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Paleodrainage of the Columbia River System on the Columbia Plateau of Washington State: A Summary

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Karl R. Fecht
Stephen P. Reidel
Ann M. Tallman

Prepared for the U.S. Department of Energy
under Contract DE-AC06-77RL01030

Rockwell International
Rockwell Hanford Operations
Richland, Washington

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Printed in the United States of America

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RHO-BW-SA-318 P

Paleodrainage of the Columbia River on the Columbia Plateau of Washington State: A Summary

Date Manuscript Completed: December 1985

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ABSTRACT

The Basalt Waste Isolation Project was established in 1976 as part of the National Waste Terminal Storage Program, now the Office of Civilian Radiation Waste Management Program. The objective of the project is to assess the suitability of the Columbia River Basalt Group on the Hanford Site as a repository medium for disposal of commercial high-level radioactive waste. As part of the geotechnical characterization activities, the project has been studying the stratigraphy of the basalt and associated sedimentary sequences and the structural evolution of the Columbia Plateau. Included in these studies is the investigation of the effects of deformation and volcanism on development of stream courses of the Columbia River system on the plateau over the past 17 million years. This investigation is part of on-going studies to understand the geologic history of the Columbia Plateau as it relates to the siting of a repository on the Hanford Site.

Over the last 17 million years, stream courses of the Columbia River system within the Washington State portion of the Columbia Plateau have evolved primarily as a result of the effects of volcanism and deformation. Repeated eruptions of Columbia River basalt in early to middle Miocene time formed a vast basaltic plain and obliterated the prebasalt drainage system. Major streams during this interval were flowing westward, apparently near the periphery of the evolving plateau and through a broad lowland in the ancestral Cascade Range generally south of the present-day Columbia River Gorge. Stream courses were controlled regionally by the westward dipping Palouse Slope and the constructional topography of Grande Ronde flows and locally by emerging structural topography. In middle Miocene time, a similar drainage system existed on the plateau that was periodically altered by eruptions of Wanapum Basalt. In middle to late Miocene time, major streams formed a well-integrated river system that flowed in a centripetal pattern from the surrounding highland across regional paleoslopes and into the central plateau. In the central plateau, the stream courses were controlled by the topographic relief of developing structures and constructional topography formed as the result of eruptions of Saddle Mountains Basalt. The major streams joined in the central plateau and flowed westward through an ancestral Columbia River Gorge in the ancestral Cascade Range.

In late Miocene time, following the Columbia River basalt eruptive episode, stream courses were controlled on a regional basis by the major paleoslopes and locally by developing structural basins. Water gaps developed through structural ridges bounding the basins. Streams deposited thick sedimentary sequences in the basins until about the middle Pliocene, when streams began a period of degradation. Major aggradational and degradational events are postulated to be the result of base level changes that may have resulted from Cascadian volcanism near the present-day Columbia River Gorge.

During the Pleistocene, glaciers that impinged on the northern Columbia Plateau and catastrophic flooding that emanated from ice margins and pluvial lakes obliterated much of the secondary drainage and caused temporary or minor changes to the major stream courses on the Columbia Plateau.

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INTRODUCTION

The Basalt Waste Isolation Project (BWIP) is investigating the feasibility of using a thick, layered sequence of the Columbia River basalts in south-central Washington as a host medium for high-level radioactive waste disposal. This project is sponsored by the U.S. Department of Energy (DOE) in conjunction with the Office of Civilian Radioactive Waste Management as mandated by the Nuclear Waste Policy Act of 1982. Rockwell Hanford Operations (Division of Rockwell International) serves as the prime contractor to the DOE for operating the BWIP.

This investigation is part of geotechnical studies designed to develop an understanding of the geologic history of the Columbia Plateau. The objective of this investigation is to determine the effects of deformation and volcanism on stream courses of the Columbia River system on the Columbia Plateau over the past 17 million years.

The present-day Columbia River system drains an area of ~670,000 km^2 and covers portions of seven states in the northwestern United States and part of southern British Columbia, Canada. The system drains the intermontane basin between the Rocky Mountains and the Cascade Range. In the heart of the intermontane basin, the Columbia River and two of its major tributaries, the Snake and Yakima Rivers, flow across basaltic terrain of the Columbia Plateau (fig. 1). On the plateau these rivers flow across broad sediment-filled basins and valleys, and through spectacular water gaps and gorges deeply entrenched into the basaltic ridges and highlands. Exposed in and overlying the basalt sequence are extensive fluvial and lacustrine sediments, buried paleochannels and paleocanyons, and hyaloclastites and pillowed basalts that mark the courses of earlier streams and the presence of ancestral lakes. These features, often many kilometers away from present river courses, suggest a long and complex history of drainage development on the Columbia Plateau.

Since the late 1800s geologists have studied the paleodrainage of the Columbia River system on the Columbia Plateau. Earlier workers, notably Willis (1887), Smith (1901, 1903), Bretz (1923, 1959), Warren (1941), Waters (1955), Mackin (1961), and Bond (1963), provided important observations and discussed the position and age of river courses before many of the stratigraphic details of the Columbia Plateau had been unraveled. It is important to note that many of their interpretations are still valid today. Recent advances in stratigraphy of the Columbia River Basalt Group have led to a better understanding in the position and age of ancestral stream courses within Washington State (Schmincke 1964, 1967a; Swanson et al. 1979a, 1979b, 1980; Myers/Price et al. 1979; Rigby et al. 1979). To date, the most definitive studies of paleostream courses on the plateau are by Schmincke (1964, 1967a) in the western and central plateau and by Swanson and Wright (1976, 1979), Swanson et al. (1979b, 1980), and Camp (1981) in the eastern plateau.

