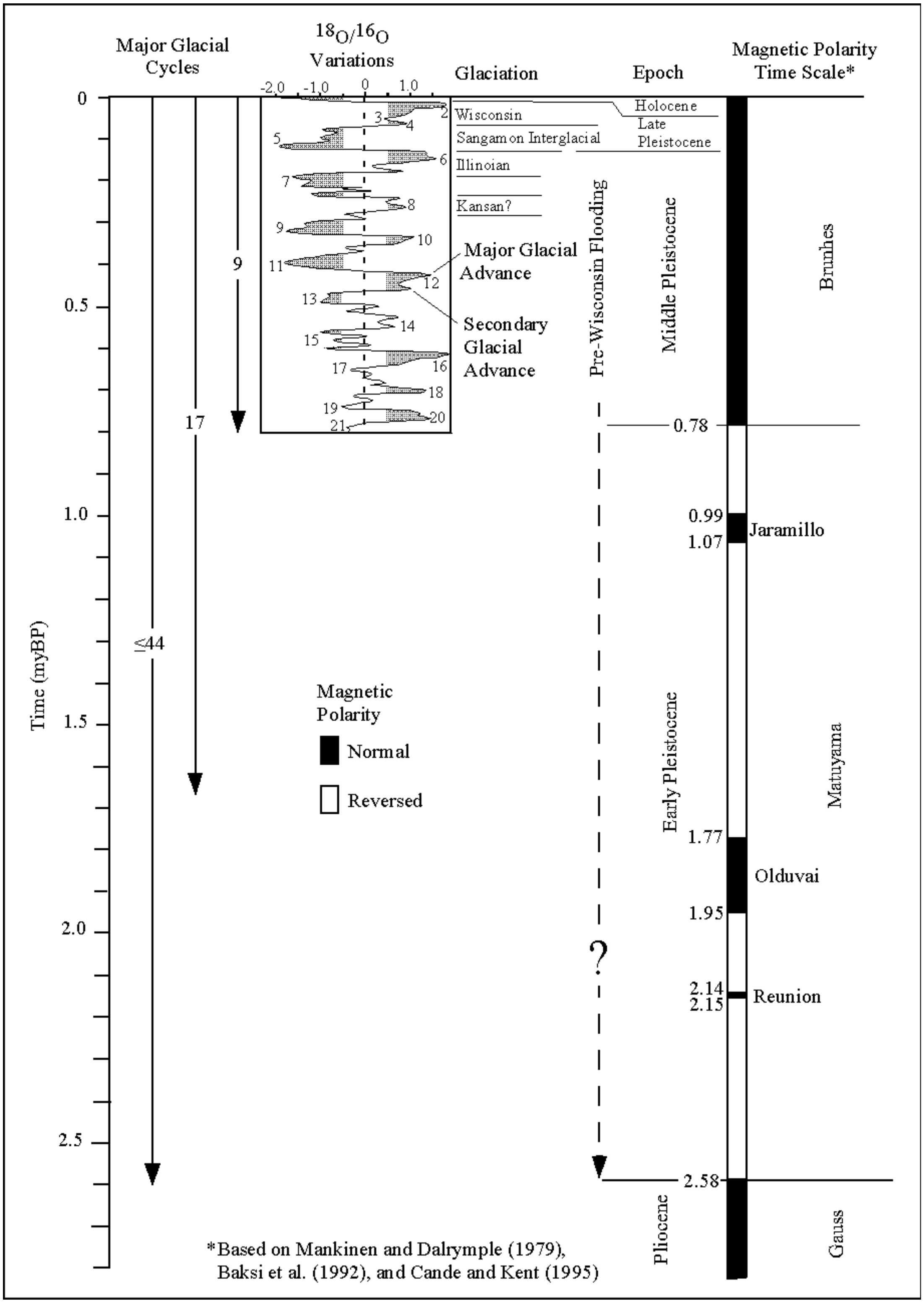


Figure A-20. Cataclysmic Flood Features in the Vicinity of Pasco Basin.[a]



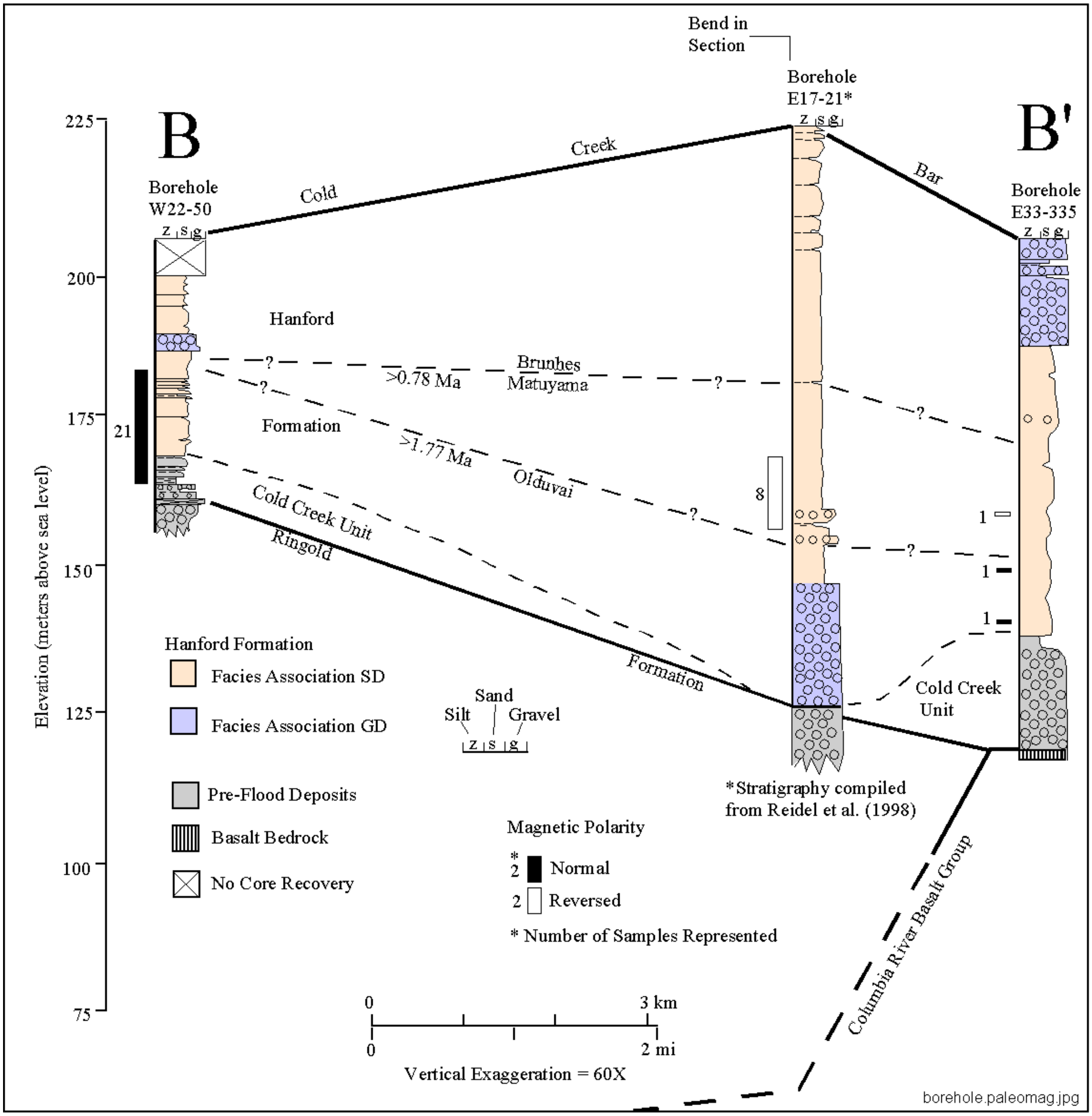
[a] DEM map shows routes for the last large-scale Pleistocene cataclysmic floods. Localities discussed in text include: PM = Pre-Mix, T = Transtate, BC = Badger Coulee, ERDF = Environmental Restoration Disposal Facility, US = U.S. Ecology, E-12B = 218-E-12B Disposal Facility, RC = Ringold Coulee, LIL = Locke Island landslide complex, KQ = Kiona Quarry. Cross-section A-A' is presented in Figure A-5, and cross-section B-B' is presented in Figure A-22.

Figure A-21. Cataclysmic Ice-Age Flooding in Relation to Quaternary Chronology.



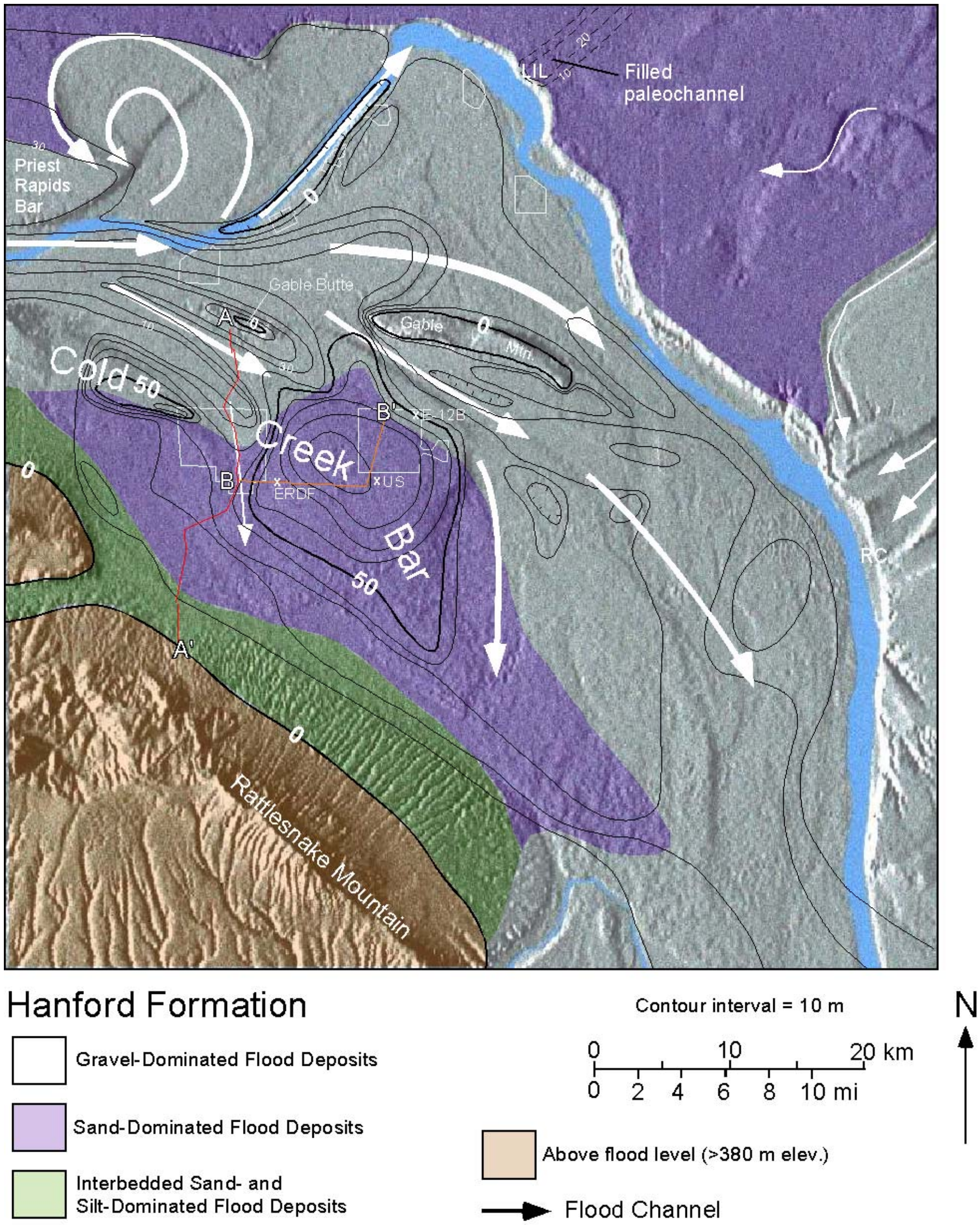
Source: Bjornstad et al. 2001.

