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QUATERNARY STRATIGRAPHY OF THE PASCO BASIN AREA, SOUTH-CENTRAL WASHINGTON

by

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INTRODUCTION

The Pasco Basin is a large topographic and structural depression which has been a depocenter for up to 300 m of non-marine, clastic sediments since (and prior to) the last eruptions of Columbia River basalt, dated at 8.5 Ma. The Pasco Basin borders the Yakima Fold Belt within the semiarid, central Columbia Plateau. It is elongate and arcuate in map view, due to change of trend in some of the structural elements bounding the basin (Fig. 1). The Pasco Basin is defined by the area east of the Hog Ranch-Naneum Ridge anticline, south of the Saddle Mountains, and north of the Rattlesnake-Wallula alignment (RAW), a series of northwest-trending anticlinal ridges and domes. The Pasco Basin merges to the east with the slightly tilted and relatively undeformed Palouse Slope.

The stratigraphy within the Pasco Basin has been unraveled since the 1940's when a variety of engineering geology and geohydrologic activities began. These included the Columbia Basin Irrigation Project (Grolier and Bingham, 1978), the siting of nuclear power plants (WPPSS, 1981; WCC, 1981; PSPL, 1982), the storage of defense nuclear wastes (Brown, 1959; R. Brown, 1960; Brown and Brown, 1965; Brown, 1979; Newcomb and others, 1972; Tallman and others, 1979; Routson and Fecht, 1979), and groundwater resource evaluation (Brown, 1979). Since 1976, the Quaternary and older deposits have been studied to test the feasibility for disposal of radioactive wastes in a geologic medium (Myers and Price, 1979; 1981; DOE, 1982; 1986).

The purpose of this section is to review and update the Quaternary stratigraphy of the Pasco Basin based on previous work as well as recent studies by the authors. Interpretations presented herein are based on a variety of methods including geologic mapping (Newcomb and others, 1972; Grolier and Bingham, 1978; Rigby and others, 1979; Lillie and others, 1978; Myers and Price, 1979), ash characterization, paleomagnetism, and numerical age dating (U-series, thermoluminescence (TL), and carbon-14). Results of age dating and tephra characterization, located on Plate 1, are presented in Tables 1 and 2, respectively.

GENERAL STRATIGRAPHIC RELATIONSHIPS

The Quaternary sediments, up to 100 m thick within the Pasco Basin, are differentiated primarily on the basis of texture, composition, and sedimentary structure, and to a lesser extent on other sedimentological features (Table 3). The discussion in this paper focuses on deposits associated with cataclysmic flood, fluvial, and eolian processes. While other Quaternary deposits are present (e.g., colluvium, mass wasting deposits), they are localized and relatively insignificant, and therefore, are not discussed further. For the purpose of discussion of sedimentary

facies, the Pasco Basin is subdivided into three stratigraphic subprovinces: the (1) central basin, (2) basin margin, and (3) ridge terrain.

CATACLYSMIC FLOOD DEPOSITS

Cataclysmic flood deposits, mostly derived from the sudden outpourings of glacial Lake Missoula (Bretz, 1959), are ubiquitous below an elevation of about 250 m in the Pasco Basin. They are divided into a coarse-grained and fine-grained facies (Table 3).

Coarse-Grained Deposits

Coarse-grained cataclysmic-flood deposits lie in or immediately adjacent to the main cataclysmic flood-channelways. Two types of coarse-grained flood deposits are recognized: a well-sorted facies and a poorly sorted facies (Table 3). Based on reversed magnetic polarity (Matuyama), a minimum age for the oldest cataclysmic flood deposits is early Pleistocene, i.e., prior to 0.79 m.y.B.P (Johnson, 1982). Reversed-polarity flood deposits are preserved within the Pasco Basin as well as the Channeled Scabland (Fig. 2). Old flood gravels on the Channeled Scabland, previously identified in Patton and Baker (1978) and Baker and Nummedal (1978), are located at Marengo, Revere, Macall, and Old Maid Coulee. These probably correlate with reversed flood deposits at Poplar Heights, Vernita Grade, and Yakima Bluffs within the Pasco Basin.

At least one middle Pleistocene episode of cataclysmic flooding is indicated by poorly sorted gravels with normal polarity capped by platy to massive, carbonate-plugged K horizons, characteristic of Stage III to Stage IV pedogenic carbonate development (Gile and others, 1966; Machette, 1985). Pedogenically altered flood deposits of this age occur along the top of a prominent flood terrace at ~140 m in the southwestern Pasco Basin northwest of Wallula Gap (Plate 1). Flood deposits of this age are also present at the Oak Street, South Bombing Range Road, Kiona Quarry, and Leslie Road localities (Fig. 2). A minimum age for the calcrete, sampled from near the Leslie Road locality and determined by the Th/U dating method (Ku and others, 1979), is about 0.20 Ma (Lab nos. RHT-10, RHT-11; Table 1). The timing of this flood episode is therefore middle Pleistocene (0.20 and 0.79 Ma).

Coarse-grained flood gravels associated with the last (late Wisconsin) episode of Missoula flooding locally overlie older flood deposits. Deposits of this age are widespread throughout the basin and characterized by weak soil development, limited to filaments and thin coatings of carbonate on the undersides of gravel clasts (Stage I).

Fine-Grained Deposits

Fine-grained cataclysmic flood deposits comprise the most extensive and voluminous Quaternary-age unit within the Pasco Basin. These deposits, which consist mostly of silt and/or sand, are divided into two facies: (1) a plane-laminated sand facies and (2) a rhythmite facies, also referred to as Touchet Beds (Flint, 1938). Plane-laminated sand, most common in the central basin, grades laterally into slack-water rhythmite deposits toward basin margins. Because plane-laminated sand occurs both within flood gravels and at the bases of proximal rhythmites (Bjornstad, 1980; Bunker, 1980) it is considered a transitional facies between the coarse-grained and rhythmite flood facies.

Three plane-laminated sand sequences were exposed in a recent excavation within the central basin (Fig. 3). These sequences may correlate with the early, middle, and late Pleistocene flood episodes, discussed above for coarse-grained flood deposits. The uppermost unit contains the Mount St. Helens "set-S" tephra couplet (Table 2), dated at 13,000 years B.P. (Mullineaux and others, 1978). The two lower plane-laminated sand sequences are capped by weakly developed and bioturbated B horizons, suggesting distinctly different ages. Additional evidence for three separate flood episodes lies with a clastic dike in the middle unit, which is neatly truncated along the contact with the upper unit (Fig. 3). The middle unit contains an abundance of fine-grained Ringold Formation (Neogene) rip-up clasts, suggesting this unit was derived from a scabland flood that entered the Pasco Basin from the northeast via Ringold Coulee (Fig. 1). Wood from within the clastic dike has been radiocarbon dated at >32 ka (Lab no. C9190; Table 1). The lower unit is at about the same stratigraphic position as the magnetically reversed flood sequence described by PSPL (1982), and therefore is probably early Pleistocene.

The second type of fine-grained flood deposit, the rhythmite facies, consists of graded beds of plane- to ripple-laminated, sand and silt deposited in slack-water areas marginal to the central Pasco Basin. Rhythmites range from 3 to 30 cm thick and often contain a distinctive series of turbidite-like sedimentary structures (Baker, 1973). Rhythmites in the southern and eastern Pasco Basin are reported in Bunker (1980, 1982) and Bjornstad (1980, 1982), respectively. Most rhythmite sequences in southern Washington are of late Wisconsin age except at two locations where older sequences are preserved. Older sequences have been observed at Cummings Bridge (Bjornstad, 1980; WCC, 1981) and Yakima Bluffs (Figs. 2 and 4).