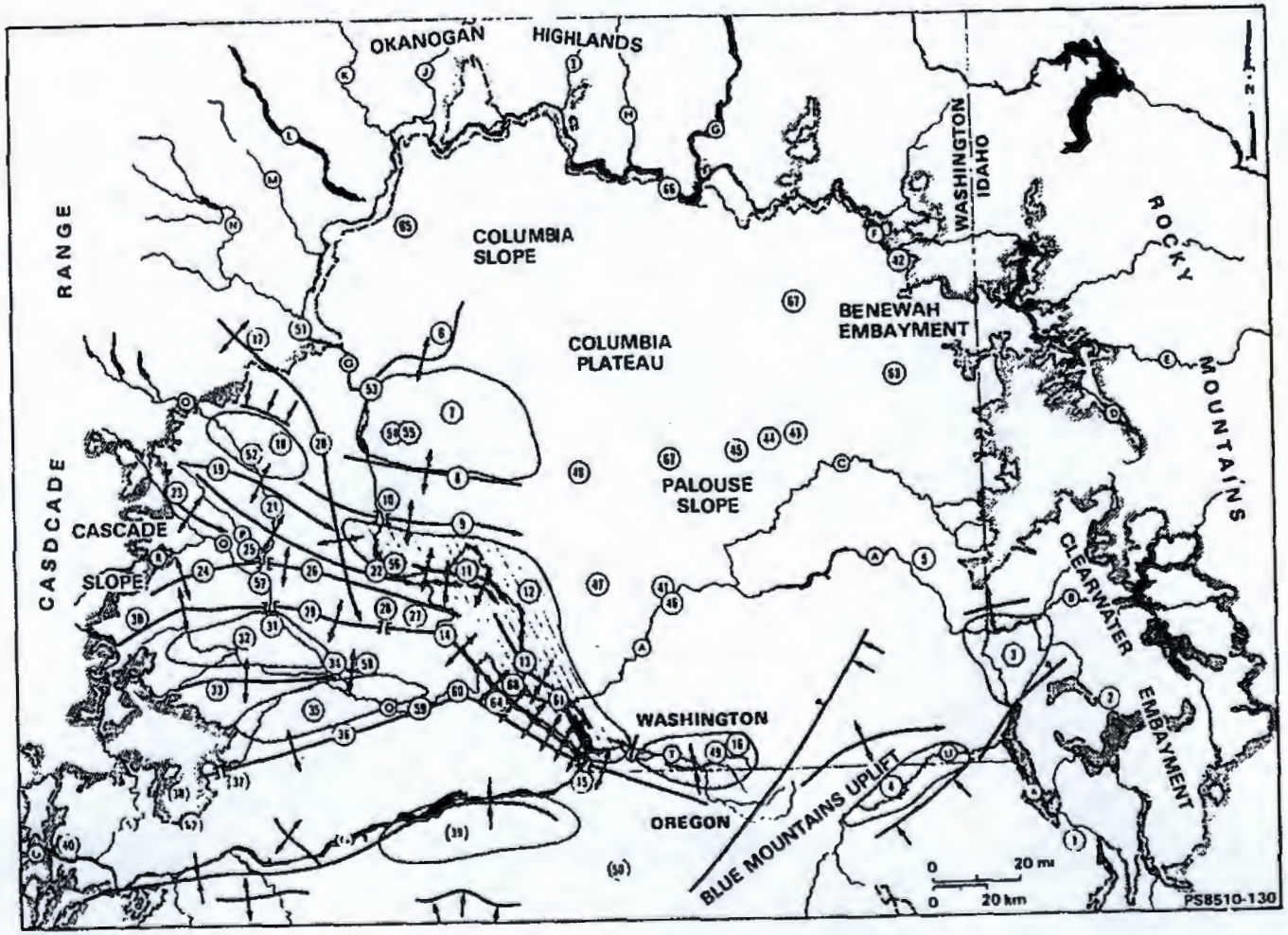

Figure 1. Location and Physiographic Map of the Northern Part of the Columbia River Basalt Province, with Map Legend and Letter and Number Keys. (sheet 1 of 4)

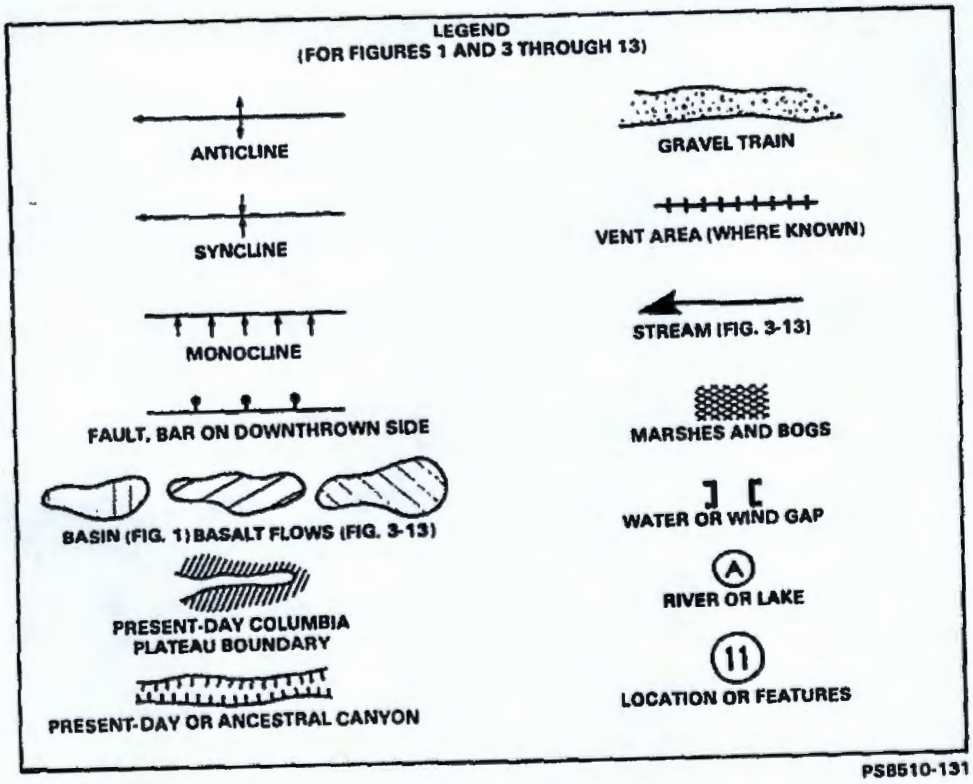

Figure 1. Legend for Figures 1, and 3 through 13. (sheet 2 of 4)

RIVERS AND LAKES

A SNAKE
B CLEARWATER
C PALOUSE
D ST. MARIES
E ST JOE
F SPOKANE
G COLUMBIA
H SANPOIL
I NESPELEM
J OKANOGAN
K METHOW
L LAKE CHELAN
M ENTIAT
N WENATCHEE
O YAKIMA
P WENAS CREEK
Q NACHES
R TIETON
S KLICKITAT
T WALLA WALLA
U GRANDE RONDE

LOCATIONS AND FEATURES

1. JOSEPH PLAINS
2. NEZ PERCE PLATEAU
3 LEWISTON BASIN
4 TROY BASIN
5. UNIONTOWN PLATEAU
6 L :EZLEY HILLS
7. QUINCY BASIN
8. FRENCHMAN HILLS
9. SADDLE MOUNTAINS
10 SENTINEL GAP
11 WAHLUKE SYNCLINE
12. PASCO BASIN
13. PASCO SYNCLINE
14. RATTLESNAKE MOUNTAIN
15. WALLULA GAP
16. WALLA WALLA BASIN
17 NANEUM RIDGE
18. KITTITAS BASIN
19. MANATASH RIDGE
20. HOG RANCH STRUCTURE
21. YAKIMA CANYON
22. UMTANUM RIDGE
23. CLEMAN MOUNTAIN
24. COWICHE MOUNTAINS
25. SELAH GAP
26. YAKIMA RIDGE
27. BLACK ROCK VALLEY
28. SUNNYSIDE GAP
29. RATTLESNAKE HILLS
30. AHTANUM RIDGE
31. UNION GAP
32. TOPPENISH BASIN
33. TOPPENISH RIDGE
34 SNIPES MOUNTAIN
35. SATUS BASIN
36. HORSE HEAVEN HILLS
37. SATUS PASS
38. SIMCOE MOUNTAINS
39. UMATILLA BASIN
40. COLUMBIA RIVER GORGE
41 DEVIL'S CANYON
42. SPOKANE
43 REVERE
44. McCALL
45. MARENGO
46 LOWER MONUMENTAL DAM
47. OLD MAID COULEE
48. WARDEN
49. WALLA WALLA
50. PENDLETON
51. WENATCHEE
52. ELLENSBURG
53. CRESCENT BAR
54. GEORGE
55. WINCHESTER WASTEWAY
56. PRIEST RAPIDS DAM
57. YAKIMA
58. SUNNYSIDE
59. PROSSER
60. CHANDLER
61. PASCO
62. GOLDENDALE
63 MALDEN
64. BADGER COULEE
65. WATERVILLE PLATEAU
66. COLUMBIA VALLEY
67. CHENEY-PALOUSE SCABLAND TRACT
68. YAKIMA BLUFFS