Figure A-22. Magnetostratigraphic Cross-Section (B-B') Across Portion of Cold Creek Flood Bar.[a]



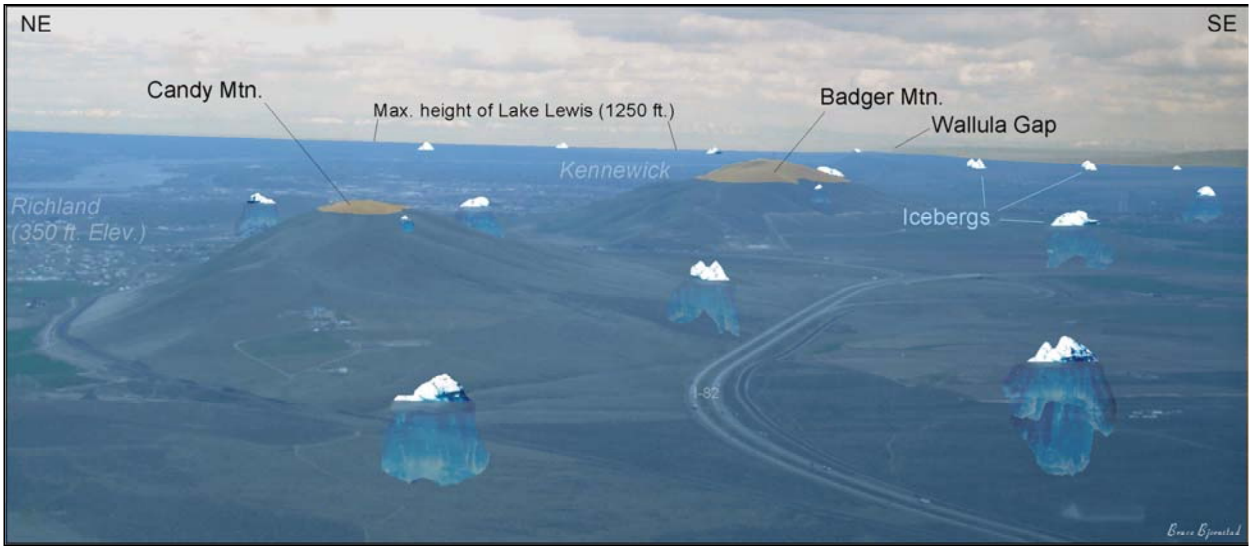
[a] Location of cross-section is shown on Figure A-20.

Figure A-23. Thickness and Facies Map of Hanford Formation for Central Pasco Basin.[a]



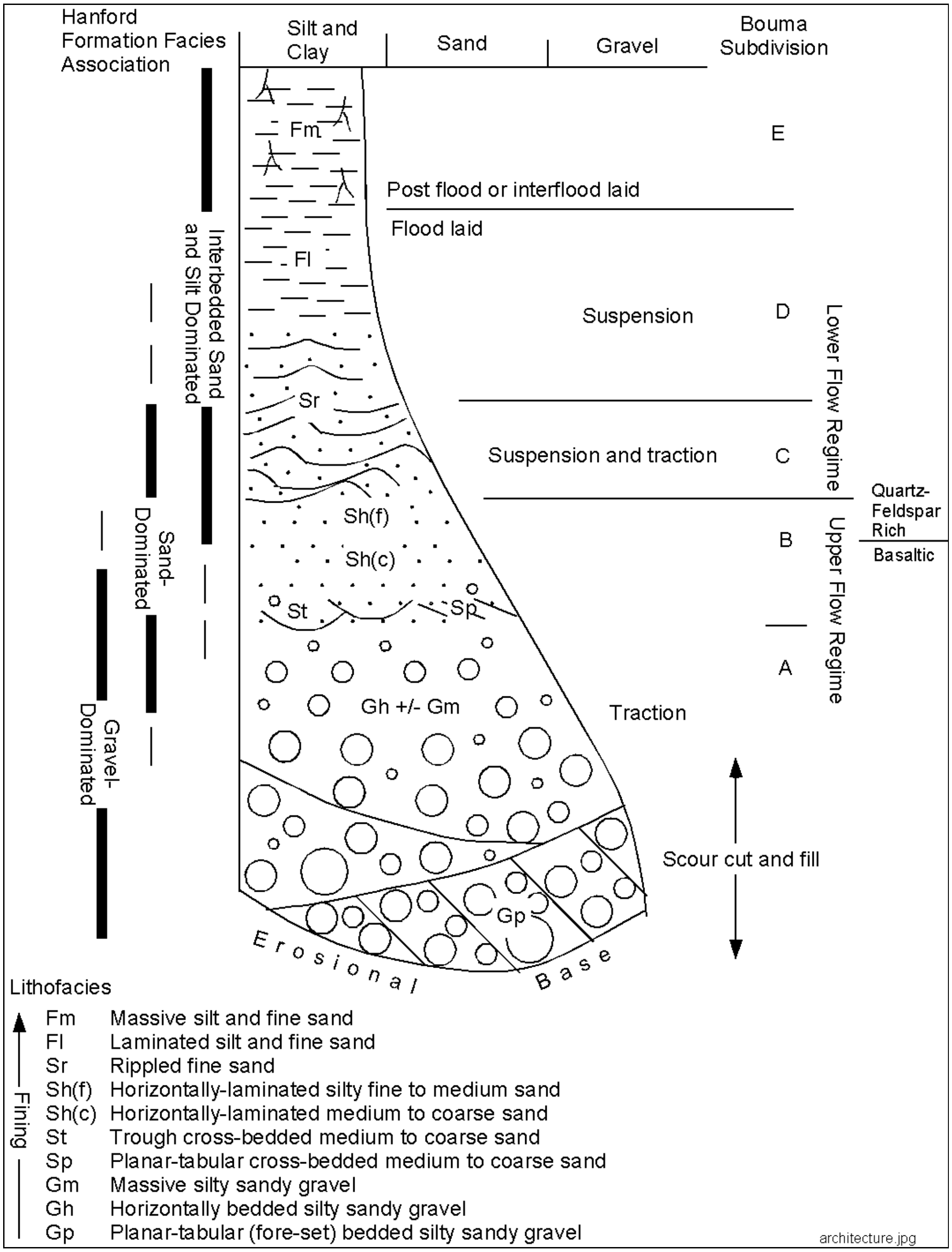
[a] Gravel-dominated flood facies dominate through the central part of the basin, while sand-dominated facies occur at higher elevations around the margins of the basin. Interbedded sand- and silt-dominated flood facies occur in backflooded areas around the perimeter of the basin. Flood deposits do occur above an elevation of 350 m (1250 ft), the height of the maximum flood in the basin. Flood deposits read their maximum thickness (~100 m) beneath Cold Creek flood bar in the west-central Pasco Basin. Localities discussed in text include: RC = Ringold Coulee, ERDF = Environmental Restoration Disposal Facility, US = U.S. Ecology landfill, E-12B = 218-E-12B Disposal Facility, and LIL = Locke Island landslide complex. Two cross sections through the flood deposits include A-A' (Figure A-5) and B-B' (Figure A-22).

Figure A-24. Lake Lewis as it Might Have Appeared in Southern Pasco Basin During Largest Ice Age Flood.[a]



[a] Water was impounded temporarily behind a hydraulic dam at Wallula Gap. Badger Coulee ("BC" on Figure A-20) is in right foreground. Erratic-bearing icebergs, derived from breakup of the ice dam, concentrated in slackwater areas around the margins of the basin.

Figure A-25. Sedimentary Architecture for Cataclysmic Ice Age Flood Deposits of Hanford Formation.[a]



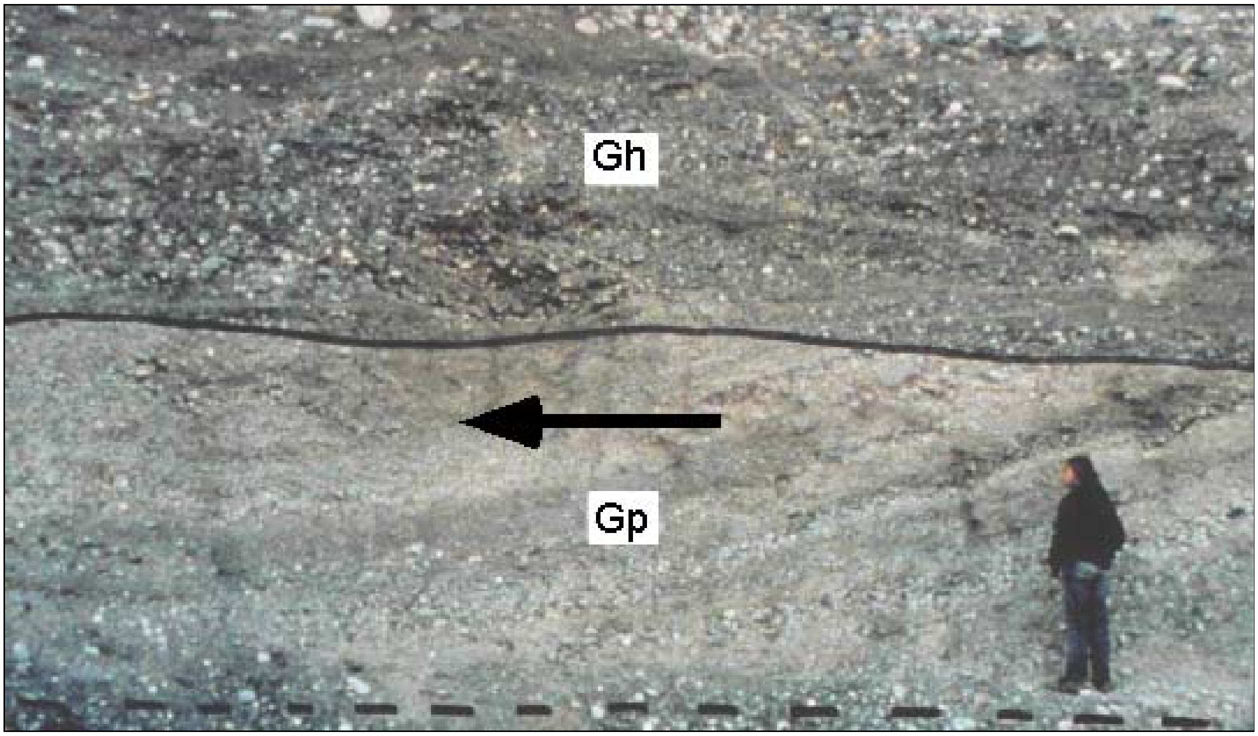
[a] The different facies associations of the Hanford formation, discussed in a later section, overlap onto separate portions of the depositional sequence. The lithofacies represented in a flood sequence is generally a function of energy level associated with flooding. Lithofacies from lower in the sequence are present nearer high-energy flood channels, whereas lithofacies toward the top of the sequence are found in lower-energy slackwater and/or backflooded environments.

Figure A-26. Example of Cataclysmic Flood Gravels Recovered with Split-Spoon from Southern Portion of 200 West Area.[a,b]

[a] Corehole 299-W11-39 (7- to 7.3-m [23- to 24-ft] depth). Core is .31 m (1 ft) long; top of core is to the right.