ALLUVIUM

Mainstream Alluvium

Alluvium from several major rivers (i.e. Yakima, Snake, and Columbia) is represented in the Pasco Basin at least since the late Tertiary (Fecht and others, 1985). Mainstream alluvium lies between the Neogene Ringold Formation and Pleistocene cataclysmic flood deposits within the central Pasco Basin. Quaternary-age alluvium is differentiated from Ringold Formation by less cementation and weathering, and from flood deposits by greater degree of roundness and basalt content of gravel clasts, which is between that of Ringold Formation and flood gravels (Table 3).

A thick sheet of well-rounded and -sorted gravels, referred to as Pre-Missoula Gravels (PSPL, 1982), disconformably overlie the Ringold Formation over much of the central basin. Based on the magnetic polarity and stratigraphic position, this unit is interpreted to be early Pleistocene in age. According to Van Alstine (1982), the upper part of this unit has reversed polarity overprinted on normal polarity; an indication that deposition occurred during a normal event (either the Jaramillo (0.90 to 0.97 Ma) or Olduvai (1.67 to 1.87 Ma) within the Matuyama reversed epoch. Pre-Missoula Gravels were interpreted by PSPL (1982) as deposits of older cataclysmic floods. Although the upper portions of this unit may be flood related, we believe the lower portion to be more characteristic of mainstream alluvium.

Mainstream alluvium of probable early-Pleistocene age is exposed along Cold Creek in a remnant gravel bar (Plate 1). The gravel bar, up to 45 m thick, probably represents the surface expression of Pre-Missoula Gravels present in the subsurface a few kilometers to the east. Elsewhere, early Pleistocene alluvium is preserved at Yakima Bluffs (Fig. 4) where mainstream alluvium (perhaps equivalent to the Pre-Missoula Gravels) is overlain by a sequence of reversed (Matuyama) overbank deposits.

Mainstream alluvium was deposited during the relatively long time intervals that separated major cataclysmic flood episodes. However, with the possible exception of the Pre-Missoula Gravels, preservation of these deposits within the Pasco Basin is rare. Borehole studies and mapping of large-scale surface excavations by the authors have failed to reveal mainstream alluvium between episodes of cataclysmic flooding. The lack of mainstream alluvial deposits is explained by either limited distribution to narrow channels near the present-day rivers or, more likely, to scouring of pre-flood river channels by cataclysmic floods, which removed most of the mainstream alluvium deposited between floods.

Sidestream Alluvium

Thin (<= 10 m) deposits of sidestream alluvium lie along the basin margins where ephemeral streams have eroded into the basalt ridges and/or the Ringold Formation. Sidestream alluvium is

transported and redeposited as basaltic gravels mixed with varying amounts of sand and silt (mostly reworked loess) in the form of alluvial fan and/or floodplain deposits.

At least three ages of sidestream alluvium are recognized within the Pasco Basin. These are differentiated on the basis of paleosol development, inclusive tephra horizons, and their stratigraphic relationship with other units. The oldest sidestream unit, rarely exposed and only in the ridge terrain, is composed of a sequence of weathered, subangular to subrounded basaltic alluvium capped by silcrete. The silcrete formed during late Pliocene and/or early Pleistocene time, perhaps under more humid conditions (Summerfield, 1983). A second younger coarse-grained sidestream alluvial unit is locally present along exposed basin margins. Unlike the silcrete-cemented unit, this unit is composed of angular, unweathered basalt clasts, cemented with one or more carbonate horizons ranging from Stage II to IV in carbonate development. Carbonate-cemented sidestream alluvium is estimated to be early to late Pleistocene in age. This is based on correlation of loess units interfingered with sidestream debris to loess of known reversed and normal magnetic polarity. The upper age of this unit is tentatively constrained at about 75 ka, based on a Th/U analysis of pedogenic-carbonate (WCC, 1981) at Finley Quarry (Fig. 1).

The youngest sidestream alluvial unit typically shows minimal soil development and overlies carbonate-cemented alluvium throughout the ridge and basin margin terrains. Sidestream alluvium contains both layers (G and B) of 11,200-year-old Glacier Peak (Mehringer and others, 1984) and/or the 6600-year-old Mazama (Wilcox, 1965) tephra (Table 2).

EOLIAN DEPOSITS

Eolian deposits include dune sand and loess. Dune sand, derived from the reworking of flood deposits since about 13,000 years ago, blankets much of the east-central Pasco Basin. Both active and stabilized cresentic-shaped dunes have formed by prevailing winds out of the southwest. Loess, on the other hand, occurs in sheets that mantle much of the upland areas surrounding the central basin (Plate 1). Loess, which accumulates more on the north and east (downwind) facing slopes of ridges, may attain thicknesses of 30 m or more; however, most loess deposits range from 5 to 10 m thick.

A total of five different-age loess units are recognized within the Pasco Basin (Table 3) and are referred to, informally, as L1 through L5. These units are differentiated on the basis of (1) position with respect to other stratigraphic units, which include sloplwash, sidestream alluvium, and slack-water flood deposits, (2) color, (3) soil development, and (4) paleomagnetic polarity (Table 3). The oldest loess unit (L1) is distinctively very compact, reddish yellow (7.5 YR-7/6), and usually capped by a silcrete. The inferred age of L1 is late Pliocene to early Pleistocene based on its siliceous character and the position of L1 with respect to the overlying unit (L2). The chemical nature

and stratigraphic position of the silcrete suggests that it predates Quaternary-age calcic paleosols. This unit occurs at only a few scattered localities in the ridge terrain.

Unit L2 consists of compact brownish yellow (10YR-6/6) loess capped by a K horizon, consisting of as much as 4 m of platy (Stage III to IV) pedogenic carbonate. L2 is present in Snively Basin where it overlies L1, and in isolated outcrops at Vernita Grade and Radar Hill (Fig. 1). Based on its predominantly reversed polarity, L2 is interpreted to be early Pleistocene. Minor normal-polarity intervals that occur within L2, at Vernita Grade (Fig. 2) for example, probably represent either the Jaramillo or Olduvai normal-polarity events within the Matuyama Epoch (0.79 to 2.48 Ma).

Unit L2 may correlate with reversely magnetized loess that occurs at lower stratigraphic levels in the Palouse region (Foley, 1982). Elsewhere, a well-sorted, massive, pale brown loess, described from boreholes in the west-central Pasco Basin, may also correlate with unit L2. This unit, also referred to as early "Palouse" soil (D. Brown, 1960; Tallman and others, 1979), lies between a highly weathered Ringold surface and cataclysmic flood deposits.

A third loess unit (L3) consists of a compact, yellowish brown (10YR-5/6) loess that is up to 7 m thick. It contains multiple paleosols consisting of both well-developed argillic B horizons and platy, carbonate-plugged (Stage III to IV) K-horizons. This unit, common in ridge terrain, is probably equivalent to the middle-to-late-Pleistocene Palouse Formation that lies east of the Pasco Basin (Newcomb, 1961). Normal magnetic polarity combined with Th/U numerical age dates on pedogenic carbonate (Lab nos. C4002, C6682-C6685; Table 1) suggest this loess unit is between 75,000 to 790,000 years old.

Unit L4 consists of multiple cycles of loose to weakly compact pale-brown (10YR-6/3) loess. This unit contains weak to moderately well developed B horizons with thin coatings, filaments, and nodules of carbonate (Stage I to II). At least one tephra (Table 2) is associated with L4: the Mount St. Helens "set M" couplet (18,000 - 20,000 yrs. B.P. (Smith, 1980)). Based on tephra and carbonate ages, L4 is middle to late Wisconsin (~20,000 to 75,000 yrs B.P.).

The youngest loess unit within the Pasco Basin, L5, includes loess deposited during and since late Wisconsin time (~20,000 years B.P.). Characteristically, it is loose, well sorted, and pale brown (10YR-6/3) in color. Soils atop or within unit L5 normally show only a simple, weak A-C horizon (Baker, 1973). Carbonate development is limited to filaments and thin particle coatings (Stage I). Tephra from three sources are associated with the L5 unit: the Mount St. Helens "set S" couplet (or triplet), Glacier Peak (layers G and B) and Mazama (Table 2).