Figure 1. Letter and Number Key. (sheet 3 of 4)

RIVERS AND LAKES

CLEARWATER	- B
COLUMBIA	- G
ENTIAT	- M
GRANDE RONDE	- U
KLICKITAT	- S
LAKE CHELAN	- L
METHOW	- K
NACHES	- Q
NESPELEM	- I
OKANOGAN	- J
PALOUSE	- C
SANPOIL	- H
SNAKE	- A
SPOKANE	- F
ST. JOE	- E
ST. MARIES	- D
TIETON	- R
WALLA WALLA	- T
WENAS CREEK	- P
WENATCHEE	- N
YAKIMA	- O

LOCATIONS AND FEATURES

AHTANUM RIDGE	- 30
BADGER COULEE	- 64
BEEZLEY HILLS	- 6
BLACK ROCK VALLEY	- 27
CHANDLER	- 60
CHENEY-PALOUSE SCABLAND TRACT	- [illegible]
CLEMAN MOUNTAIN	- 23
COLUMBIA RIVER GORGE	- 40
COLUMBIA VALLEY	- 66
COWICHE MOUNTAINS	- 24
CRESCENT BAR	- 53
DEVIL'S CANYON	- 41
ELLENSBURG	- 52
FRENCHMAN HILLS	- 8
GEORGE	- 54
GOLDENDALE	- 62
HOG RANCH STRUCTURE	- 20
HORSE HEAVEN HILLS	- 36
JOSEPH PLAINS	- 1
KITTITAS BASIN	- 18
LEWISTON BASIN	- 3
LOWER MONUMENTAL DAM	- 46
MALDEN	- 63
MANATASH RIDGE	- 19
MARENGO	- 45
McCALL	- 44
NANEUM RIDGE	- 17
NEZ PERCE PLATEAU	- 2
OLD MAID COULEE	- 47
PASCO	- 61
PASCO BASIN	- 12
PASCO SYNCLINE	- 13
PENDLETON	- 50
PRIEST RAPIDS DAM	- 56
PROSSER	- 59
QUINCY BASIN	- 7
RATTLESNAKE HILLS	- 29
RATTLESNAKE MOUNTAIN	- 14
REVERE	- 43
SADDLE MOUNTAINS	- 9
SATUS BASIN	- 35
SATUS PASS	- 37
SELAH GAP	- 25
SENTINEL GAP	- 10
SIMCOE MOUNTAINS	- 38
SNIPES MOUNTAIN	- 34
SPOKANE	- 42
SUNNYSIDE	- 58
SUNNYSIDE GAP	- 28
TOPPENISH BASIN	- 32
TOPPENISH RIDGE	- 33
TROY BASIN	- 4
UMATILLA BASIN	- 39
UMTANUM RIDGE	- 22
UNION GAP	- 31
UNIONTOWN PLATEAU	- 5
WAHLUKE SYNCLINE	- 11
WALLA WALLA	- 49
WALLA WALLA BASIN	- 16
WALLULA GAP	- 15
WARDEN	- 48
WATERVILLE PLATEAU	- 65
WENATCHEE	- 51
WINCHESTER WASTEWAY	- 55
YAKIMA	- 57
YAKIMA BLUFFS	- 68
YAKIMA CANYON	- 21
YAKIMA RIDGE	- 26

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Figure 1. Alphabetical Key (sheet 4 of 4)

The purposes of this paper are to (1) summarize the geologic evidence for ancestral stream courses, (2) present the Neogene and Pleistocene evolution of the Columbia River drainage system, and (3) demonstrate the dynamic interaction between geologic events and paleodrainage on the Columbia Plateau of Washington State since the onset of Columbia River basalt volcanism ~17 m.y.B.P. Emphasis throughout the paper is placed on south-central Washington and on post-middle Miocene units where the authors have been conducting extensive field studies. The paper builds on previous observations of paleostream deposits and their inferred courses, and attempts to delineate the main courses of ancestral streams and define the geomorphic and structural features that have controlled the positions of ancestral streams.

GENERAL STRATIGRAPHIC RELATIONS

The Columbia Plateau is composed of a series of thick Miocene tholeiitic basalt flows that are, in places, interbedded with and overlain by clastic sediments of Miocene age and younger (fig. 2). The basalt flows collectively form the Columbia River Basalt Group that consists of five formations, four of which are exposed in Washington State; the Imnaha, Grande Ronde, Wanapum, and Saddle Mountains Basalts (Swanson et al. 1979a). The Imnaha Basalt is restricted to exposures along the Snake River Canyon, whereas Grande Ronde, Wanapum, and Saddle Mountains Basalts occur throughout much of the Columbia Plateau. Sedimentary rocks of Miocene age interbedded with the basalt in Washington State are designated as the Ellensburg Formation (Smith 1901, 1903) in the western and central plateau (Waters 1955; Mackin 1961; Schmincke 1964, 1967a, 1967b; Waitt 1979; Swanson et al. 1979b) and the Latah Formation and related sediments along the eastern margin of the plateau (Pardee and Bryan 1926; Kirkham and Johnson 1929; Griggs 1976). In the western plateau, the Ellensburg Formation, in part, overlies the basalt sequence (Russell 1893; Smith 1901, 1903; Waters 1955; Schmincke 1967a, 1967b).

Overlying the Columbia River Basalt Group and Miocene sedimentary rocks in topographic and structural lows of Washington are the Miocene-Pliocene Ringold Formation in the Quincy and Pasco Basins (Merriam and Buwalda 1917; Newcomb et al. 1972; Grolier and Bingham 1978; Tallman et al. 1981); an "old gravel and clay" unit in the Walla Walla Basin (Newcomb 1965); the Pliocene Thorp Gravel in the Kittitas Valley (Waitt 1979); gravels equivalent in lithology and age to the Thorp Gravel in the Yakima Valley (Bentley 1977; Rigby et al. 1979; Campbell 1983) and gravels of the Lewiston Basin (Webster et al. 198).

The Quaternary stratigraphy is dominated by Pleistocene glacial deposits along the northern margin of the plateau and glaciofluvial deposits that occur in topographic lows of the plateau and in the Channeled Scabland of the eastern plateau (Bretz 1923, 1959; Baker 1973; Baker and Nummedal 1978; Rigby et al. 1979; Myers/Price et al. 1979; Waitt 1979). Flooding down the Snake River Canyon in the late Pleistocene from Lake Bonneville resulted in deposition of gravel in the Lewiston Basin area (Swanson 1984). Loess and dune sand of Pleistocene and Holocene age blanket most of the high terrain of the plateau (Russell 1893, 1901; Fryxell and Cook 1964; Rigby et al. 1979).