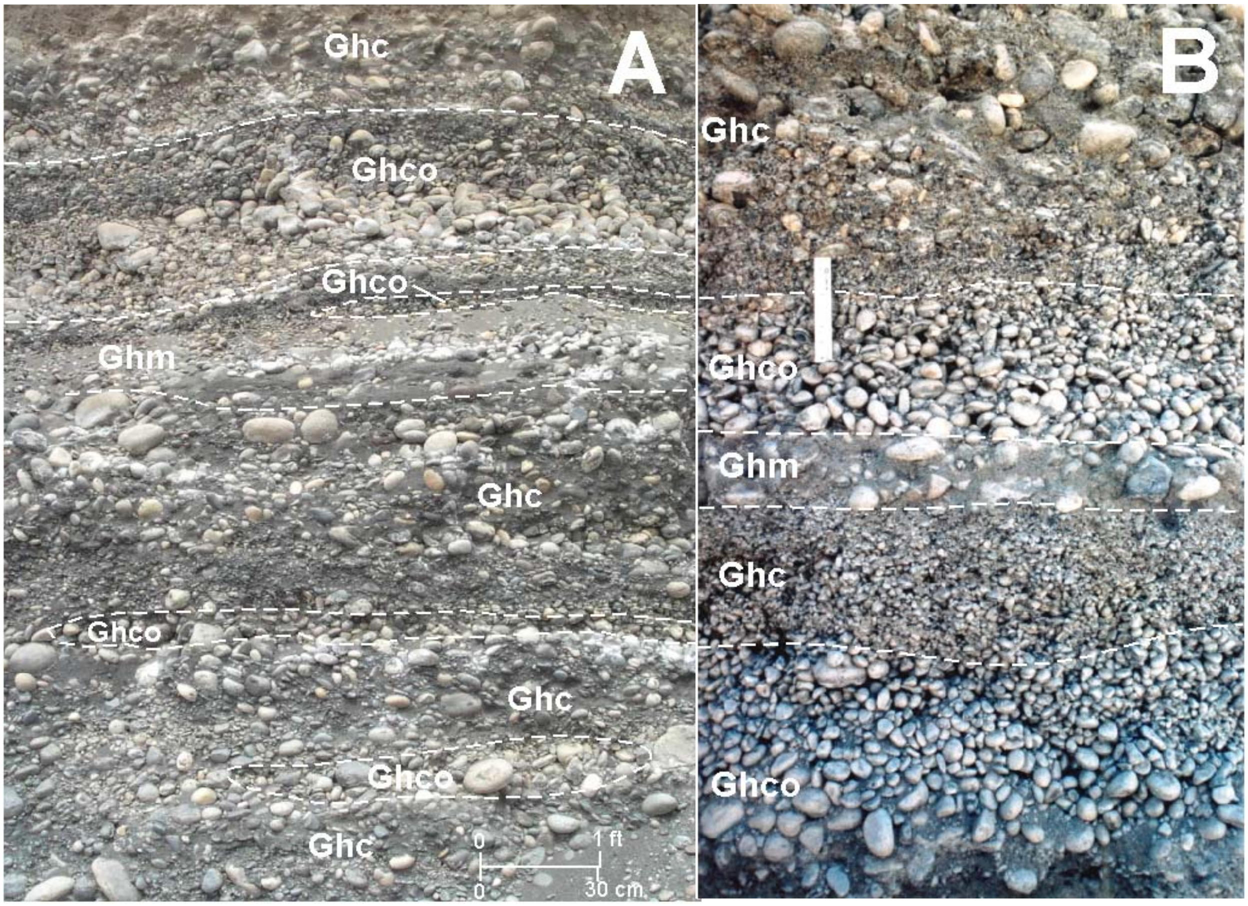
[b] Consists of loose, poorly sorted, grayish brown, silty sandy pebble gravel.

Figure A-27. Flood-Gravel Sequence Displaying Both Horizontally Bedded (Gh) and Large-Scale Planar-Tabular (Foreset-Bedded) (Gp) Lithofacies.[a]



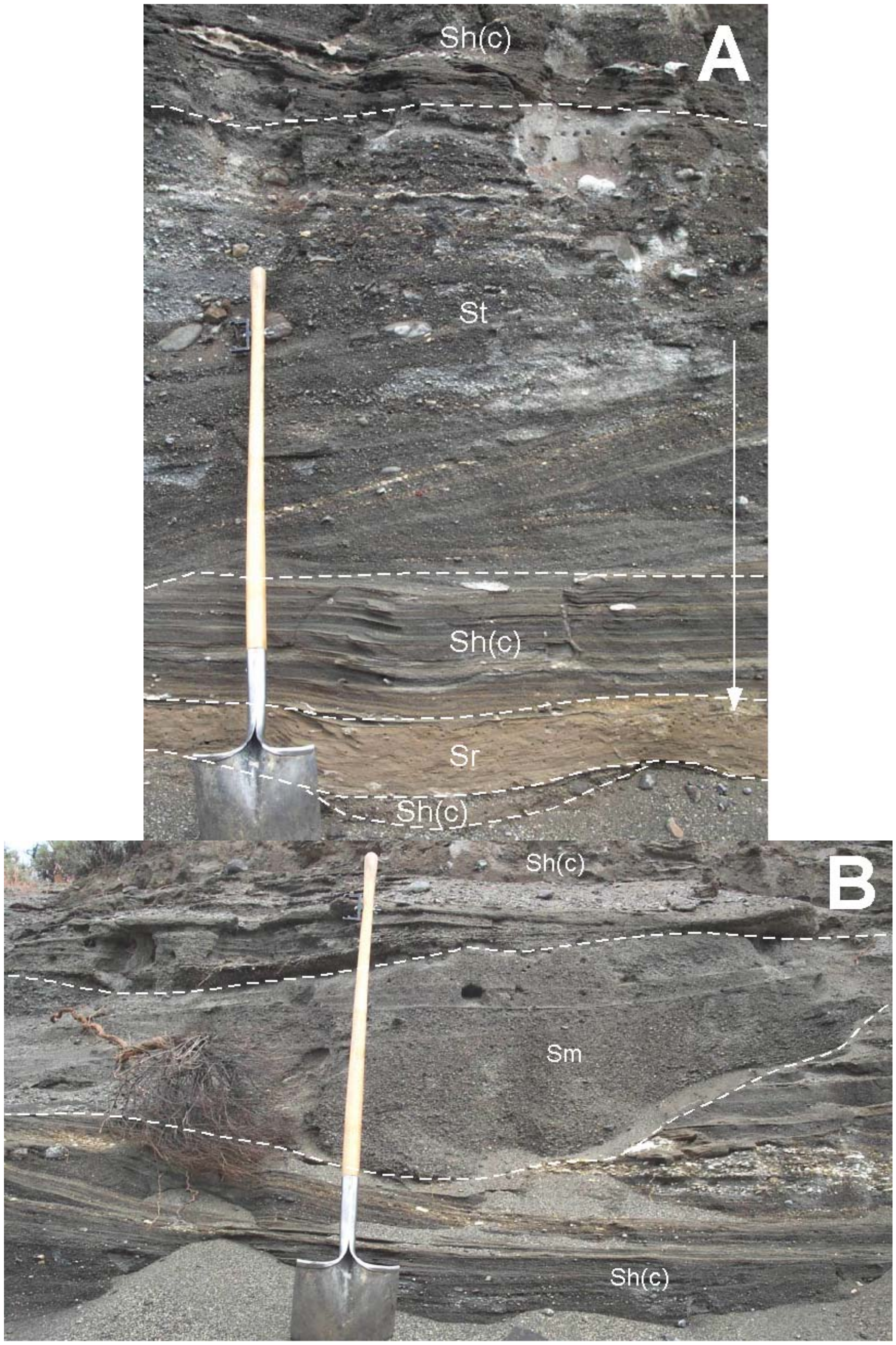
[a] Arrow indicates paleocurrent direction.

Figure A-28. Fine-Scale Facies Variations Observed Within Two Separate Sequences of Horizontally Bedded Cataclysmic Flood Gravels (Lithofacies Gh).[a]



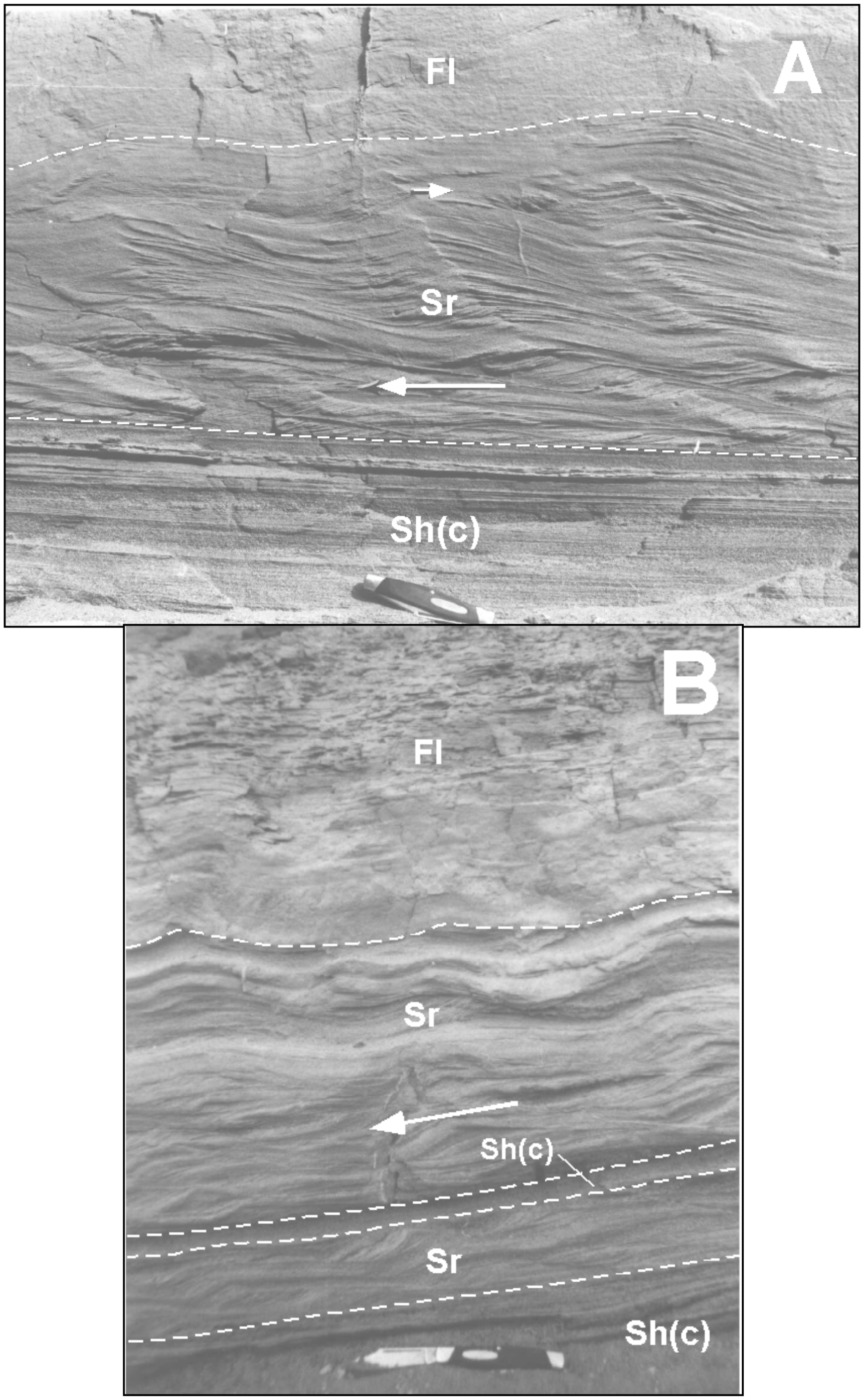
[a] As indicated in these photos, considerable heterogeneity and discontinuity exists within gravel-dominated facies of the Hanford formation.