DISCUSSION

Early Pleistocene age deposits are rarely present within the Pasco Basin and surrounding area for two reasons. One reason is due to a significant drop in base level following deposition of the Ringold Formation (R. Brown, 1960; Newcomb and others, 1972; Bjornstad, 1985), which probably began sometime in the late Pliocene. The cause of this incision (up to 150 m in the Pasco Basin) is unknown at this time (Fecht et al., 1985) but is probably due to a change in climate and (or) tectonic activity. A second reason is the subsequent erosion and redistribution of Pleistocene (and older) deposits by cataclysmic flooding. An upper limit on the age of incision is 900,000 years based on a date of basaltic lava from Haystack Butte which lies near the present base level in the Columbia River Gorge (Bela, 1982). Downcutting was probably regional in extent (Fecht and others, 1985) since evidence for a similar event is reported for several other areas in the Columbia Basin (Cochran, 1978; Tolan and Beeson, 1984). Indications are that base level has remained relatively constant following late-Pliocene and/or early Pleistocene incision.

CONSTRAINTS ON FLOODING WITHIN THE PASCO BASIN

Cataclysmic floods inundated the Pasco Basin several or more times during the Pleistocene. Net erosion by these floods was minimal and probably only associated with the earliest floods; later floods only partially incised into older flood deposits before backfilling with deposits of the most recent flood.

At least three major flooding episodes (early, middle, and late Pleistocene) are recognized in the Pasco Basin. These episodes are distinguished by changes in magnetic polarity (Fig. 2), truncated clastic dikes, and soil development atop flood sequences. However, many more minor flood events probably occurred during each of these major episodes. Deciphering the history of cataclysmic flooding in the Pasco Basin is complicated, not only by floods from multiple sources (glacial Lake Missoula and Lake Bonneville), but also by the fact that paths of Missoula floodwaters migrated and changed course with the advance and retreat of the Cordilleran Ice Sheet (Craig and Underberg, 1984; Baker and Bunker, 1985). The best record of flooding is preserved for the last Missoula flood which apparently came down the Columbia River (Waitt, 1982).

The evidence for cataclysmic flooding in the Pasco Basin, besides the sediments themselves, include high-water marks and faint strandlines along the basin margins. These were left behind as a result of hydraulic damming and the formation of "Lake Lewis" (Allison, 1933) behind Wallula Gap (Fig. 5). Lake formation may have initiated in the Columbia River Gorge, however, as indicated by similar high-water marks both above and below Wallula Gap. High-water marks for Lake Lewis, inferred from ice-rafted erratics on ridges, range from 370 to 385 m, which is 20 to 35 m higher than reported previously (Baker, 1973;

Waitt, 1980). A series of weak strandlines are interpreted from photolineaments between the 245- and 305-m levels along the northeastern flank of Rattlesnake Mountain. A flood origin is inferred based on exposures in trenches that cross these features. The lack of well-developed strandlines and the absence of typical lake deposits overlying flood deposits suggest Lake Lewis was short-lived (Waitt, 1980).

Flood deposits are distributed such that coarse-grained deposits lie toward the center of the basin and fine-grained deposits toward the margins; a similar pattern was most likely repeated during most flood episodes. The two coarse-grained facies, poorly sorted and well sorted (Table 3), are generally confined to relatively narrow trains within or near flood channelways. The plane-laminated sand facies occurs as a broad sheet over most of the central basin. Paleocurrent indicators within beds of plane-laminated sand are unidirectional, generally south or west, within the Pasco Basin (Fig. 5).

Rhythmite facies occur in slack-water areas around the margins of the basin and were deposited by multidirectional currents, including upvalley. Individual rhythmites fine and thin both laterally and vertically (Bunker, 1980; Bjornstad, 1980). Occassionally, within late-Pleistocene fine-grained flood sequences, rhythmites overlie plane-laminated sand facies, but not vice versa. Multiple floods may be represented where evidence for subaerial activity (e.g., airfall tephra, bioturbation, and/or eolian sand) lie between rhythmites. Similar observations have been reported by Waitt (1980) and Bunker (1982). In contrast, similar evidence for subaerial exposure has not been observed within the plane-laminated sand facies. Poorly sorted flood gravels lie both above and below slack-water deposits, whereas the well-sorted flood gravels are generally only present above slack-water deposits. The following is a simplified flood model based on the above observations.

SIMPLIFIED CATACLYSMIC FLOOD MODEL

A generalized model for the the last Missoula flood in the Pasco Basin consists of three phases: (1) large-scale erosion, followed by (2) deposition associated with lake filling, and finally (3) deposition and erosion associated with lake retreat. Previous flood episodes show a similar pattern of erosion and deposition. However, the distribution of facies probably differed depending on where the main floodwaters entered the basin.

Erosional Phase

The first effect floodwaters had on the basin was to cause extensive erosion, downcutting, and reworking of preexisting deposits. Floodwaters that entered from the north (Othello Channels and Esquatzel Coulee) and east (Cheney-Palouse tract) carried large volumes of Columbia River basalt and Palouse loess

while floods moving down the Columbia River ripped up and reworked loose alluvial and glacial outwash deposits. Within the Pasco Basin, on the other hand, floodwaters mostly scoured into weakly consolidated, older flood deposits, the fluvial-lacustrine Ringold Formation, and to a lesser extent, basalt and loess.

Waxing Lake Lewis Phase

Floodwaters entering the Pasco Basin quickly exceeded outflow at the narrow constriction in the Horse Heaven Hills (Wallula Gap) and/or the Columbia River Gorge. This resulted in hydraulically impounded floodwaters that formed a short-lived lake in the basin referred to as "Lake Lewis" (Allison, 1933). As the lake filled, poorly-sorted flood gravels rapidly aggraded due to rising base level and waning current velocity along the bed.

Foreset-bedded, poorly sorted gravel deposits in the eastern basin suggest this area was strongly influenced by flood-water from the northeast down the Snake River (Lindberg and Brown, 1981). These floodwaters were either associated with a Missoula flood(s), directed down the Cheney-Palouse scabland tract, or perhaps a Lake Bonneville flood (Malde, 1968). Deposits from the Lake Bonneville flood, the last of which occurred about 14,000 to 15,000 yrs. B.P. (Scott and others, 1982), have not been positively identified within the Pasco Basin, probably because of erosion and/or burial by later floods from Lake Missoula.

Away from aggrading flood channels plane-laminated sand was deposited. Eventually, as the lake rose, the central basin was extensively covered by a sheet of plane-laminated sand. Along the margins of the basin, in backflooded valleys, floodwaters deposited one or more rhythmites. Rhythmites locally overlie plane-laminated sand, as on the downstream sides of flood bars, for example.

The number of floods represented in any particular flood sequence is debatable (Baker and Bunker, 1985). Waitt (1980, 1985) proposed that each graded bed of a rhythmite sequence represents one of 40 or more separate flooding events from glacial Lake Missoula. An alternative hypothesis for the development of rhythmites is through transient flood surges during a single flood (Bretz, 1929; Baker, 1973; Bjornstad, 1980, 1982; Bunker, 1982; Rigby, 1982).

Based on distinct unconformities, only three major flood episodes (early, middle, and late Pleistocene) are recognized in the Pasco Basin, although the occassional presence of weathered horizons, eolian material, and/or tephra included within rhythmite facies suggest there were multiple late Pleistocene floods as well. Similar evidence for multiple flooding is absent, however, within sequences of plane-laminated sand, although this may only signify erosion associated with succeeding floods.

Aggradation within Lake Lewis decreased as the last of the floodwaters entered the basin. A broad, southeastward-prograding delta, referred to as Priest Rapids bar (Bretz, 1928), developed

as floodwaters expanded beyond a flow constriction at Sentinel Gap. This bar, which probably began to form in the early Pleistocene, aggraded during subsequent floods reaching its present height (210 m) in the late Pleistocene (Fig. 5).