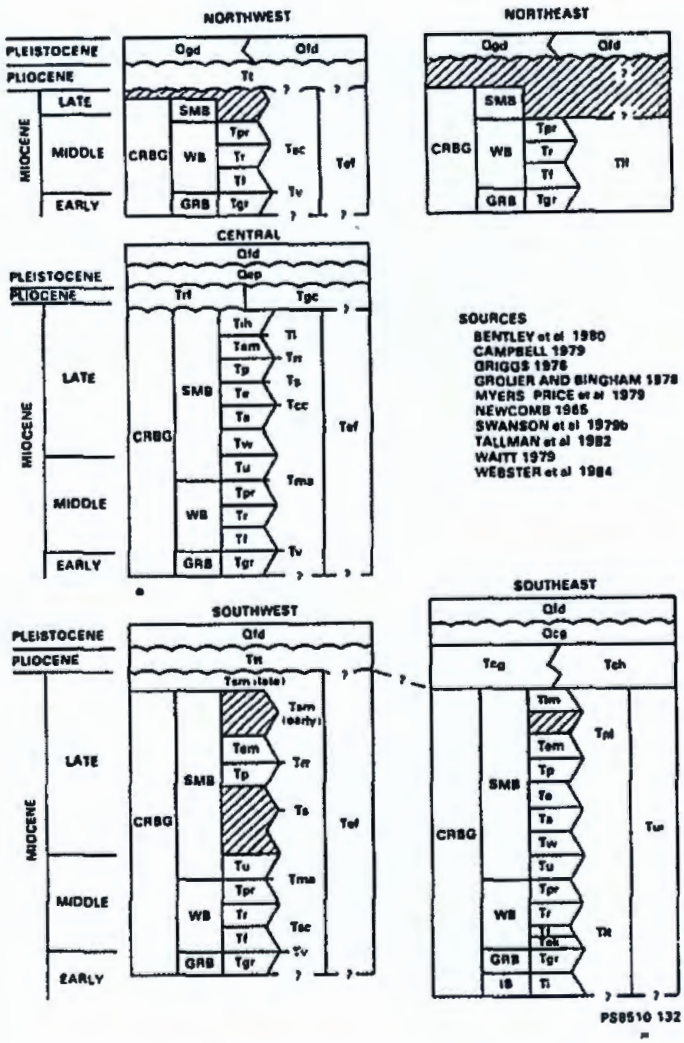

Figure 2. Generalized Stratigraphy of the Columbia Plateau within Washington State with Geologic Unit Abbreviations. (sheet 1 of 2)

BASALT SEQUENCE

- Tlm LOWER MONUMENTAL MEMBER
- Tih ICE HARBOR MEMBER
- Tem ELEPHANT MOUNTAIN MEMBER
- Tp POMONA MEMBER
- Te ESQUATZEL MEMBER
- Ta ASOTIN MEMBER
- Tw WILBUR CREEK MEMBER
- Tu UMATILLA MEMBER
- Tpr PRIEST RAPIDS MEMBER
- Tr ROZA MEMBER
- Tf FRENCHMAN SPRINGS MEMBER
- Tek ECKLER MOUNTAIN MEMBER
- Tgr - GRANDE RONDE BASALT UNDIFFERENTIATED
- Ti - IMNAHA BASALT UNDIFFERENTIATED
- CRBG - COLUMBIA RIVER BASALT GROUP
- SMB - SADDLE MOUNTAINS BASALT
- WB - WANAPUM BASALT
- GRB - GRANDE RONDE BASALT
- IB IMNAHA BASALT

SEDIMENTARY SEQUENCE

- Qgd GLACIAL DEPOSITS
- Qfd PROGLACIAL FLOOD DEPOSITS
- Qep - EARLY PLEISTOCENE STREAM DEPOSITS
- Qcg CLARKSTON GRAVELS
- Tt THORP GRAVEL
- Ttt - THORP-TYPE GRAVEL
- Trf - RINGOLD FORMATION
- Tgc - "OLD GRAVEL AND CLAY" UNIT
- Tsm - SNIPES MOUNTAIN CONGLOMERATE
- Tcg - CLEARWATER GRAVELS
- Tch - CLARKSTON HEIGHTS GRAVEL
- Tnl - NORTH LEWISTON GRAVEL
- Tl - LEVEY MEMBER
- Trr - RATTLESNAKE RIDGE MEMBER
- Ts - SELAH MEMBER
- Tcc - COLD CREEK MEMBER
- Tma - MABTON MEMBER
- Tsc - SQUAW CREEK MEMBER
- Tv VANTAGE MEMBER
- Tui - UNNAMED INTERBEDS IN CLEARWATER EMBAYMENT
- Tlf - LATAH FORMATION
- Tlt - LATAH-TYPE DEPOSITS
- Tef ELLENSBURG FORMATION

Figure 2. Nomenclature. (sheet 2 of 2)

IDENTIFICATION OF STREAM COURSES

Ancestral stream courses on the Columbia Plateau are delineated using the distribution, texture, and composition of fluvial sequences, as well as erosional features, intracanyon flows, hyaloclastites, and pillowed basalts associated with the basalt sequences. Stream courses are most commonly delineated based on the distribution of fluvial sediments, which occur either as narrow and well-confined channel deposits or as broad extensive sheets. Commonly found within the laterally extensive fluvial sediments are narrow trains of gravel that are inferred to mark the main channels of ancestral streams. The composition of the detrital sediments is used to determine the general provenance of the headwaters of major streams and their tributaries. Volcaniclastic sediments were derived principally from the volcanic terrain of the southern and central Cascade Range to the west of the plateau. Sediments composed mainly of plutonic and metamorphic debris were derived from the northern Cascade Range, the Okanogan Highlands to the north of the plateau, and/or the foothills of the Rocky Mountains to the east of the plateau. Metabasalt clasts present in interbeds and supra-basalt sediments in the Lewiston area, on the Palouse Slope, and locally in the central Columbia Plateau serve to distinguish the major streams draining the northern and northeastern Columbia Plateau from major streams draining the eastern plateau. Fluvial deposits composed mostly of basaltic sediments are generally assumed to have come from streams that originated on the plateau or whose drainage area is mostly within the plateau.

In places, narrow steep-walled canyons have been carved into the basalt by streams. Ancestral canyons eroded into basalt were particularly common in the eastern plateau of Washington during the middle to late Miocene (Swanson et al. 1980; Camp 1981) and were later filled with lava to form "intracanyon flows." Traces of the intracanyon flows are important evidence for defining the position of ancestral streams (Swanson and Wright 1979; Tolan and Beeson 1984). During the Pleistocene, narrow steep-walled canyons were also scoured into the basalt by catastrophic glaciofluvial floodwaters. These channels generally remain only partially filled with sediments and form the anastomosing channels of the Channeled Scabland (Bretz 1923).

The intraflow character of basalt units also indicates the presence of ancestral streams or lakes. Hyaloclastites and pillowed basalts that resulted from the rapid quenching of lava upon entering water (Fuller 1931; Waters 1960) are common to many flows in the northern and western Columbia Plateau. The areal extent of these features aids in defining the position of ancestral streams or lakes and has been particularly useful in defining major stream drainage during the emplacement of Grande Ronde and Wanapum Basalts. However, hyaloclastites and pillowed basalts are not commonly associated with ancestral streams in the central or eastern Columbia Plateau except on the immediate margin of the eastern plateau. Apparently, lavas that were erupted in the eastern plateau commonly dammed the upper reaches of streams on the Palouse Slope and the lavas flowed down essentially dry stream channels (Swanson et al. 1979b; Camp 1981).