Figure A-29. Sand-Dominated Lithofacies Observed Within Flood Deposits at Johnson Creek.[a]



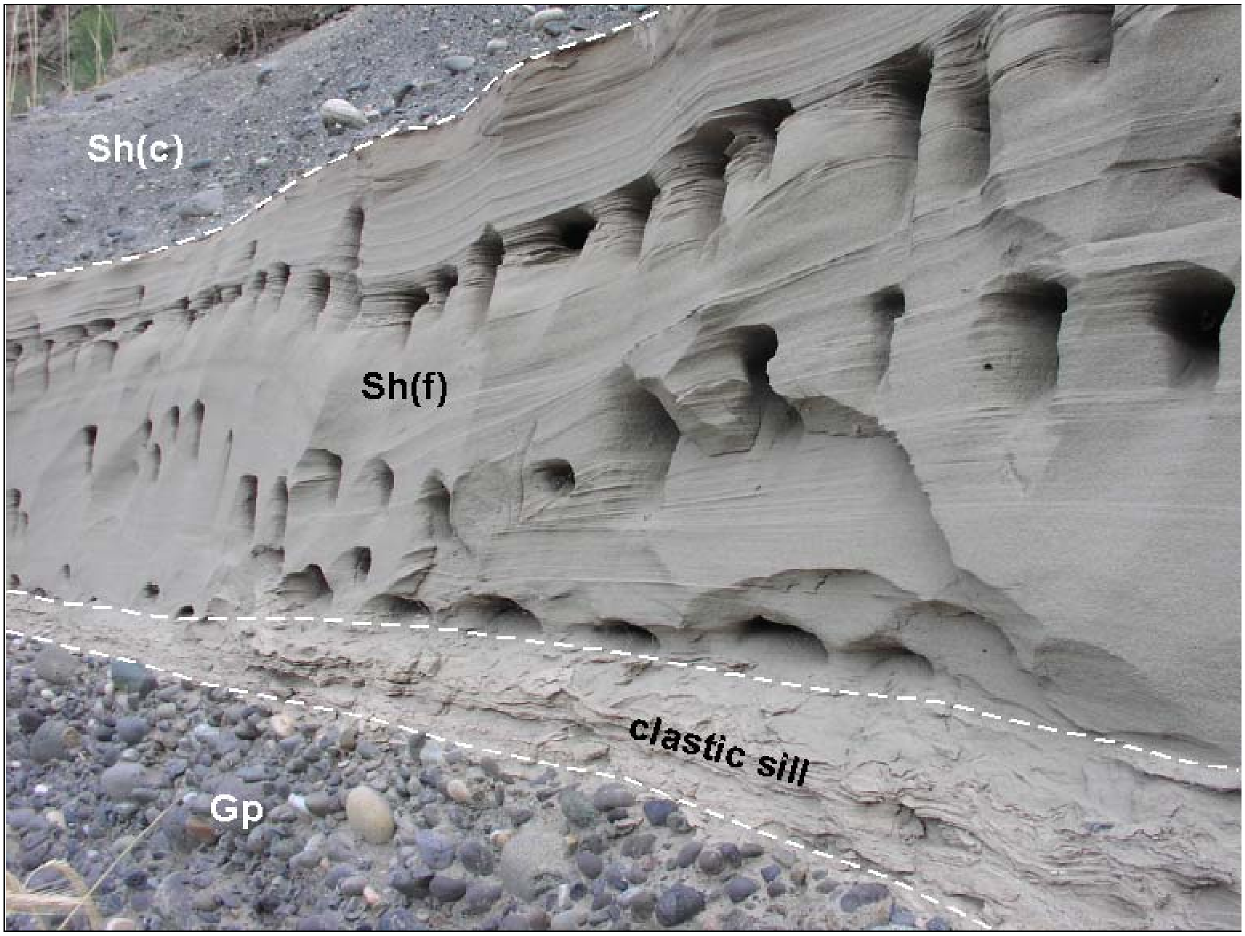
[a] As marked in the figure, (A) shows the interval of reverse grading (coarsening upward) is indicated by arrow. Rhizoliths present in the lower half of photo. (B) shows massive sand (Sm), which cuts into the underlying coarse-grained horizontally-laminated flood sands (Sh[c]), likely represents a debris-flow deposit laid down during, or soon after, flooding. Light-colored clasts are semi-consolidated diatomaceous rip-up clasts from the Ellensburg Formation. Location is identified as "JC" on Figure A-19.

Figure A-30. Sand and Silt-Dominated Lithofacies in Slackwater Flood Rhythmites from Walla Walla Valley.[a]



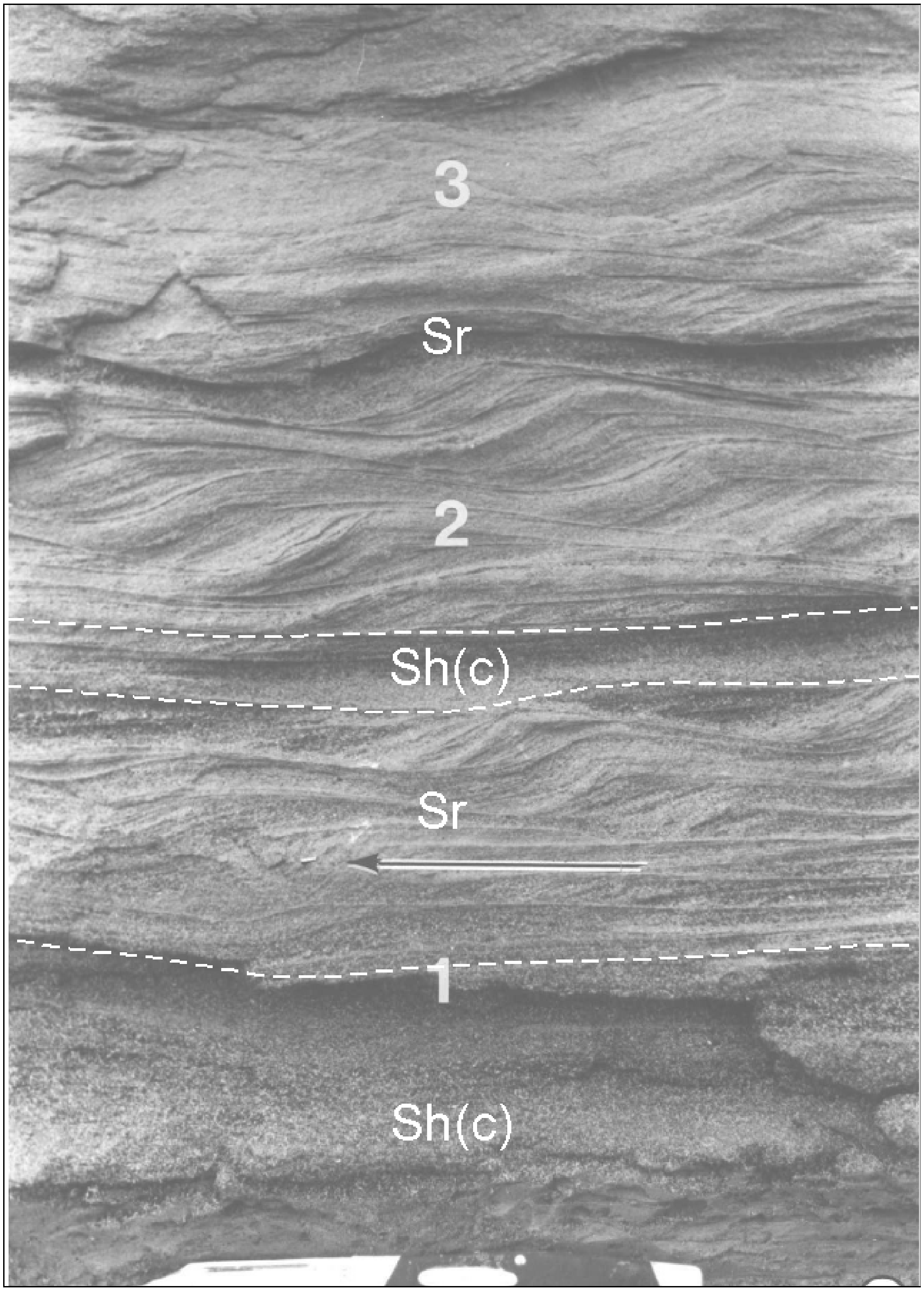
[a] As marked in the figure, (A) shows characteristic upward gradation in texture and structural development. Facies Sr shows typical upward transition from climbing- to draped-current-ripple laminations, which coincides with a change from dominantly tractive- to suspension-load sedimentation (Figure A-25). Arrows indicate paleocurrent direction (upvalley to left). (B) shows the secondary pulse in current energy is represented in the lower right by the Sr-Sh(c)-Sr sequence.

Figure A-31. Example of Sh(f) Lithofacies.[a]



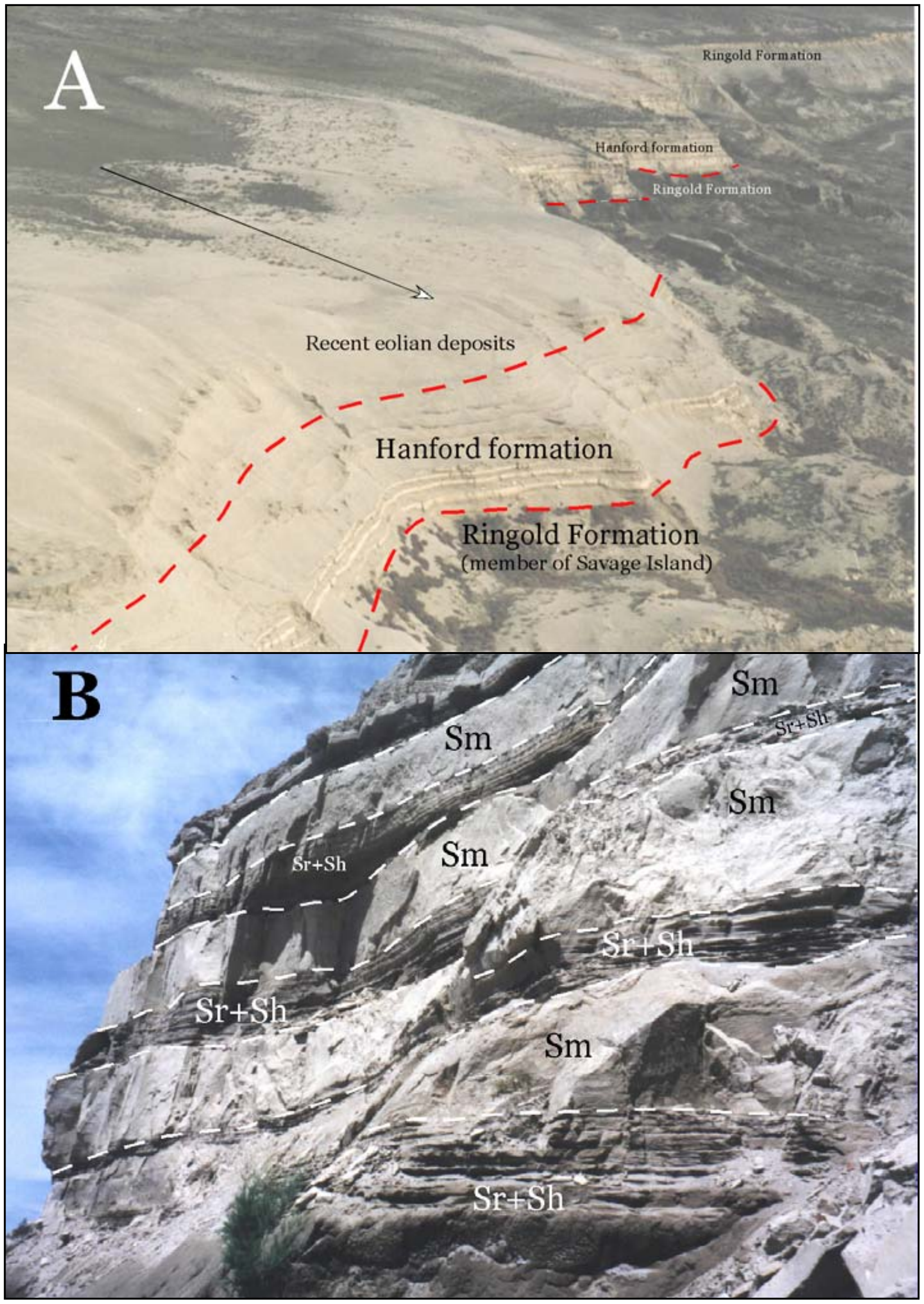
[a] A bed of horizontally-laminated (and locally planar-tabular cross-bedded) silty fine- to medium-grained sand (Sh[f]) lies between a bed of foreset-bedded, planar-tabular silty sandy gravel (Gp) below and matrix-supported gravelly horizontally-laminated coarse sand (Sh[c]) above. Tabular clastic sill, which runs along the top of the underlying Gp unit, connects the two vertical clastic dikes shown in Figure B-5a. Lower Smith Canyon locality, identified as “SC” on Figure A-19.