Waning Lake Lewis Phase

Lake Lewis began to recede once discharge through Wallula Gap exceeded the amount of floodwater entering the basin, probably within weeks or less of flood initiation (Baker, 1973). Floating icebergs concentrated in slack-water areas, where they became stranded and melted, leaving behind bergmounds (Fig. 5) atop the rhythmite facies (Fecht and Tallman, 1978). As Lake Lewis drained, floodwaters became channelized as current energy along the bed increased, forming a network of anastomosing channels (Fig. 5). Several well developed eroded flood bars (i.e., terraces) formed in the central basin including Priest Rapids, Cold Creek, and Gable Mountain bars. With the drop in local base level, the waxing-stage aggradational plain that filled the central basin, was incised. This is reflected in the central basin where floodwaters moving southeastward incised into the aggradational, plane-laminated sand plain leaving behind a hanging valley at the mouth of Ringold Coulee (Fig. 5). Most clastic dikes, ubiquitous in flood deposits throughout the Pasco Basin, appear to have formed through forcible injection during waning stages of flooding (Black, 1979; WCC, 1981) during this time. Finally, as the last floodwaters drained from Lake Lewis, reworked well-sorted gravel facies (Table 3), lacking clastic dikes, were deposited in a narrow train extending from Sentinel Gap to Wallula Gap and from near the Yakima Horn to the Columbia River.

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FIGURES

Plate 1. Quaternary geology of the Columbia Plateau. Use data from RHO-BWI-ST-4 (Geologic Studies of the Columbia Plateau) and unpublished Fecht maps. Plate might include:

- o distribution of Quaternary stratigraphic units (early and middle versus late Pleistocene flood deposits; alluvial fans; loess; landslide debris; colluvium; alluvium; active versus stabilized Holocene dune sand)
- o locations of analytical data (tephra characterization, C-14, U-series, TL dates) tied to Tables 1 and 2.

Figure 1. Location Map

Figure 2. Correlation of pre-Wisconsin floods for the Pasco Basin and Channeled Scabland

Figure 3. Stratigrpahic relationships among flood deposits at the FMEF site. At least three flood sequences are interpreted based on erosional unconformities at A and B.

Figure 4. Photomosaic trace of the Yakima Bluffs exposure

Figure 5. Late-Pleistocene cataclysmic flood features for the central Columbia Plateau

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TABLE 1. RADIOMETRIC AGE DATES ON QUATERNARY DEPOSITS IN THE PASCO BASIN

Lab No.	Analysis	Location (Section/Township/Range)	Stratigraphic Position	Age Date*	Remarks
C9190	C-14	18/11N/28E	Within truncated clastic dike in flood deposits	>32	Wood fragments
RHT-42	Th/U	NENE11/8N/28E	Pre-Wisconsin flood gravel	115 +/-10 (230)	
DH-21-88.6	Th/U	NENE10/12N/25E	Sidestream alluvial gravel	82 +26/-19	
C4002	Th/U	NE24/13N/31E	Loess over pre-Wisconsin flood gravel	>350	
C6102	Th/U	SESW29/8N/30E	Alluvial fan	95 +/-10 (173 +20/-15)	Carbonate-coated gravel
C6129	Th/U	724/12N/28E?	Pre-Wisconsin flood gravel over Touchet Beds	88 +/-9 (205 +45/-30)	
C6132	Th/U	S6/12N/23?E	Flood gravel	34 +/-3 (101 +/-10)	Carbonate-coated gravel
C6133	Th/U	S6/12N/23?E	Flood gravel	37 +/-3 (45 +/-3)	Carbonate-coated gravel
C6259	Th/U	SWSE6/9N/28E	Flood gravel	114 +/-10 (221 +40/-25)	Carbonate-coated gravel
C6664	Th/U	NWNW4/7N/29E	Loess	>400	Calcrete
C6674	Th/U	19E/12N/25E	Alluvium	109 +60/-38	Siliceous calcrete
C6682	Th/U	SE4/14N/29E	Loess	136 +39/-51	
C6683	Th/U	SE4/14N/29E	Loess	76 +/-6	
C6684	Th/U	SE4/14N/29E	Loess	241 +73/-47	
C6685	Th/U	SE4/14N/29E	Loess	122 +34/-25	
C9052	Th/U	NWNE29/9N/27E	Flood gravels	>210	Carbonate-coated gravel; resample of C9260
C9116	Th/U	NE16/9N/28E	Reversed flood gravels	92 +/-8 (205 +/-20)	
C9260	Th/U	NWNE29/9N/27E	Flood gravels	>400	Carbonate-coated gravel; resample of C9052
C9264	Th/U	SWNW25/(9N/28E	Flood gravels	>400	Same as RHT-10, RHT-11
C9278	Th/U	12/12N/25E	Buried Pleistocene alluvial fan	44 +/-8	
C9279	Th/U	12/12N/25E	Buried Pleistocene alluvial fan	127 +19/-16	
C9286	Th/U	?Center29/13N/29E?	Cold Creek terrace gravel	142 +97/-52	
C9286	Th/U	?Center29/13N/29E?	Cold Creek terrace gravel	164 +inf./-90	
C9288	Th/U	SENE8/10N/27E	Pleistocene alluvium	65 +/-10	Calcrete
DH-24-84.6	Th/U	NENE3/12N/25E	Sidestream overbank alluvium	111 +39/-26 (>600)	Calcrete
DH-25-86.7	Th/U	SESE3/12N/25E	Sidestream alluvial gravel	>157 (240 +40/-30)	
DH-26-74.5	Th/U	NESE22/12N/25E	Sidestream alluvial gravel	110 +33/-28 (240 +/-40)	
RHT-10	Th/U	SENW25/9N/28E	Pre-Wisconsin flood gravel	200 +250/-70	Same as RHT-11, C9264
RHT-11	Th/U	SENW25/9N/28E	Pre-Wisconsin flood gravel	220 +380/-70	Same as RHT-10, C9264
RHT-37	Th/U	?NWSW10/9N/27E?	Pre-Wisconsin flood gravel	145 +/24 (230)	
RHT-6	Th/U	SWNE11/13N/27E	Loess over Ringold Formation	>500	
W14-7-129	Th/U	SWSE1/12N/25E	Sidestream alluvial gravel	155 +inf./-88 (>400)	
W15-14-164.2	Th/U	SWSW1/12N/25E	Sidestream alluvial gravel	122 +75/-47 (>600)	
C9278	TL	12/12N/25E	Buried Pleistocene alluvial fan	400 +/-65	Carbonate-coated gravel
C9279	TL	12/12N/25E	Buried Pleistocene alluvial fan	290 +/-27	Carbonate-coated gravel
C9279	TL	12/12N/25E	Buried Pleistocene alluvial fan	300 +/-33	Carbonate-coated gravel
DH-21-88.6	TL	NENE10/12N/25E	Sidestream alluvial gravel	288 +/-71	
DH-24-84.6	TL	NENE3/12N/25E	Sidestream overbank alluvium	823.3 +/-158.9	Calcrete
DH-25-86.7	TL	SESE3/12N/25E	Sidestream alluvial gravel	171.1 +/-20.9	
DH-26.74.5	TL	NESE22/12N/25E	Sidestream alluvial gravel	333.2 +/-30.9	
RHT-37	TL	?NWSW10/9N/27E?	Pre-Wisconsin flood gravel	280 +/-60	
W14-7-129	TL	SWSE1/12N/25E	Sidestream alluvial gravel	370.2 +/-57	
W15-14-164.2	TL	SWSW1/12N25E	Sidestream alluvial gravel	19.4 +-4.1	