CONTROL OF STREAM COURSES

Geologic features controlling the courses of major streams on the Columbia Plateau include (1) the broad, gently dipping regional paleoslopes, (2) constructional topography developed by the emplacement of lava flows and volcaniclastic debris and, less commonly, by sedimentary sequences, and (3) structurally uplifted ridges and subsided synclines and basins.

Three major paleoslopes have provided the primary control for stream drainage on the Columbia Plateau in Washington State: (1) the westward-dipping Palouse Slope on the eastern plateau, (2) the southward-dipping Columbia Slope on the north, and (3) the eastward-dipping Cascade Slope on the west (see fig. 1). The Palouse Slope is the most extensive of the three paleoslopes. During the emplacement of the Grande Ronde and Wanapum Basalts, the Palouse Slope was the dominant topographic feature of the plateau. It extended from the foothills of the Rocky Mountains and gently dipped westward to the ancestral Cascade Range (Swanson et al. 1979b). The Columbia Slope, which gently dips southward into the Pasco Basin (Schmincke 1964, 1967a) formed as the result of subsidence of the central Columbia Plateau starting at least by early to middle Miocene, but apparently had little effect on stream courses until about middle Miocene. The Cascade Slope is underlain by volcaniclastic and pyroclastic debris that was transported eastward from the ancestral Cascade Range onto the plateau.

Emplacement of lava flows and deposition of sedimentary detritus formed constructional topography that forced realignment of stream courses. Basalt flows dammed streams and led to the development of streams running marginal to flow fronts during most of the Columbia River basalt eruptive episode. In the western plateau during the Miocene, volcanic eruptions and eastward-flowing streams in the ancestral Cascade Range aggraded volcanic lahars and volcaniclastic sediments out onto the plateau and into the major drainage channel. In the Pleistocene, catastrophic floodwaters deposited thick sequences of gravel that clogged and blocked drainages in the Pasco Basin forcing streams to establish new courses.

Folding on the Columbia Plateau has resulted in the shifting of stream courses away from developing structural ridges and into adjacent developing structural lows and in the entrenching of streams into structural ridges. The shifts in stream courses resulting from deformation have occurred mainly along the margins of the plateau and in the Yakima Fold Belt of the western plateau where folding has been most extensive. There are portions of the Columbia and Yakima Rivers that are antecedent to the uplift of the Yakima folds. The antecedent streams have incised deep gorges and water gaps between structural basins. The eastern plateau has remained relatively undeformed except for the gentle westward-dipping Palouse Slope and the basins in southeastern Washington. Streams on the eastern plateau are consequent flowing essentially westward down the Palouse Slope.

DISCUSSION

EARLY TO MIDDLE MIOCENE

Grande Ronde lava erupted from fissures in the southeastern Columbia Plateau between 16.5 and 15.5 million years ago (McKee et al. 1977; Long and Duncan 1982) and inundated the intermontane basin between the Rocky Mountains and the ancestral Cascade Range (Smith 1901; Waters 1961; Swanson et al. 1979b). Streams flowing in a centripetal drainage system into the intermontane basin area prior to Grande Ronde eruptions were obliterated by repeated advances of lava (Bond 1963; Conners 1976; Waters et al. 1981). Flows of Grande Ronde Basalt built constructional topography that formed a rather featureless westward-dipping regional paleoslope (Palouse Slope) (Swanson et al. 1979a; Landon et al. 1982). The constructional topography had sufficient relief to cause the establishment of new river courses along the margins of basalt flows. The rapid eruption rate of Grande Ronde Basalt allowed insufficient time for development of a well-integrated drainage system during most of early to middle Miocene time.

Exposures of Grande Ronde Basalt on the margins of the plateau and in the present-day Columbia River Gorge area exhibit colonnade-entablature jointing that in places overlie pillowed basalts and hyaloclastites (Fuller 1931; Waters 1960; Bond 1963; Tabor et al. 1980, 1982; Tolan 1982). Vesicular flow tops of Grande Ronde flows are frequently eroded. Sedimentary interbeds in Grande Ronde Basalt are abundant and decrease in thickness and abundance from the margins onto the center of the plateau (Griggs 1976; Bentley et al. 1980; Tabor et al. 1980, 1982). In the central plateau, Grande Ronde Basalt is known only in deeply incised canyons and from drill holes. The basalt sequence is typified by colonnade-entablature joints with few hyaloclastites or pillowed basalts and by the relative absence of erosional features or interbeds. These observations of the internal character of Grande Ronde flows suggest that most major stream activity was restricted to near the margins of the plateau. There is evidence based on local variations of flow thickness and rare, thin sedimentary interbeds from borehole data in the Pasco Basin (Raymond and Tillson 1968; Myers/Price et al. 1979) to suggest the presence of local lakes and possibly small streams that formed a poorly-integrated drainage system in the central Columbia Plateau during the early to middle Miocene.

Sedimentary interbeds in the Grande Ronde Basalt along the northeastern plateau form part of the Latah Formation (Pardee and Bryan 1926; Griggs 1976) and related "Latah-type" units (Kirkham and Johnson 1929; Bond 1963). These sediments range from claystone to fine-grained sandstone, with laminated siltstone predominant. Coarse-grained sandstone and conglomerate are also present, but are less abundant (Griggs 1976). The sedimentary interbeds are mainly composed of arkosic detritus derived from older crystalline terrain to the north and east of the present-day plateau. Interbeds that occur along the western and northwestern plateau form part of the Ellensburg Formation (Smith 1901, 1903; Mackin 1961; Waters 1955; Schmincke 1967a, 1967b; Waitt 1979). Ellensburg sediments range from claystones to conglo-

merates with siltstone and sandstone most common. The Ellensburg sediments consist of arkosic material in the northwestern plateau and entirely volcaniclastic material farther west (Swanson 1967; Bentley et al. 1980; Tabor et al. 1980, 1982).

Based on observations of fluvial sediments and the internal character of basalt flows, Grande Ronde lava dammed streams flowing from the surrounding highlands, forming a deranged drainage pattern with shallow, freshwater lakes developed behind lava flow fronts on the plateau margin. Small lakes, marshes, and possibly small streams were present in the central plateau. Ponded water and low-energy fluvial environments aggraded fine-grained sediments and formed bogs and marshes, as attested by the abundance of organic debris mixed with fine-grained sediments. In places, continued drainage into lakes resulted in the formation of streams that deposited coarser-grained sediments. The ponded water and streams were repeatedly inundated by subsequent lava flows resulting in the intercalation of basalt and sediments. Subsequent to each eruption, streams during early to middle Miocene time were probably flowing marginal to various basalt flows in an often poorly-integrated ancestral Columbia River drainage system (fig. 3). Streams in the northern and western portions of the forming plateau generally flowed between the Grande Ronde Basalt margin and the south-sloping Okanogan Highlands from northern Idaho across northern Washington, as suggested by Willis (1887). Here, the Columbia River essentially has remained in the same position along the northern margin of the Columbia Plateau since it was established during emplacement of Grande Ronde Basalt. Ancestral streams continued to flow near the plateau margin southward along the foothills of the ancestral Cascade Range, where arkosic sands transported from north of the plateau apparently mixed with, and were diluted by, the volcaniclastic and pyroclastic sediments derived from the ancestral Cascades (Swanson 1967; Bentley et al. 1980). In the central plateau, small lakes and apparently small streams were probably controlled by the Palouse Slope and the constructional topography of basalt flows. Streams that drained the area of the Columbia Plateau during this time flowed through a broad low in the ancestral Cascade Range at the present-day site of Mt. Hood (Beeson and Moran 1979) and on to the Pacific Ocean.