Figure A-32. Example of Multiple Normal and Reverse Gradations.[a]



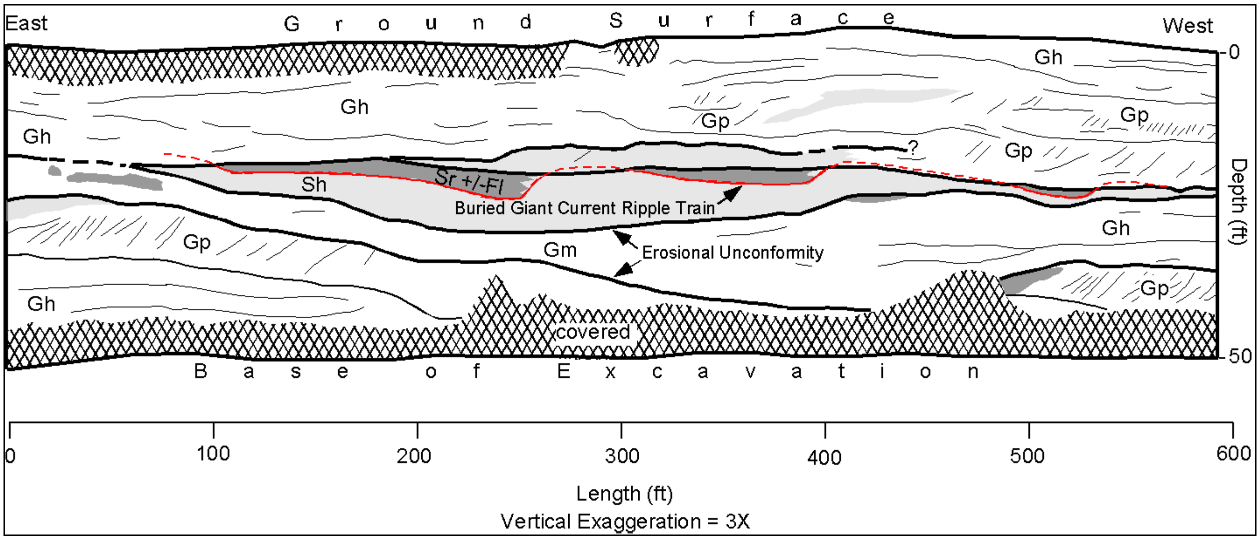
[a] Alternating gradations between horizontally-laminated coarse sand (Sh[c]) and rippled fine sand (Sr). Continuous deposition occurred during three pulses from a waning current that moved from right to left (upvalley). Walla Walla Valley.

Figure A-33. Sand-Dominated Lithofacies Association (SD) Exposed Along White Bluffs at Locke Island Landslide Complex.[a]



[a] Sand-dominated facies association (SD) of the Hanford formation fills a paleochannel incised into the Ringold Formation along the White Bluffs. (A) shows aerial view looking southeast. Distinctly bedded flood deposits, consisting of mostly light-colored sand, stand in stark contrast to impermeable silts and clays of the Ringold Formation. Perched groundwater saps out along the contact between Ringold and Hanford formations leading to massive landslides in the area. Axis of old paleochannel filled with flood deposits (arrow) trends approximately normal to the bluff face. Note Hanford formation pinches out along the bluff face in the distance. (B) Close up view of rhythmically bedded Sh/Sr and Sm facies. Locality is identified by the letters “LIL” on Figure A-20.

Figure A-34. Gravel-Dominated Facies Association (GD) in South Wall of E-12B Excavation.[a]



[a] Traced from photomosaic collected soon after initial excavation in 1993. Asymmetry of ripples and dip of foreset beds (Gp) indicate paleoflood current direction was from right to left. Train of buried giant current ripples is also shown in Figure A-34. As many as four erosional unconformities are indicated by truncated or scoured beds of finer-grained sand or silt within this sequence. These unconformities may represent separate floods or pulsations from a single flood. Identified as "E-12B" on Figure A-20.

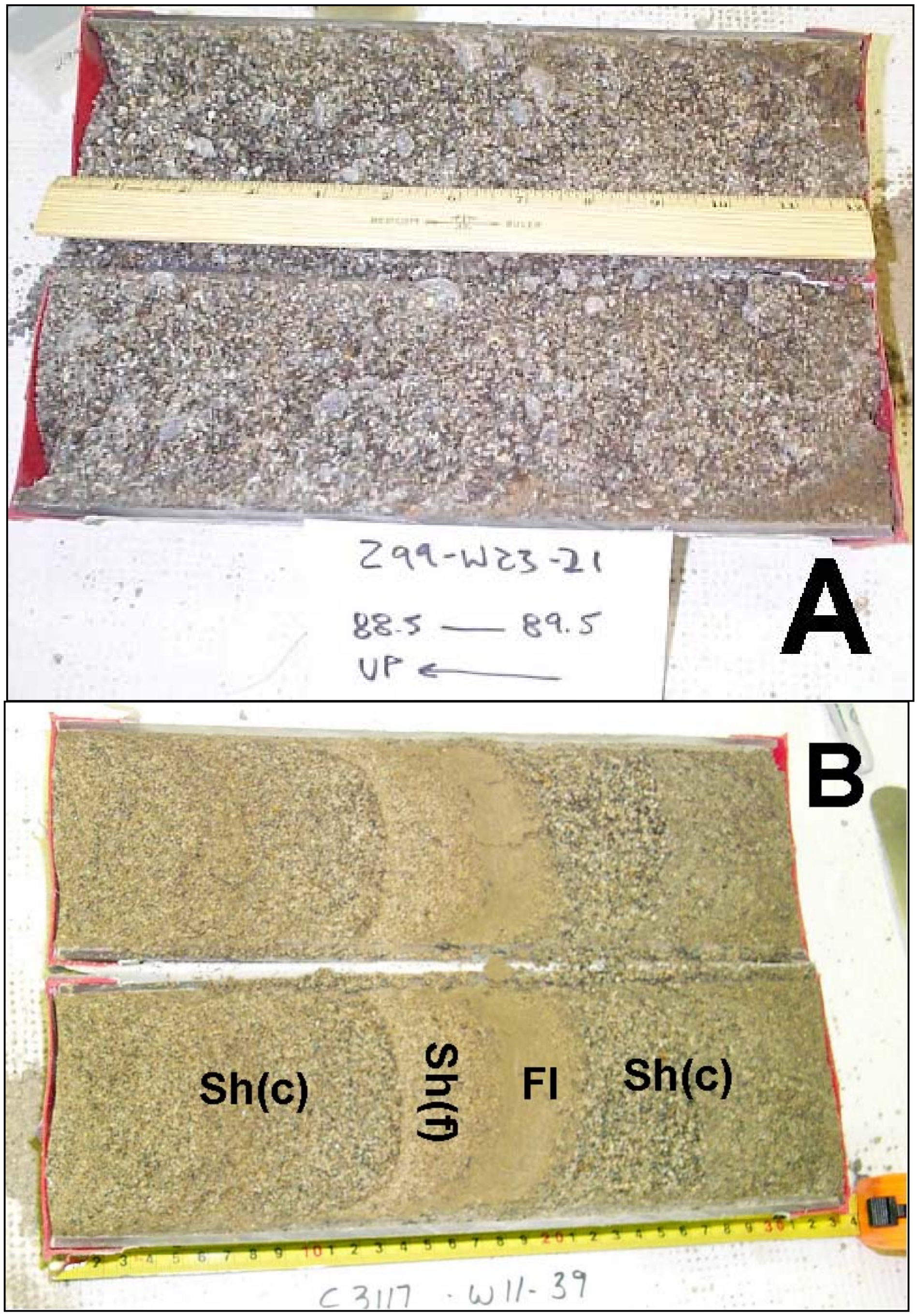
Figure A-35. Train of Buried Giant Current Ripples in North Wall of E-12B.[a]

[a] Waning flood current was from left to right. Photo taken several months after excavation shows fine-grained deposits (Sr+/-Fl), which retain more moisture, demarking the giant-ripple boundaries with vegetation. Finer-grained facies thin to a few centimeters over ripple crests (C) and thicken to 1 m (3.3 ft) or more in the troughs (T). Average ripple chord length is 60 m [196.9 ft] and amplitude is 1.8 m (5.9 ft)(Lewis et al. 1993). These finer-grained strata can be traced along the entire 450-m (492.3-yd) length of the exposure. See also Figure A-33.

Figure A-36. Sand-Dominated Facies Association (SD) at Johnson Creek.[a]

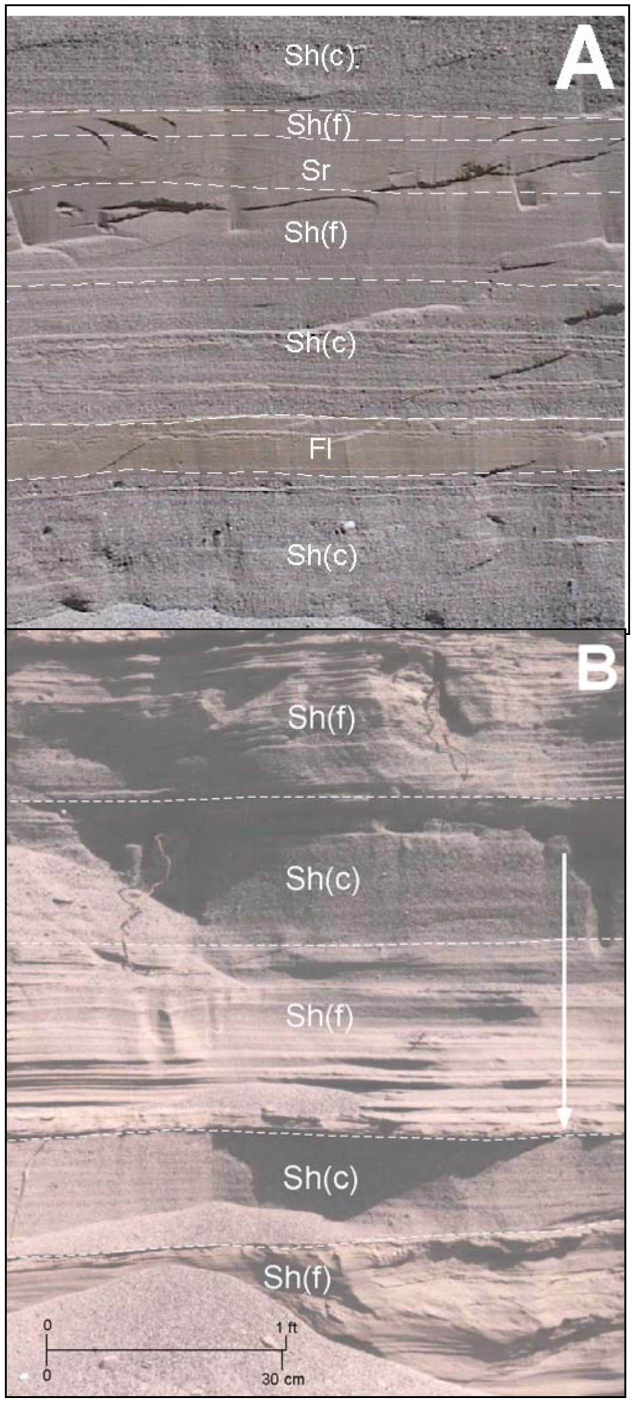
[a] Consists of mostly dark gray, basaltic St and Sh(c) facies, with a thin zone of finer-grained brown Sr toward base of exposure. See more detailed photos in Figure A-28. Identified as "JC" on Figure A-19.