*Probable age in thousands of years. Maximum age in parentheses

TABLE 2. SAMPLES OF QUATERNARY TEPHRA FROM THE PASCO BASIN

Lab No.	Stratigraphic Position	Location (Section/Township/Range)	Results	Remarks
BB82007	Slopewash	SWNW36/11N/28E	Glacier Peak "G"	
BB82019	Slopewash	SWNW36/11N/28E	Glacier Peak "B"	
BB82023	Displaced slopewash in recent landslide	NENE35/11N/28E	Glacier Peak	
C6123	Post-flood alluvium/loess	?SENW28/12N/28E?	Glacier Peak "B"	
C6124	Post-flood alluvium/loess	?SENW28/12N/28E?	Glacier Peak "G"	
SWL-83-69	Corfu landslide sag pond; 19' depth	NENW10/15N/27E	Glacier Peak "B"	
SWL-83-70	Corfu landslide sag pond; 19' depth	NENW10/15N/27E	Glacier Peak	
BB817	Slopewash	SENW3/12N/28E	Mazama	
BB82022	Slopewash and/or loess	NWNW36/11N/28E	Mazama	In landslide scarp 8' below ground surface
C1007	Alluvium	W22/13N/23E	Mazama	
C5003		SW35/13N/36E	Mazama	
C6093	Alluvium	NWSW30/8N/30E	Mazama	Second from bottom tephra layer in series C6093-6096
C6094	Alluvium	NWSW30/8N/30E	Mazama	Second from top tephra layer in series C6093-6096
C6095	Alluvium	NWSW30/8N/30E	Mazama	Top tephra layer in series C6093-6096
C6096	Alluvium	NWSW30/8N/30E	Mazama	Bottom tephra layer in series C6093-6096
C6652	Dune sand	Richland Landfill	Mazama	
C6653	Loess	SENE6/13N/28E	Mazama	
C6656		NESE6/6N/29E	Mazama	
C9071	Dune sand	NENE11/13N/26E	Mazama	
C9076		?Dry Ck. Valley, up from Rattlesnake Sp.?	Mazama	
C9083		?Cold Creek Valley?	Mazama	
C9233	Foreset-bedded in flood deposits	SE15/9N/28E	Mazama	
C9302	Talus	15N/23E	Mazama	
RHT-28	Dune sand	NWSE17/9N/27E	Mazama	
SWL-83-63	Corfu landslide sag pond	NENW10/15N/27E	Mazama	5 foot depth
SWL-83-65	Corfu landslide sag pond	NENW10/15N/27E	Mazama	10 foot depth
C6099	Loess below Touchet Beds	30/8N/30E	Mount St. Helens "M"	
RHT-30	Flood gravel	NWSE20/9N/25E	Mount St. Helens "M"	Underlies Mount St. Helens "set S"
BB82028	Slack-water flood deposits	11/12N/25E	Mount St. Helens "set S"	
BB82035	Slack-water flood deposits	SE24/11N/28E	Mount St. Helens "set S"	
BB83017	Slack-water flood deposits	SE35/7N/32E	Mount St. Helens "set S"	
BB83018	Slack-water flood deposits	SESE29/13N/25E	Mount St. Helens "set S"	
C1018	Touchet Beds	NW6/6N/25E	Mount St. Helens "set S"	
C5001	Loess	SWSE12/13N/37E	Mount St. Helens "set S"	
C5004	Loess	27/12N/33E	Mount St. Helens "set S"	
C6100	Touchet Beds	SESW29/8N/30E	Mount St. Helens "set S"	
C6104	Between Touchet Beds and loess	SESW29/8N/30E	Mount St. Helens "set S"	
C6127	Slack-water flood deposits	NENE25?/12N/24E	Mount St. Helens "set S"	Lower tephra of couplet
C6128	Touchet Beds	NWNE29/12N/25E	Mount St. Helens "set S"	
C6463	Sand lens in flood gravel	NWNE1/9N/27E	Mount St. Helens "set S"	Upper tephra of couplet
C6654	Loess	SENE6/13N/28E	Mount St. Helens "set S"	
C6655	Loess	SENE6/13N/28E	Mount St. Helens "set S"	Upper tephra of couplet
C9087	Touchet Beds	SESW12/9N/26E	Mount St. Helens "set S"	
C9281	Silt in prospect pit	NWSE15/11N/26E	Mount St. Helens "set S"	
C9290	Slack-water flood deposits	NENE3/12N/25E	Mount St. Helens "set S"	
RHB 11-1	Touchet Beds	WNW18/6N/34E	Mount St. Helens "set S"	
RHB 14-8	Touchet Beds	SWSW5/6N/34E	Mount St. Helens "set S"	
RHB 23-1	Touchet Beds	NENE32/7N/33E	Mount St. Helens "set S"	
RHB 29-1	Touchet Beds	NENW29/7N/32E	Mount St. Helens "set S"	
RHT-25	Touchet Beds	SWSE30/13N/25E	Mount St. Helens "set S"	
RHT-26	Touchet Beds	NWSE17/9N/27E	Mount St. Helens "set S"	
RHT-29	Flood gravel	NWSE20/9N/25E	Mount St. Helens "set S"	
RHT-32	Loess		Mount St. Helens "set S"	
RHT-33	Touchet Beds	NESE14/9N/27E	Mount St. Helens "set S"	Upper tephra of couplet (RHT-34 = lower)
RHT-34	Touchet Beds	NESE14/9N/27E	Mount St. Helens "set S"	Lower tephra of couplet (RHT-33 = upper)
RHB-13F	Older slack-water flood sequence	SE35/7N/32E	Unknown	

TABLE 3. CHARACTERISTICS OF QUATERNARY UNITS WITHIN THE PASCO BASIN

Stratigraphic unit	Texture*	Mafic content (%)		Color	Alteration	Structure		Fabric	Sorting	Roundness		Geometry	Terrain	Associated tephra	Magnetic polarity†	Age
		Framework	Matrix			Primary	Secondary			Mode	Range					
CATACLYSMIC FLOOD DEPOSITS																
COARSE GRAINED																
Poorly-sorted facies	ZS-BG	80-90	10-30	Gray to dark gray	Stage II-IV pedogenesis	Foreset bedded, graded bedding	Clastic dikes	Framework supported; open work	Poor	Subangular	Angular to well rounded	Erosional terrace remnants, dolos	Central basin	Mount St. Helens S Mount St. Helens M	N, R	Early to late Pleistocene
Well-sorted facies	GB-BG	30-80	10-30	Gray to dark gray	- -	Foreset bedded	- -	Framework supported	Moderate to well	Subrounded	Subangular to well rounded	Gravel tracts	Central basin	- -	- -	Early(?) to late Pleistocene
FINE GRAINED																
Plane-laminated sand facies	ZS-GS	- -	10-70	Gray to dark gray	- -	Graded bedding, plane- to foreset lamination	Clastic dikes	Uniform	Poor to moderate	Subangular	Angular to rounded	Broad sheets	Central basin to basin margin	Mount St. Helens S	N	Early(?) to late Pleistocene
Rhythmite facies	Z-S	- -	5-30	Light gray to gray	Occasional weak weathered horizons	Normal and reverse graded bedding; plane to ripple lamination	Load structures; clastic dikes	Uniform	Poor to moderate	Subangular	Angular to rounded	Broad sheets	Backflooded basin margins	Mount St. Helens S	N, R	Early to late Pleistocene
ALLUVIAL DEPOSITS																
Mainstream facies	GS-BG	20-40	5-20	Light gray	- -	Massive to crudely bedded	- -	Framework supported; weakly imbricated	Moderate to well	Subrounded	Subangular well rounded	Gravel trains and/or sheets	Central basin	Mazama	N, R	Early Pleistocene to Holocene
Sidestream facies	SZ-BG	90	10-50	Brown to gray	Stage I-IV pedogenesis	Massive to laminated and bedded	Pedogenic	Framework supported	Poor to moderate	Subangular	Angular to subrounded	Fans to gravel trains	Ridge to basin margin	Mazama Glacier Peak G and B	N, R	Late Pleistocene(?) to Holocene
EOLIAN DEPOSITS																
DUNE SAND	ZS-S	- -	5-20	Light gray	Stage I pedogenesis	Massive to large scale crossbedded	- -	Uniform	Moderate to well	Subangular	Subangular to rounded	Crescentic-shaped dunes	Central basin	Mazama	- -	Late Pleistocene to Holocene
LOESS																
L5	SZ-ZS	- -	5	Pale brown	- -	Massive	- -	Uniform	Well	Subangular	Subangular to rounded	Discontinuous sheets	Ridge to basin margin	Mazama Glacier Peak G and B	N	Late Pleistocene to Holocene
L4	CSZ-ZS	- -	5	Pale brown	Stage I-II pedogenesis	Massive	Pedogenic	Uniform	Moderate to well	Subangular	Subangular to rounded	Discontinuous sheets	Ridge to basin margin	Mount St. Helens S Mount St. Helens M	N	Late Pleistocene
L3	CSZ-ZS	- -	5	Yellowish brown	Stage III-IV Pedogenesis	Massive	Pedogenic	Uniform	Poor to moderate	Subangular	Subangular to rounded	Discontinuous lenses	Ridge	- -	N	Middle to late Pleistocene
L2	SCZ-ZS	- -	5	Brownish yellow	Stage III-IV Pedogenesis	Massive	Pedogenic	Uniform	Poor	Subangular	Subangular to rounded	Discontinuous lenses, sheet in central basin (?)	Ridge to central basin (?)	- -	R, N	Early Pleistocene
L1	SCZ-ZS	- -	5	Reddish yellow	Silcrete cementation	Massive	Pedogenic	Uniform	Poor	Subangular	Subangular to rounded	Irregular thin (< 3 m) lenses	Ridge	- -	- -	Late Pleiocene(?) to early Pleistocene