MIDDLE MIOCENE

A hiatus in Columbia River basalt volcanism at the end of the Grande Ronde eruptive episode is represented by sediments of the Vantage Member of the Ellensburg Formation (Mackin 1961; Swanson et al. 1979b). West of the present-day Pasco and Quincy basins, fluvial sediments of the Vantage Member occur between the Grande Ronde and Wanapum Basalts. South and east of these present-day basins, a highly weathered flow top, or saprolite, caps the uppermost flow of Grande Ronde Basalt (Swanson and Wright 1976; Swanson et al. 1979a; Myers/Price et al. 1979; Gardner et al. 1981) suggesting a lengthy interlude of perhaps several hundred thousand years between the end of the Grande Ronde volcanic episode and renewed Columbia River Basalt volcanism.

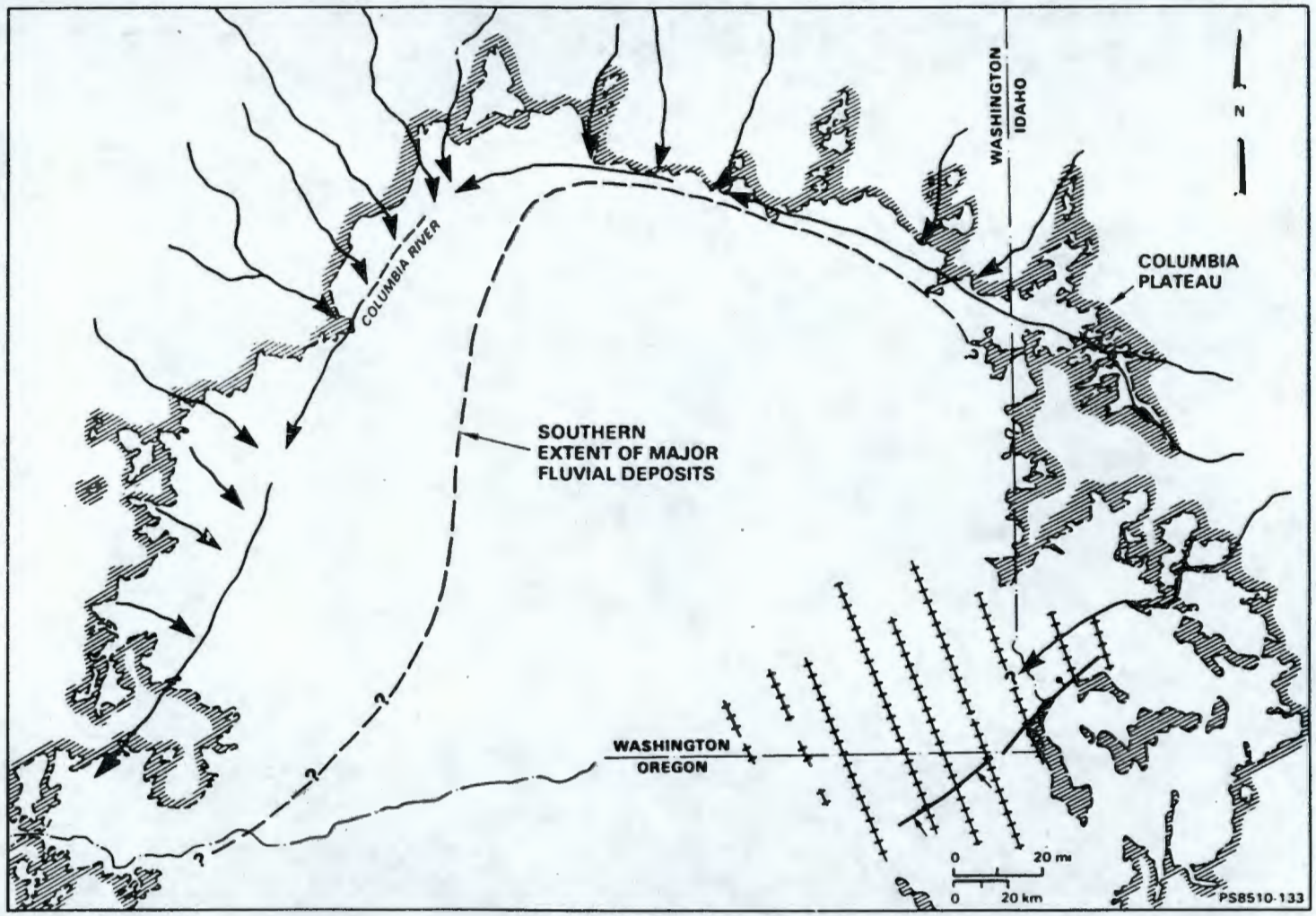

Figure 3. Stream Drainage on the Northern Part of the Columbia Plateau during the Early to Middle Miocene, Grande Ronde Time. (See figure 1, sheet 2 for symbol legend.)

West of the present-day Pasco and Quincy basins, the Vantage Member is composed of fine-grained arkosic and volcaniclastic sediments (Mackin 1961; Diery and McKee 1969; Myers/Price et al. 1979; Bentley et al. 1980). The volcaniclastic sediments increase in abundance westward and in the upper Wenas Valley, the Vantage Member is composed of entirely volcaniclastic debris (Schmincke 1967a). This suggests that tributary streams draining the volcanic terrain in the ancestral Cascade Range were flowing onto the western portion of the forming plateau. The presence of arkosic sediments in the central plateau suggests that the ancestral Columbia River had been diverted from near the margins of the plateau southeastward into the central plateau area (fig. 4).

The presence of volcaniclastic sediments on the western plateau is probably due to (1) deposition of thick sequences of debris by eastward-flowing streams from active volcanic terrain of the Cascade Range, or (2) uplift of the ancestral Cascades relative to subsidence of the plateau as suggested by the offlap of Grande Ronde Basalt, or (3) both. Distribution of sediments over much of the western plateau suggests that the streams probably were initially flowing over a rather broad, flat plain before becoming confined to relatively narrow courses.

The diversion of the ancestral Columbia River from its former marginal course to a course flowing onto the plateau near Wenatchee was originally interpreted to be in response to lavas spreading from two converging lava flows (Chappell 1936). Subsequent workers have measured numerous north- and northwest-trending basalt flow directions in the northwestern plateau, suggesting a lava source to the south or southeast that is consistent with the location of dikes for Grande Ronde Basalt in the southeastern plateau (Swanson et al. 1979a). Also, mapping in the northwestern plateau has shown that feeder dikes present in the Cascade Range and the northwest margin of the present-day plateau are not sources for Columbia River basalts (Swanson 1967). The east-dipping, foreset-bedded pillowed basalts mapped by Chappell (1936) apparently are local features and do not represent a lava source to the west (Swanson 1967).