Figure A-37. Sand-Dominated Facies Association (SD) in Core Samples from Southeastern 200 West Area.[a]



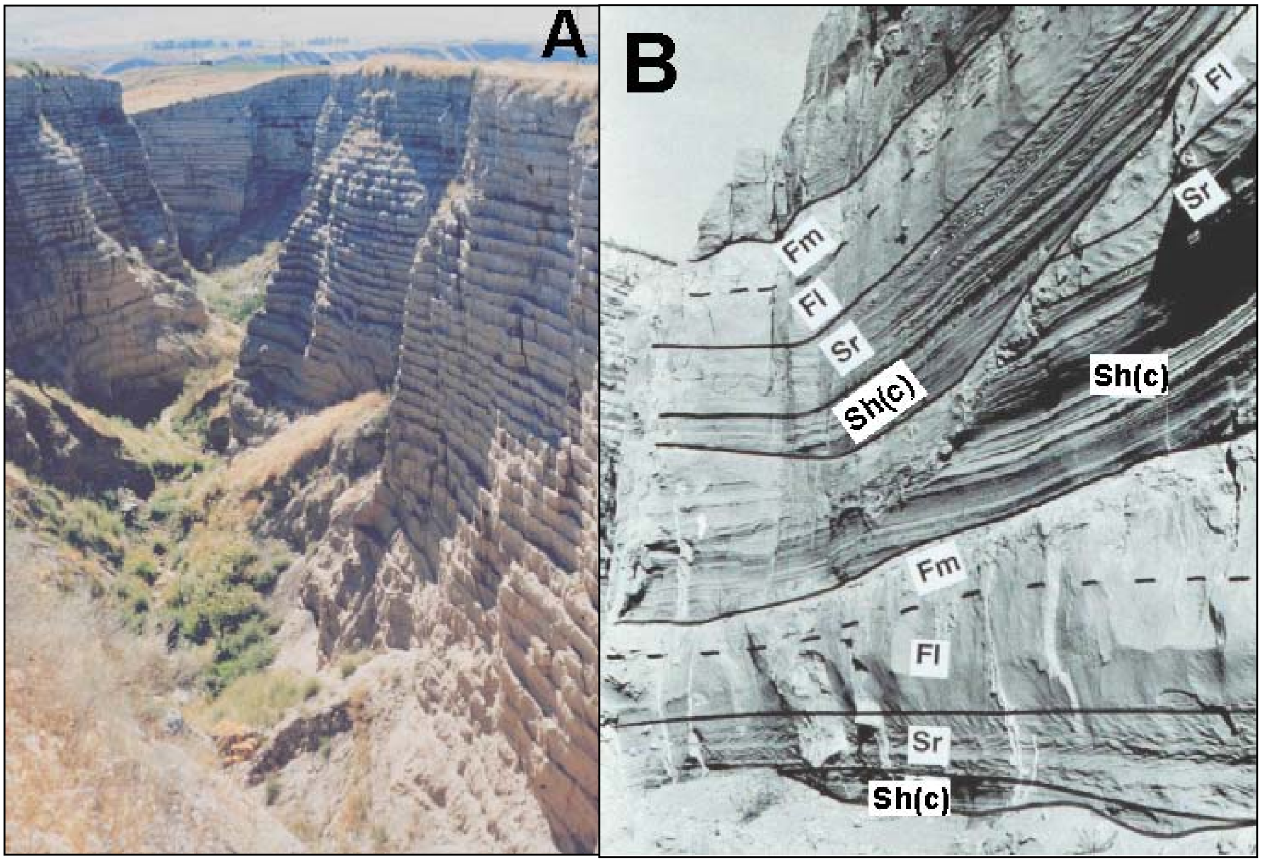
[a] As marked in figure, (A) is pebbly, matrix-supported, basaltic sand (Sh[c] or St/Sp) in borehole 299-W23-21 (depth of 27 to 27.3 m [88.5 to 89.5 ft]). Top of core is to left. (B) shows two layers of horizontally laminated, medium to coarse, "salt and pepper" sand [Sh(c)] separated by a fining upward layer of laminated silty fine sand (Sh[f]) to silt (Fl). Borehole 299-W11-39 (depth of 14.9 to 15.3 m [49 to 50 ft]). Top of core is to right. Note drilling-induced drag folding along edges of core liner.

Figure A-38. Excavation Exposures of the Sand-Dominated Facies Association (SD) in West-Central Pasco Basin.[a]



[a] As marked in figure, (A) shows multiple facies transitions at base of the ERDF excavation (approximately 15 m [50 ft] below ground surface, approximately 200 m [650 ft] in elevation). (B) shows the alternating layers of Sh(c) and Sh(f) at about the 3 m (10 ft) depth exposed within a shallow excavation adjacent to borehole DH-24. Down arrow coincides with interval of reverse grading, suggesting continuous sedimentation over this interval.

Figure A-39. Interbedded Sand- and Silt-Dominated Facies Association (ISSD) at Burlingame Canyon.[a,b]



[a] As marked in figure, (A) is looking down the 30-m (98.4-ft)-deep canyon. Base of the flood sequence is not exposed. Mount St. Helens “set S” ash is present on the 12th rhythmite below the top of the flood sequence. (B) shows the facies relations for several rhythmites near the base. Bottoms of beds are characterized by horizontally laminated, medium- to coarse-grained sand (Sh[c]), grading up into ripple-laminated fine sand (Sr), and finally laminated (Fl) to massive (Fm) fine sand and silt.

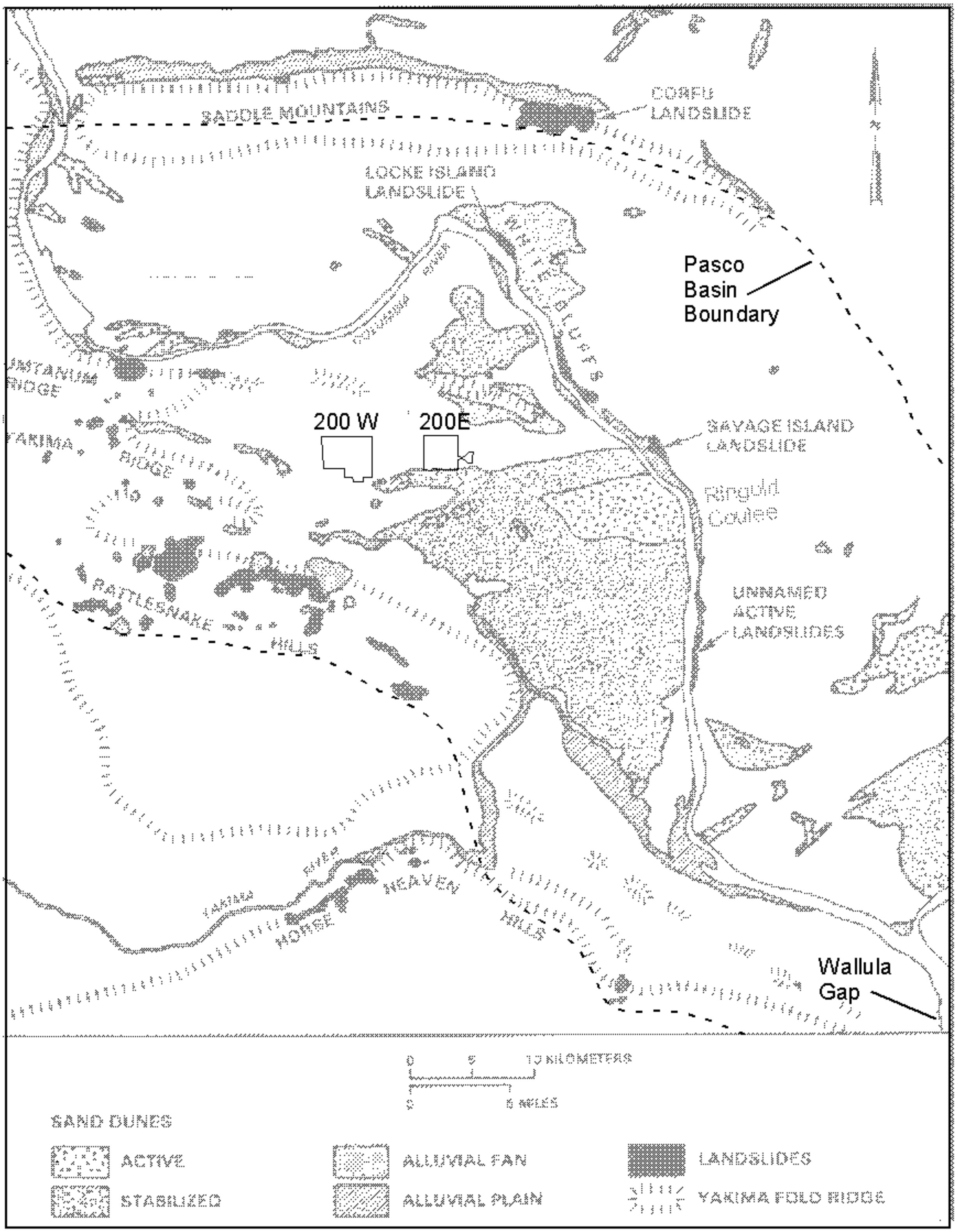
[b] Location identified with the letters “BC” on Figure A-19.

Figure A-40. Comparison of Subdivisions Historically Used for Hanford Formation Within 200 Areas.

	200 West								200 East				
Facies Association[1]	Last et al. (1989)	Connelly et al. (1992a)	Lindsey et al. (1992b)	Lindsey et al. (1994b)	Johnson et al. (1999)	Lindsey et al. (2000)	Sobcyzk (2000)	Wood et al. (2001)	Last et al. (1989)	Connelly et al. (1992b)	Lindsey et al. (1992a)	Lindsey et al. (1994b)	Wood et al. (2000)
SD				H1a	Hanford Gravel Unit B	H1a (gravelly sand to slightly silty sand)	Hanford Unit B Hanford Silty Sand						
GD	Coarse-Grained Sequence	Coarse-Grained Sequence	Coarse-Grained Sequence	H1	Hanford Gravel Unit A	H1	Hanford Unit A	Coarse-grained Sequence (H1)	Upper Coarse-Grained Unit	Upper Gravel Sequence	Upper Gravel Sequence	H1	Upper Gravel Sequence (H1)
SD	Basal Slackwater Sequence	Fine-Grained Sequence	Fine-Grained Sequence	H2	Hanford Sands	H2	Lower Hanford	Fine-Grained Sequence (H2)	Middle Sand Unit	Sandy Sequence	Fine Sequence	H2	Sand Sequence (H2)
GD				H3		H2a H3						H2a H3	
SD					Sands	H4							
GD or CCU									Lower Coarse-Grained Unit	Lower Gravel Sequence	Lower Gravel Sequence		Lower Gravel Sequence (H3)

[1] Hanford formation: SD = Sand-Dominated, GD = Gravel-Dominated; CCU = Cold Creek Unit

Figure A-41. Late-Quaternary to Holocene Landforms Within Pasco Basin.



Source: Modified after DOE 1988.

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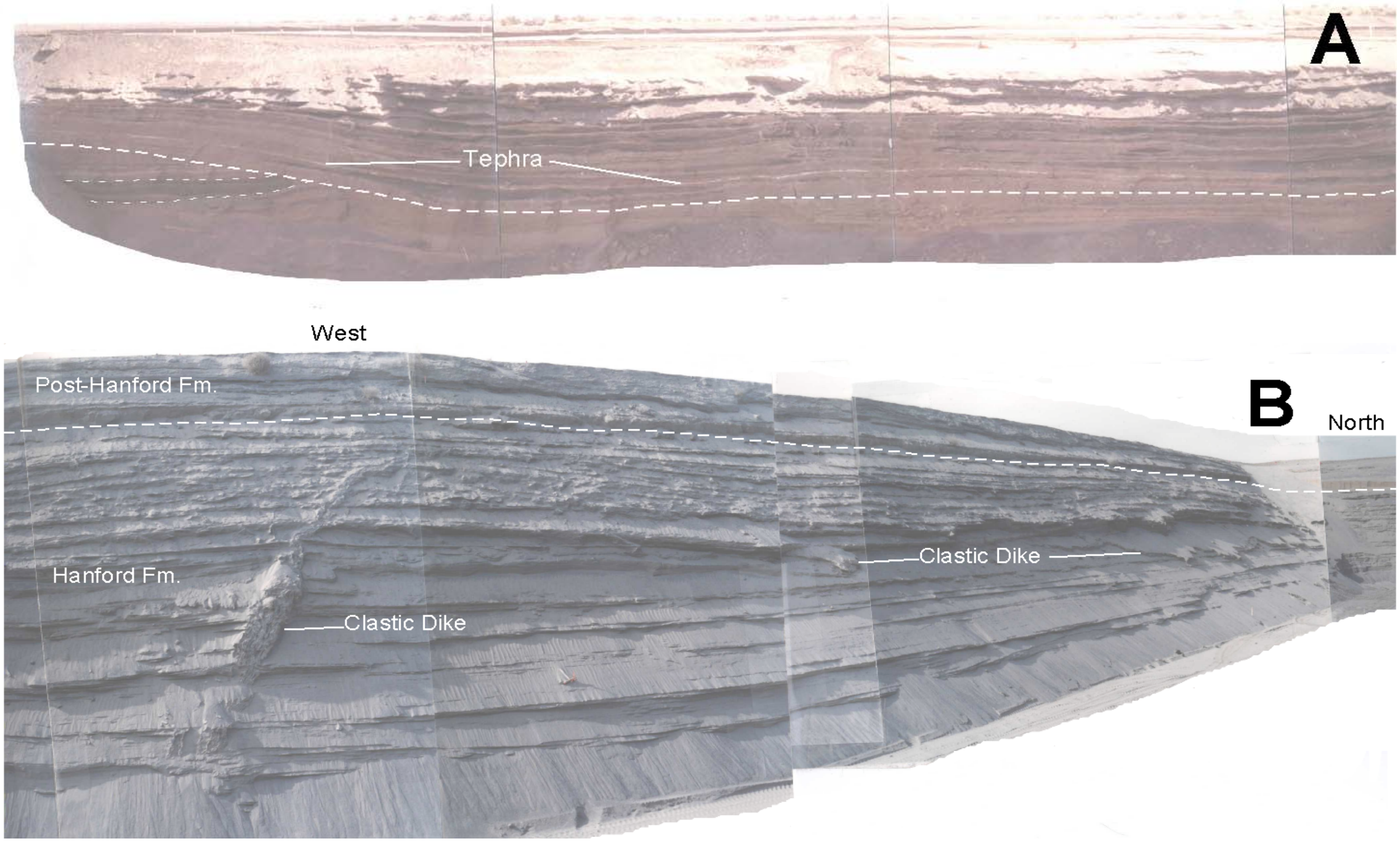
APPENDIX B