* Cr=clay, Z=silt, S=sand, G=gravel

† N=normal, R=reversed

RHO-BW-SA-563A

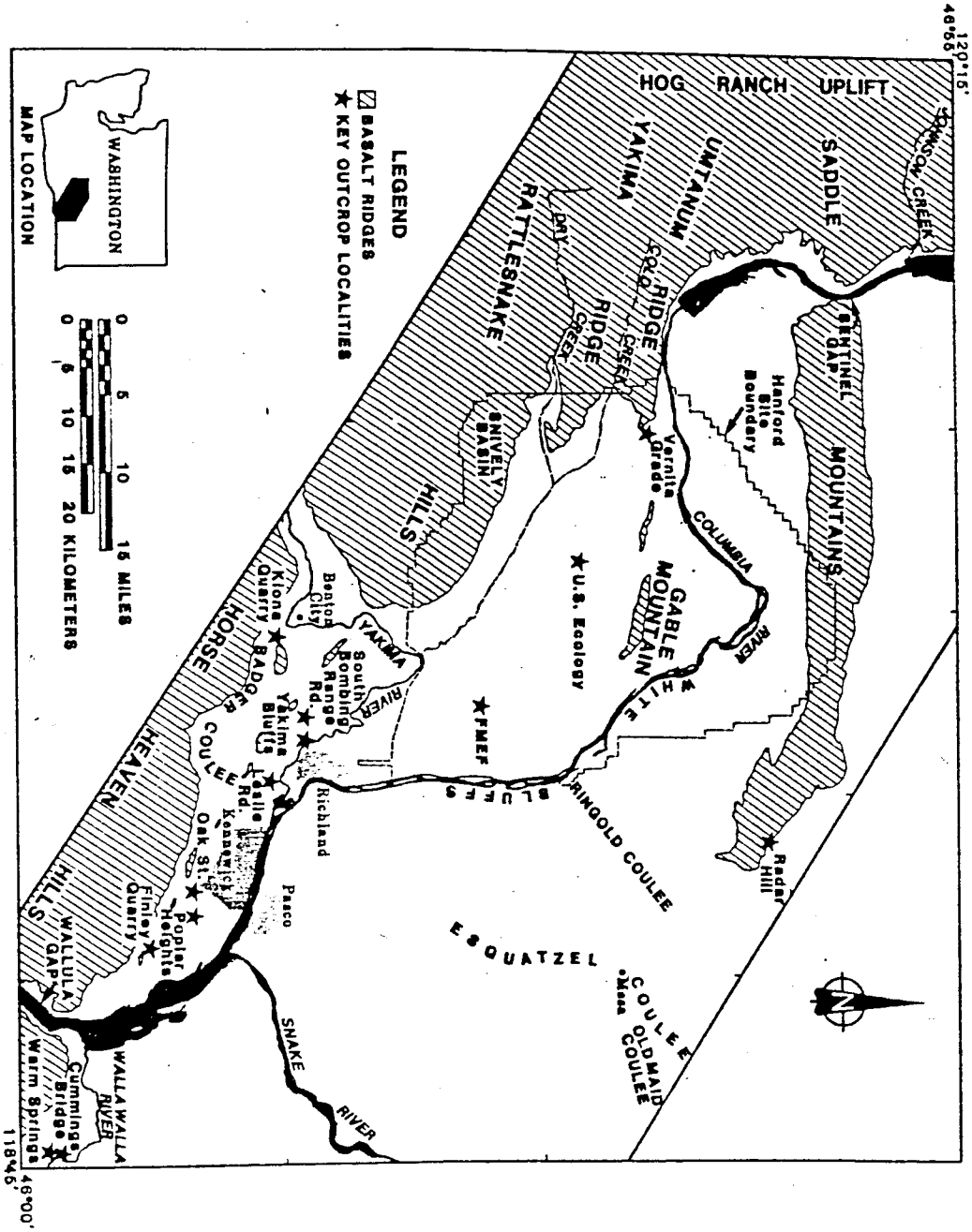
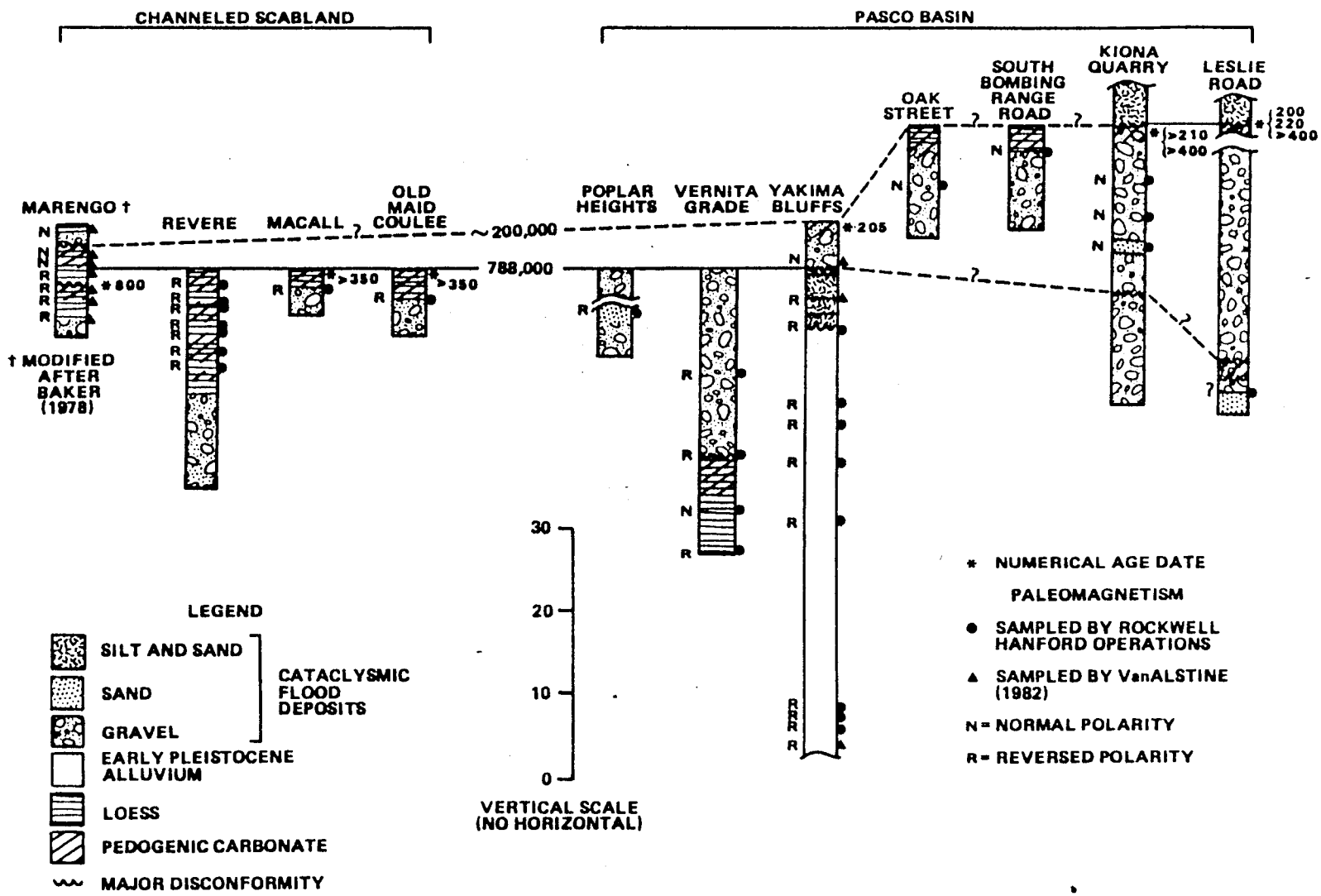