Another possible hypothesis for diversion of the ancestral Columbia River onto the plateau is uplift of the Wenatchee Mountains, a hypothesis that was rejected by Chappell (1936). Recent mapping southeast of Wenatchee suggests that the ancestral Columbia River was diverted onto the plateau as a result of uplift of the Naneum Ridge structure (Swanson et al. 1979a). Uplift of the Naneum Ridge structure created the Wenatchee Mountains and the broad Hog Ranch structure of Mackin (1961). Evidence for structures controlling the diversion is found in the thickness and composition of the Vantage Member south of Wenatchee. Field mapping has shown that the Vantage Member thins both east and west of the course of the present-day Columbia River from Cresent Bar to the Saddle Mountains (Grolier 1965; Grolier and Bingham 1978; Alto 1955; Tabor et al. 1982). Locally, the Vantage thickens in structural lows, and thins and pinches out on structural highs where a well-developed saprolite is often present atop Grande Ronde Basalt. These

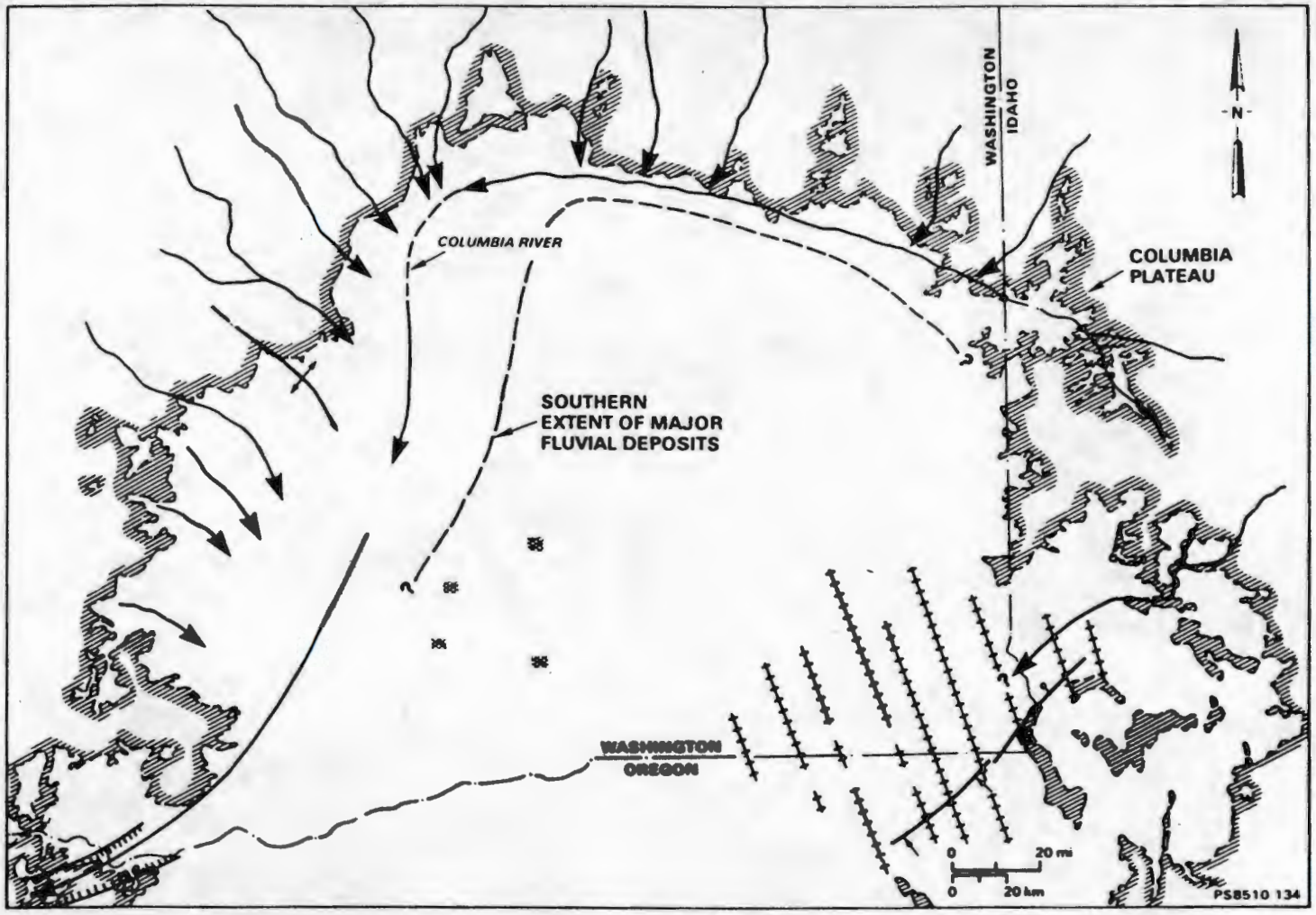

Figure 4. Stream Drainage on the Northern Part of the Columbia Plateau during the Middle Miocene, Vantage Time. (See figure 1, sheet 2 for symbol legend.)

observations are consistent with structurally controlled topography developing throughout the Columbia Plateau by late Grande Ronde time (Reidel 1978; Beeson and Moran 1979; Camp and Hooper 1981; Landon et al. 1982).

The ancestral Columbia River, once diverted onto the plateau, apparently flowed southwest across the plateau and through the Cascade Range to the general vicinity of present-day Mt. Hood (Tolan and Beeson 1984) (see fig. 4). The main stream channel followed the southwest trending Mt. Hood syncline into western Oregon.

Stream drainage on the plateau was abruptly changed by renewed Columbia River basalt volcanism. Wanapum Basalt erupted from fissure systems in the eastern Columbia Plateau in the middle Miocene from ~15.5 to 13.6 m.y.B.P. (McKee et al. 1977). The Frenchman Springs, Roza, and Priest Rapids Members of the Wanapum Basalt form much of the surface of the present plateau. Emplacement of Wanapum Basalt continued to build the constructional high of the westerly dipping Palouse Slope. However, the central plateau was continuing to subside in the middle Miocene, as evident from the ponding of flows in structural lows (Reidel et al. 1980; Reidel and Fecht 1981).

Initial eruptions of Frenchman Springs lava engulfed the ancestral Columbia River and ancestral lake(s) in the western plateau. The lowermost flows, termed Ginkgo flows (Mackin 1961; Bentley 1977), contain thick hyaloclastites and pillowed basalts at their base that are areally extensive from east of Wenatchee southwestward to the Columbia River Gorge (Mackin 1961; Lefebvre 1966; Diery 1967; Bentley et al. 1980). The emplacement of Ginkgo flows apparently restricted a deranged ancestral Columbia River to a course in the western plateau (fig. 5).

Overlying the Frenchman Springs Member in the Yakima and Vantage areas is the Squaw Creek Member of the Ellensburg Formation (Swanson et al. 1979b). The member consists of diatomite in the Vantage area and grades westward into sandstones and conglomerates composed partly of volcaniclastic detritus and partly of plutonic and metamorphic detritus (Mackin 1961). The diatomite facies of the Squaw Creek Member is interpreted by Mackin to represent the accumulation of diatoms in a lake impounded by the uppermost flow of the Frenchman Springs Member in the Vantage area.