ADDITIONAL OUTCROP EXPOSURES OF THE HANFORD FORMATION IN THE PASCO BASIN

TABLE OF CONTENTS

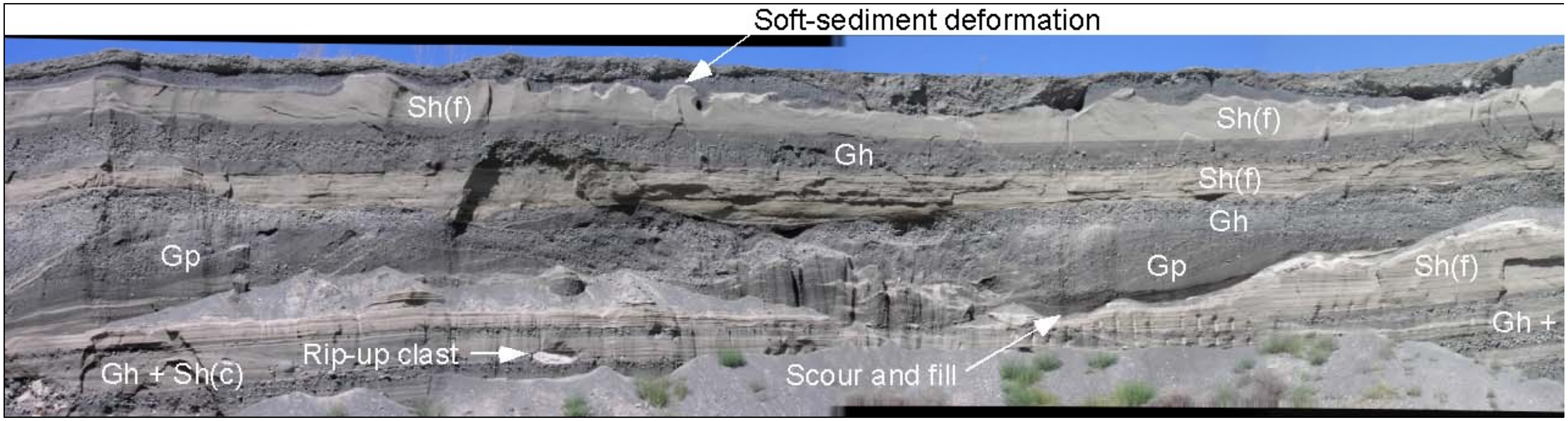
FIGURES

Figure B-1. Facies Association SD at Two U.S. Ecology Excavations.[a]



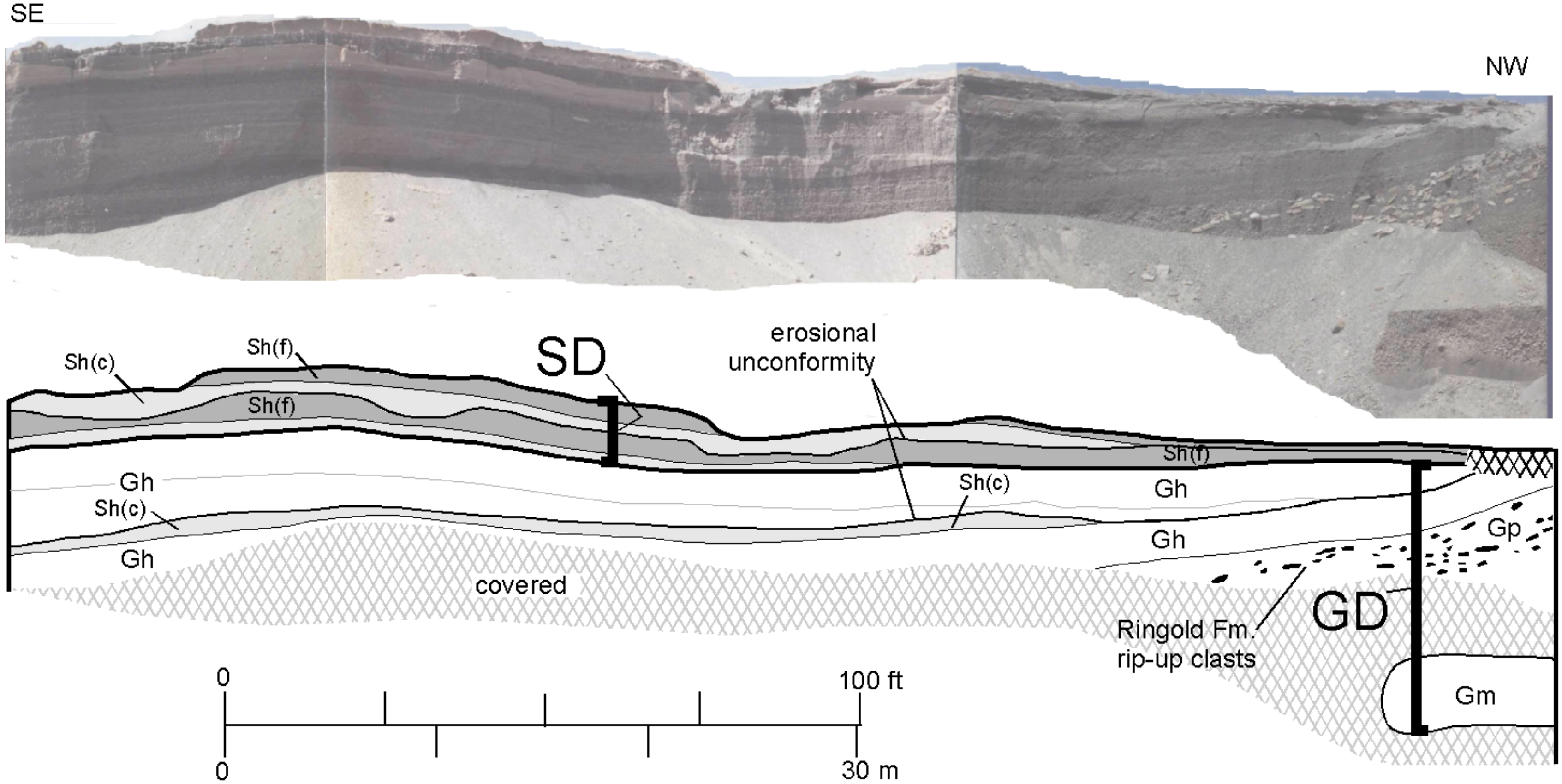
[a] Excavations, up to 15 m (50 ft) deep, are located within a few hundred meters of each other. Subparallel flood beds become thinner and finer grained toward the top of the section. Lithofacies within individual beds are predominantly Sh facies locally capped with Sr to Fl/Fm facies. Base of flood sequence is not exposed. (A) view is looking south. Mount St. Helens "set S" tephra, dated at 13,000 years before present, lies just above single angular unconformity within flood sequence (long dashed line). (B) Represented is mostly Sh facies capped by Sr to FL/Fm facies. Beds become thinner and finer grained toward the top. Two clastic dikes are shown; left dike is normal to trench, right dike strikes about parallel to the trench and dips slightly to the east toward trench axis. Location identified by the letters "US" on Figure A-20.

Figure B-2. Facies Association GD at Transtate Borrow Pit (Lower Exposure). [a]



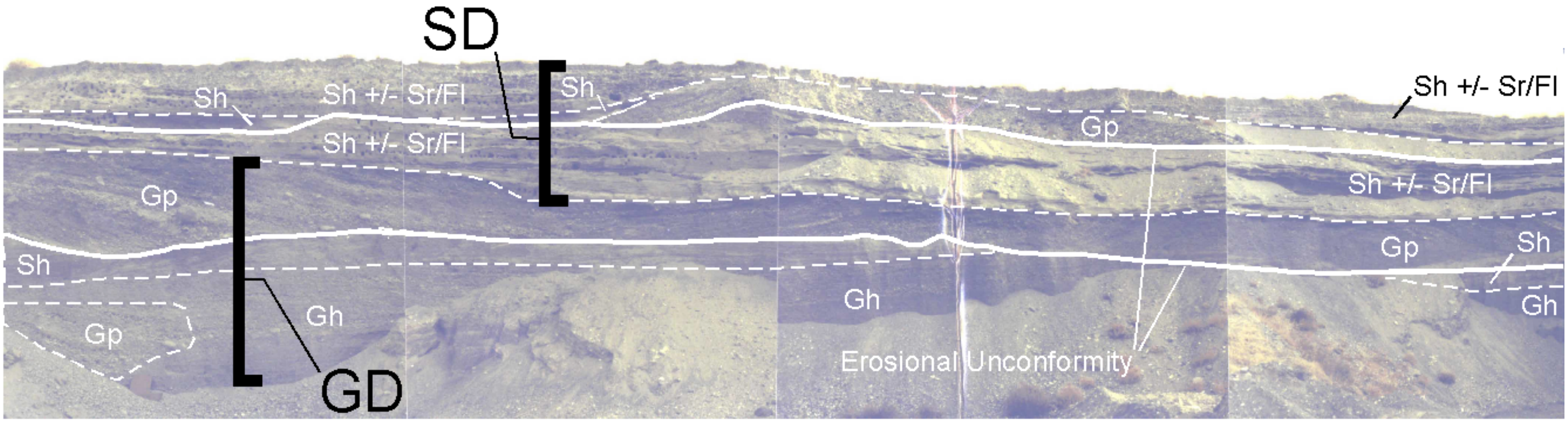
[a] Other features common to high-energy cataclysmic flood deposits include soft-sediment deformation, channel scour and fill, and rip-up clasts. Note lack of clastic dikes. Photograph taken in July 2001. See Figure B-3 for upper portion of exposure at the same locality. Location identified by the letter "T" on Figure A-20.