120°15'
46°55'
HOG RANCH UPLIFT
SADDLE
MOUNTAINS
SENTINEL GAP
Hanford Site Boundary
Vernita Grade
COLUMBIA RIVER
Radar Hill
GABLE MOUNTAIN
U.S. Ecology
FMEF
RINGOLD COULEE
ESQUATZEL
COULEE
OLDMAID COULEE
Mesa
SNAKE RIVER
WALLA WALLA RIVER
Cummings Bridge
Warm Springs
46°00'
118°45'
YAKIMA RIDGE
UMTANUM
COLD CREEK
RIDGE
DRY CREEK
RATTLESNAKE
SHIVELY BASIN
HILLS
LEGEND
BASALT RIDGES
KEY OUTCROP LOCALITIES
WASHINGTON
MAP LOCATION
0 5 10 15 MILES
0 5 10 15 20 KILOMETERS
Benton City
Kiona Quarry
BADGER COULEE
HORSE HEAVEN HILLS
YAKIMA RIVER
South Bombing Range Rd.
Yakima Bluffs
Leslie Rd.
Kennewick
Richland
Pasco
Oak St.
Poplar Heights
Finley Quarry
WALLULA GAP

Fig. 1



CORRELATION OF PRE–WISCONSIN FLOODS FOR THE PASCO BASIN AND CHANNELED SCABLAND

Fig. 2

RHO-BW-SA-563A

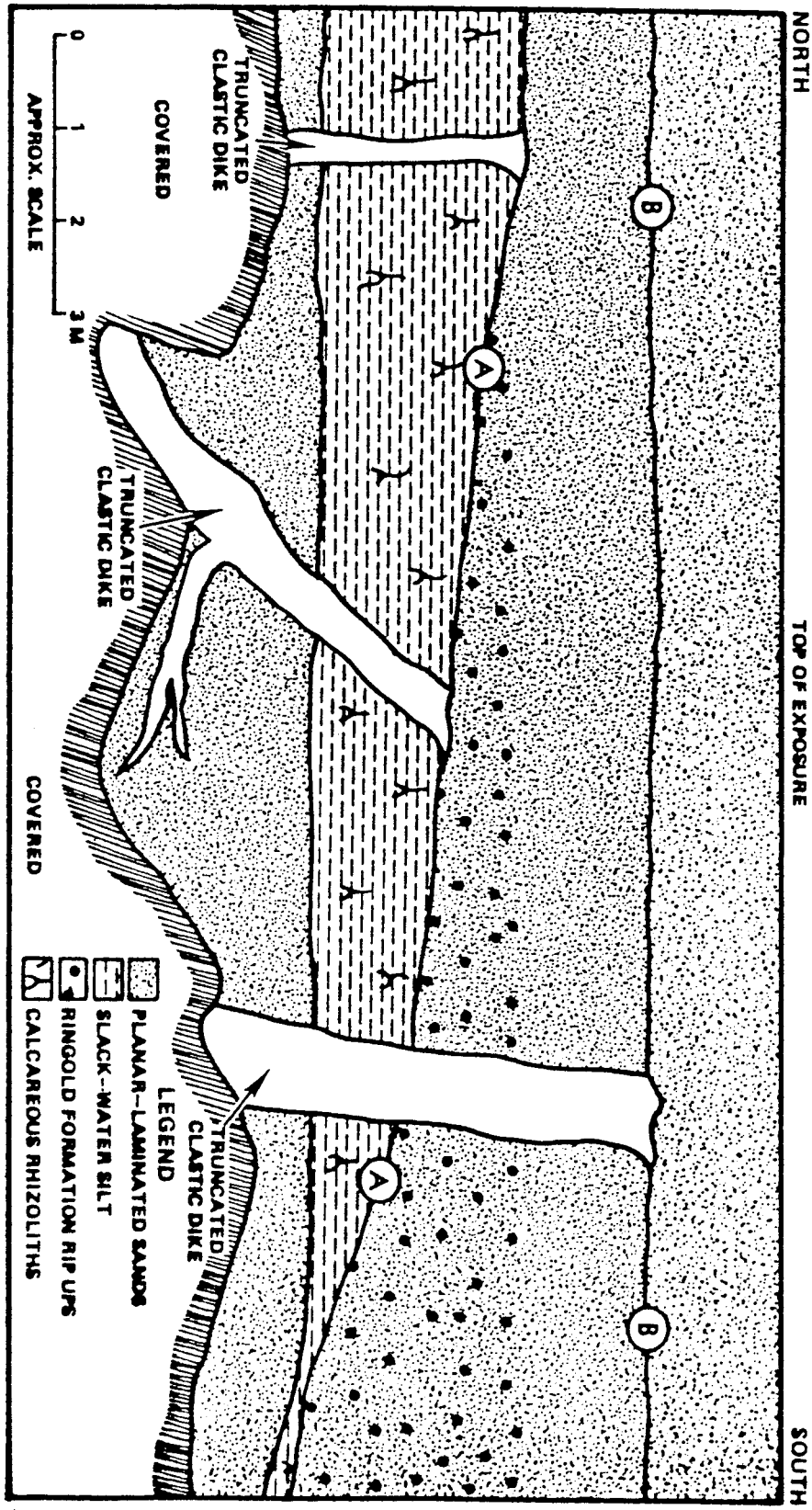

NORTH
TOP OF EXPOSURE
SOUTH
B
A
A
B
TRUNCATED CLASTIC DIKE
COVERED
TRUNCATED CLASTIC DIKE
TRUNCATED CLASTIC DIKE
COVERED
0
1
2
3 M
APPROX. SCALE
LEGEND
PLANAR-LAMINATED SANDS
SLACK-WATER SILT
RINGOLD FORMATION RIP UPS
CALCAREOUS RHIZOLITHS