Figure B-3. Facies Associations GD and SD at Transtate Borrow Pit (Upper Exposure).[a]



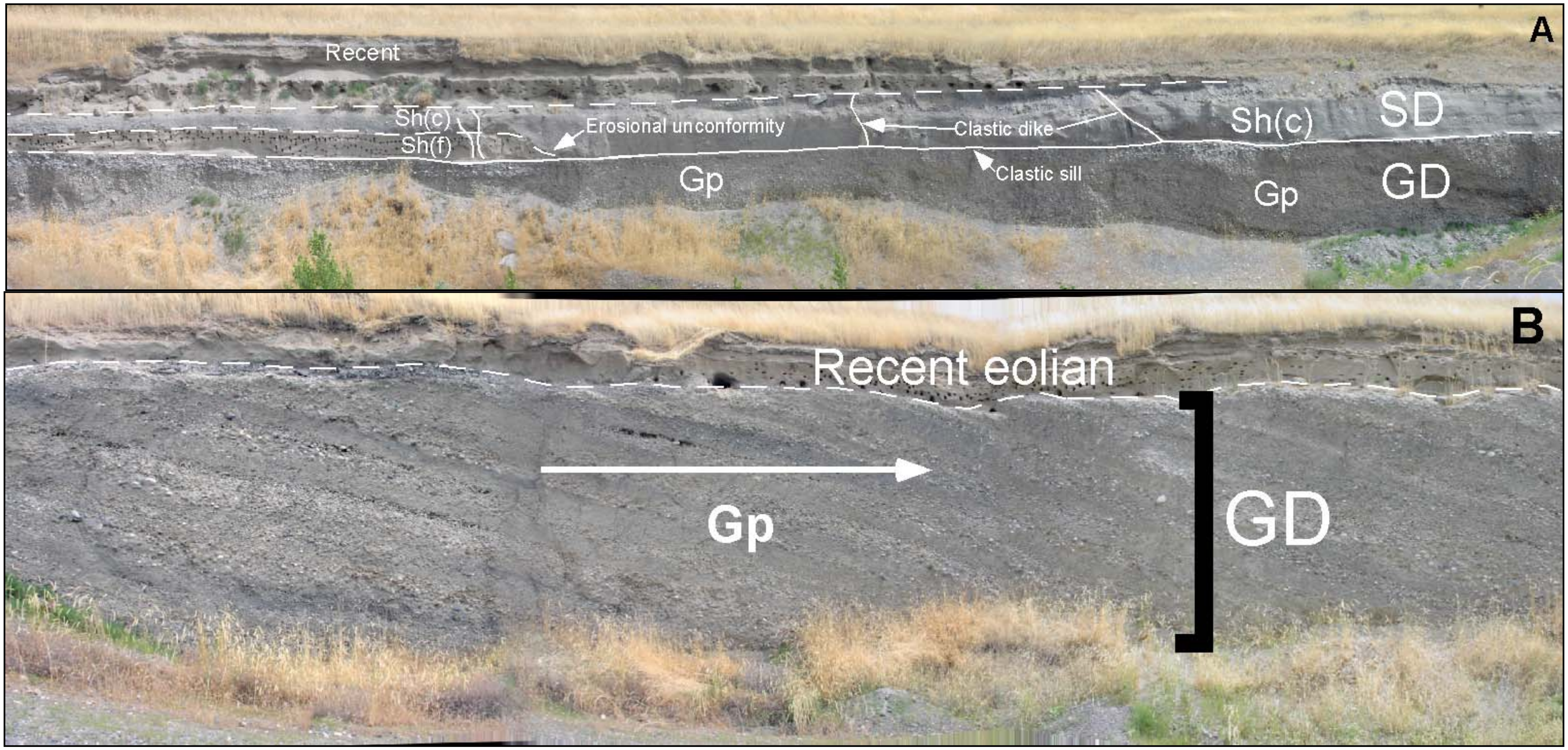
[a] Sand-dominated facies association overlies gravel-dominated facies association. Sequence offlaps to the left (southeast). Semi-consolidated Ringold Formation rip-up clasts were eroded from nearby Ringold outcrops along west side of Esquatzel Coulee. Photograph taken in mid-1980s. See Figure B-2 for lower portion of exposure at the same locality. Location identified by the letter "T" on Figure A-20.

Figure B-4. Facies Associations GD and SD at the Mouth of Ringold Coulee. [a]



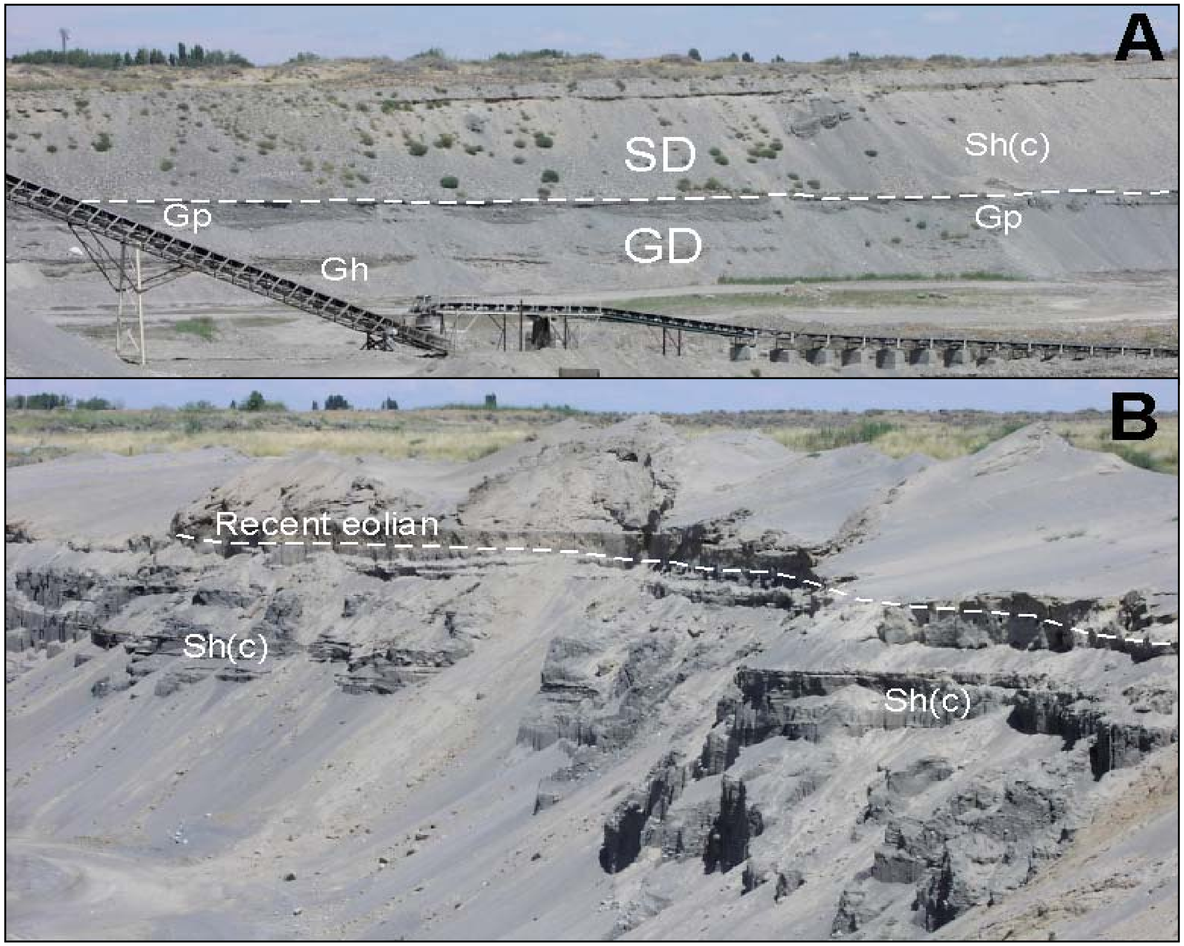
[a] Sand-dominated facies association overlies gravel-dominated facies association. Heavy white lines represent erosional unconformities. Location identified by letters “RC” on Figure A-20.

Figure B-5. Facies Associations GD and SD at Lower Smith Canyon Borrow Pit. [a]



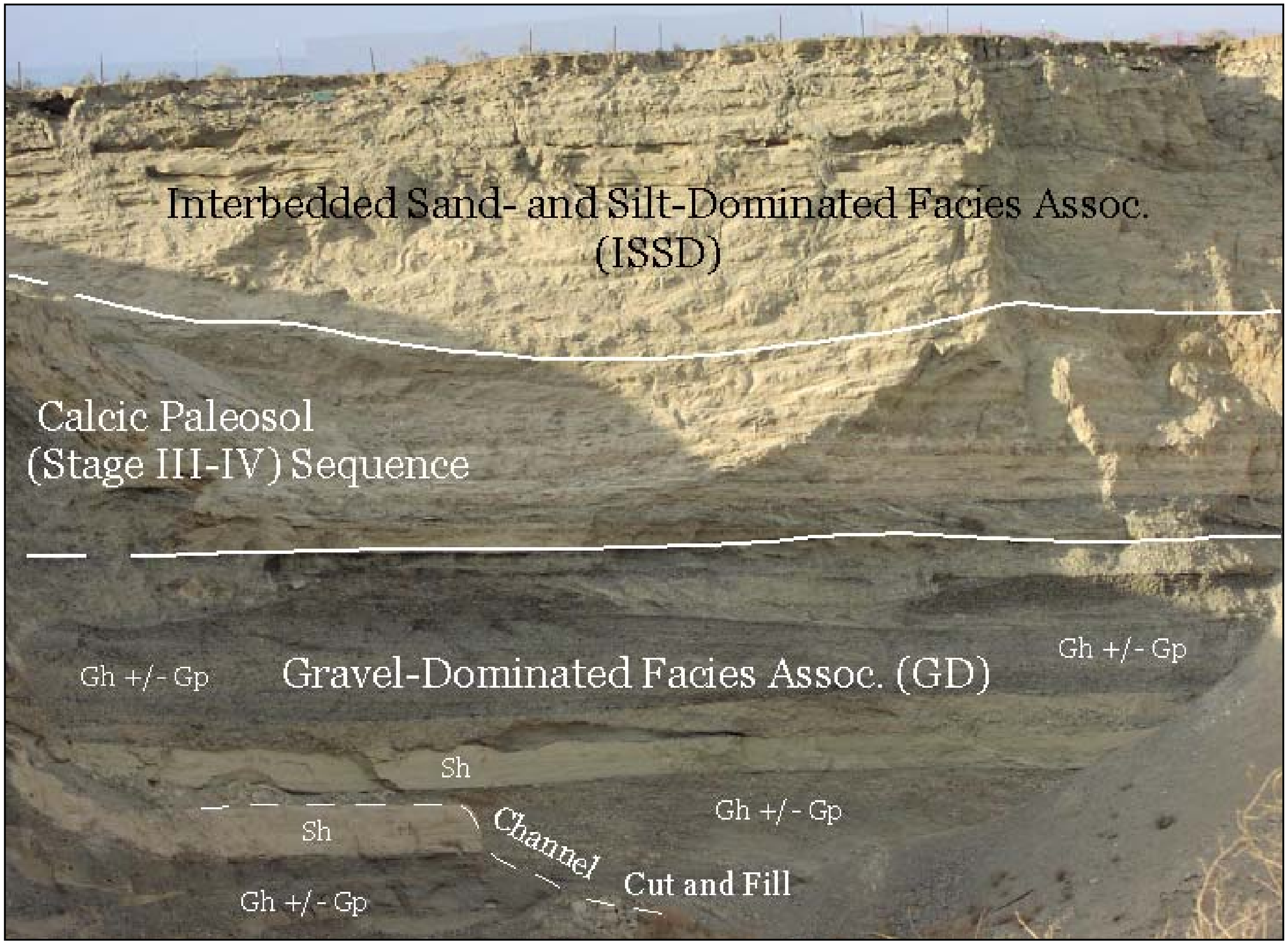
[a] (A) clastic sill runs along top of cataclysmic flood gravels, occasionally projecting upward into dikes. Fine-grained horizontally laminated sand (Sh[f]) locally scoured and filled with coarser-grained Sh(c). (B) planar-tabular (foreset-bedded) flood gravels (Gp) occur as single thick (4- to 5-m [13- to 16-ft]) unit that progrades downvalley (direction of arrow). Location identified by the letters “SC” on Figure A-19.

Figure B-6. Facies Association GD and SD at Pre-Mix Borrow Pit. [a]



[a] (A) 10 m (33 ft) or more of sand-dominated facies overlie a gravel dominated sequence. (B) Close up of sand-dominated facies, consisting of mostly horizontally laminated, basaltic medium- to coarse-grained sand [facies Sh(c)]. Location identified by the letters "PM" on Figure A-20.

Figure B-7. Facies Associations GD and ISSD Separated by a Calcic Paleosol Sequence at Kiona Quarry. [a]



[a] Fine-grained flood rhythmite sequence (ISSD) overlies a thick paleosol sequence. Gravel-dominated facies association (GD) at base is associated with much older pre-Wisconsin flood event(s). Location identified by the letters “KQ” on Figure A-20.

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