Fig. 3

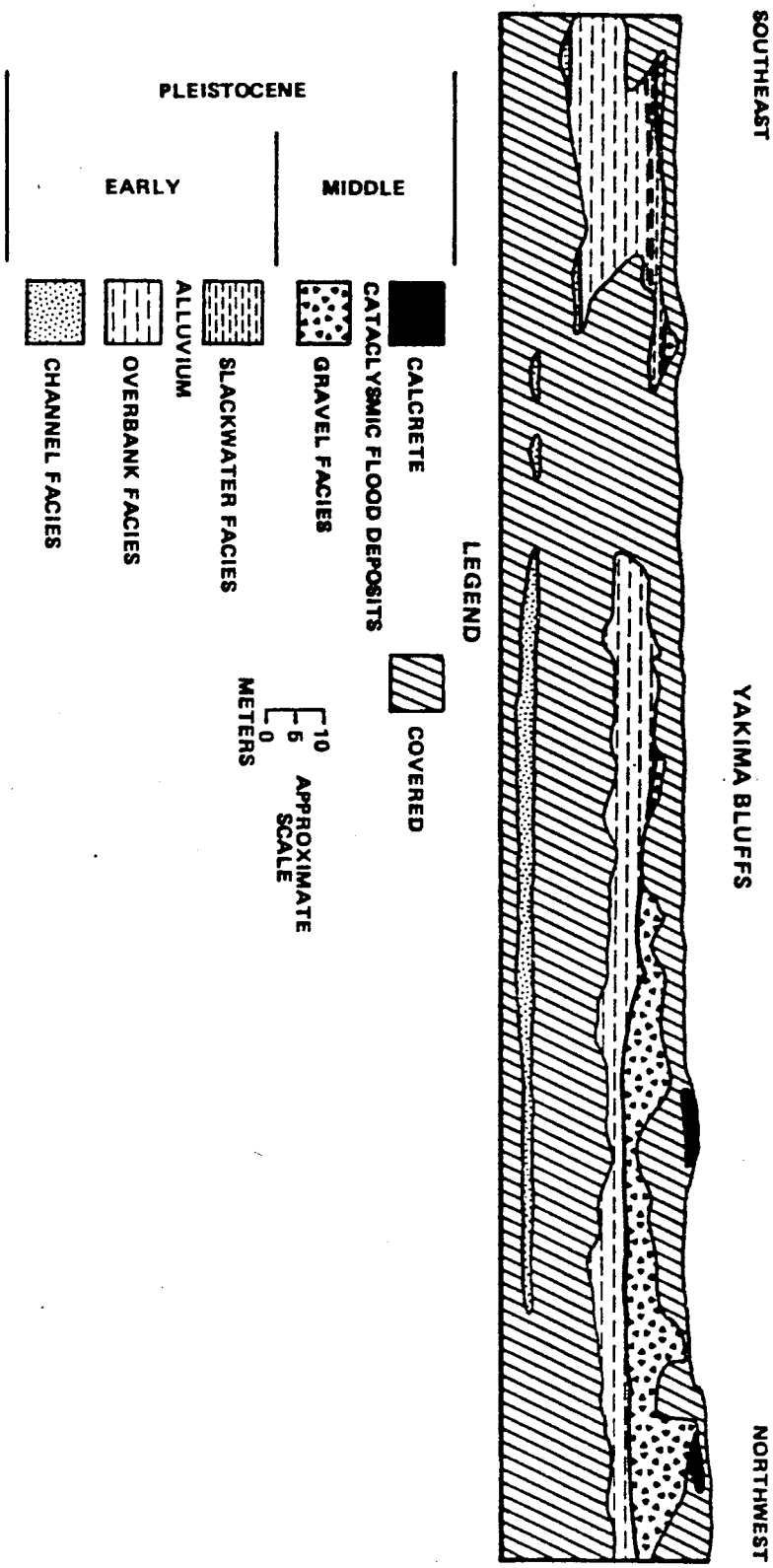

SOUTHEAST
YAKIMA BLUFFS
NORTHWEST
LEGEND
COVERED
CALCRETE
CATACLYSMIC FLOOD DEPOSITS
GRAVEL FACIES
SLACKWATER FACIES
ALLUVIUM
OVERBANK FACIES
CHANNEL FACIES
PLEISTOCENE
MIDDLE
EARLY
10
5
0
METERS
APPROXIMATE SCALE

Fig. 4

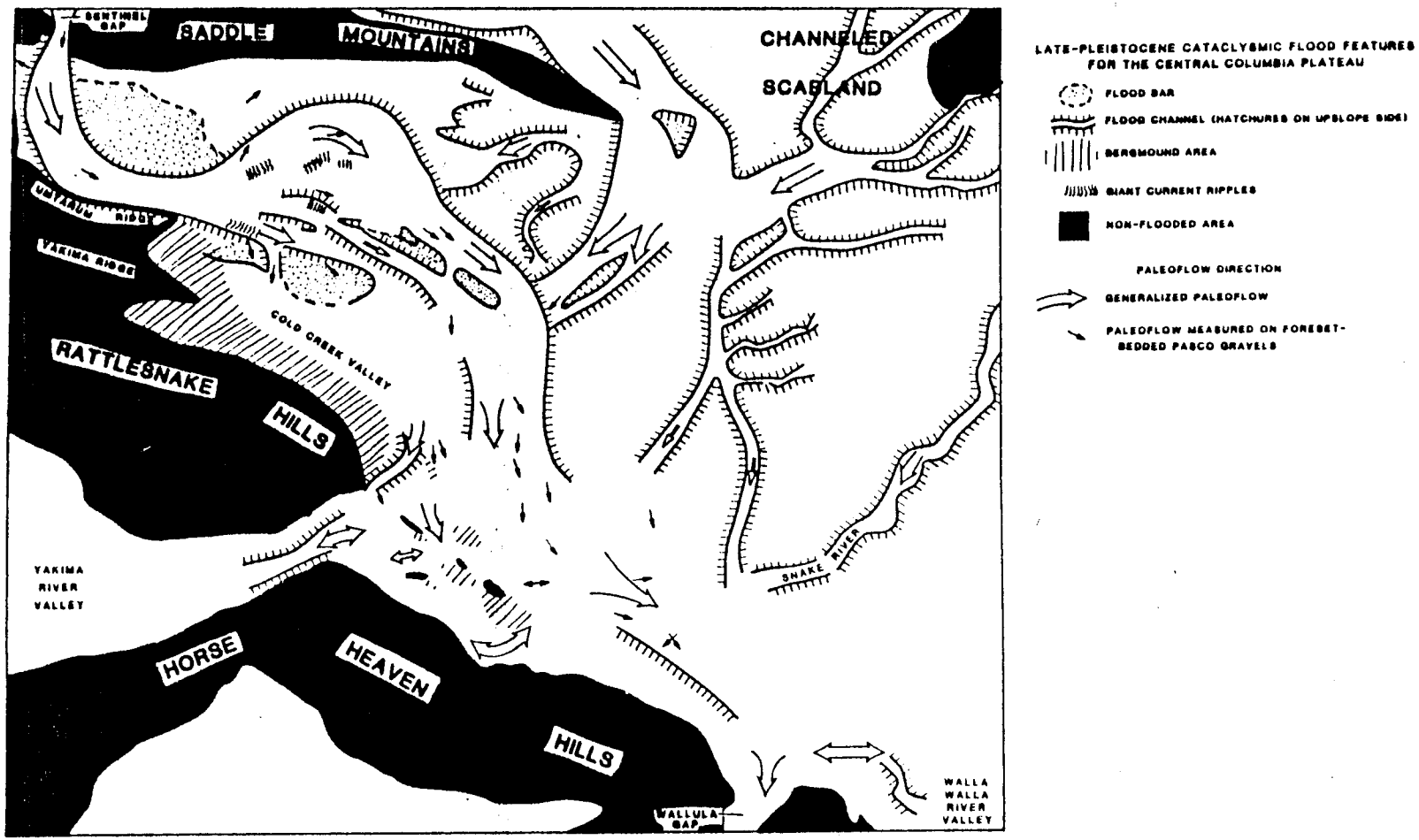


Fig. 5

RHO-BW-SA-563A