Eruption of the Roza and Priest Rapids Members of the Wanapum Basalt apparently maintained stream courses on the western Columbia Plateau in Washington. The western margins of the Roza and Priest Rapids flows apparently continued to restrict the south-flowing portion of a deranged ancestral Columbia River and east-flowing tributaries from the ancestral Cascade Range to the western plateau. In the northern and northeastern plateau, the Priest Rapids flows encroached on the plateau margin and inundated the St. Joe and St. Maries Rivers in the Benewah Embayment. The Priest Rapids flows filled the river channels in the embayment and older channels cut into the Latah Formation and Grande Ronde Basalt near Spokane (Swanson et al. 1979b). Farther southwest near Malden, the basal Priest Rapids flow is pillowed over a wide area (Griggs 1976), suggesting that the lava dammed and inundated a local drainage system that was flowing westward onto the eastern

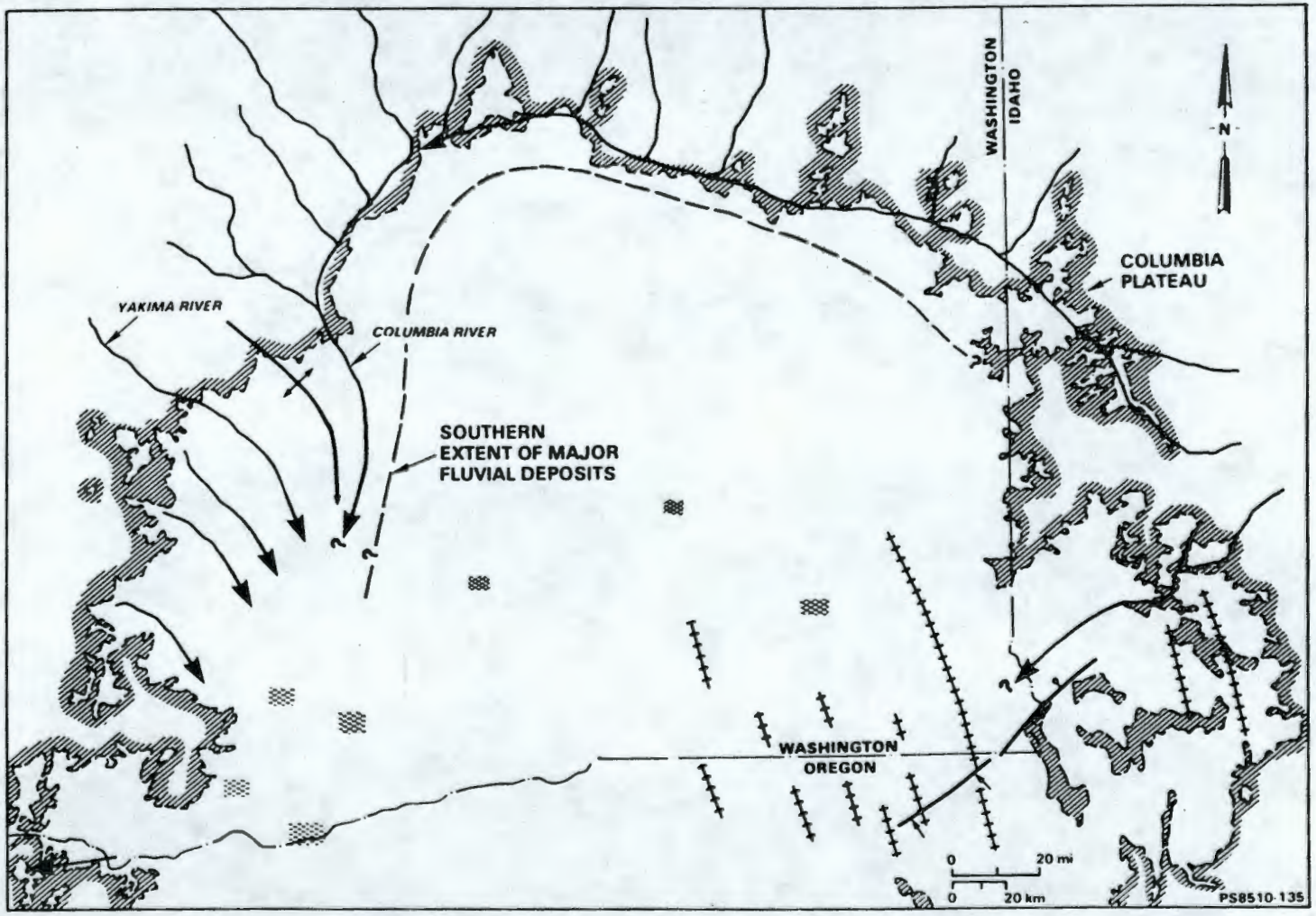

Figure 5. Stream Drainage on the Northern Part of the Columbia Plateau during the Middle Miocene, Wanapum Time. (See figure 1, sheet 2 for symbol legend.)

margin of the plateau. However, the ancestral Columbia River and its tributaries in the northeastern portion of the Columbia Plateau reestablished courses along the northern plateau margin.

In the southeast Columbia Plateau, the effects of emplacement of Wanapum or Grande Ronde flows on drainage (i.e., the ancestral Clearwater and Salmon Rivers) from the Clearwater Embayment are not accurately known. However, the absence of interbedded sediments and erosional features associated with Grande Ronde and Wanapum flows on the Palouse Slope on the north side of the emerging Blue Mountains suggests streams draining the Clearwater Embayment may have been flowing south during early Miocene time.

MIDDLE TO LATE MIOCENE

During middle to late Miocene time, Columbia River basalt volcanism was waning, and flows of the Saddle Mountains Basalt were areally restricted to ancestral river canyons and valleys in the eastern plateau, the subsiding central portion of the plateau, and river canyons through the ancestral Cascade Range (Myers/Price et al. 1979; Swanson et al. 1980; Waters 1973; Tolan 1982). With less frequent basaltic eruptions, a relatively well-integrated river system deposited sediments over extensive parts of the central and western plateau (Mason 1953; Laval 1956; Schmincke 1964). Deformation within the Yakima Fold Belt of the western plateau, which was largely masked by earlier frequent and voluminous volcanic eruptions, formed subtle topographic features of sufficient relief to control the distribution of Ellensburg sediments and Saddle Mountains flows (Reidel et al. 1980; Reidel and Fecht 1981). The subsidence of the central plateau, which was initiated at least by the time of Grande Ronde flows, formed slopes gently dipping toward the structural and topographic low of the central plateau. These slopes also controlled the distribution and thickness of sediments and basalt flows.

As the central plateau was subsiding, the ancestral Columbia River began entrenching itself to about its present position along the northern and northeastern margin of the plateau (fig. 6). South of Wenatchee, the course of the ancestral Columbia River shifted from a southwesterly course along the flow fronts of Wanapum flows to a more southerly course as a result of continued uplift of the Hog Ranch structure. The river was shifted to a course flowing south down the forming Columbia Slope (Schmincke 1964, 1967a) and through the structural low in the Saddle Mountains at Sentinel Gap. Laterally, the river was controlled by the Hog Ranch structure to the west and the Palouse Slope to the east. The timing of the shift appears to have preceded the eruption of the Saddle Mountains flows, based on the abundance of arkosic sediments that are present within the Mabton Member of the Ellensburg Formation in the Pasco Basin and vicinity (Myers/Price et al. 1979; Reidel and Fecht 1981). Following the shift to a southerly course from Wenatchee to Sentinel Gap, the Columbia River began entrenching into its present position as a result of continued uplift of ridges and subsidence of the central plateau.

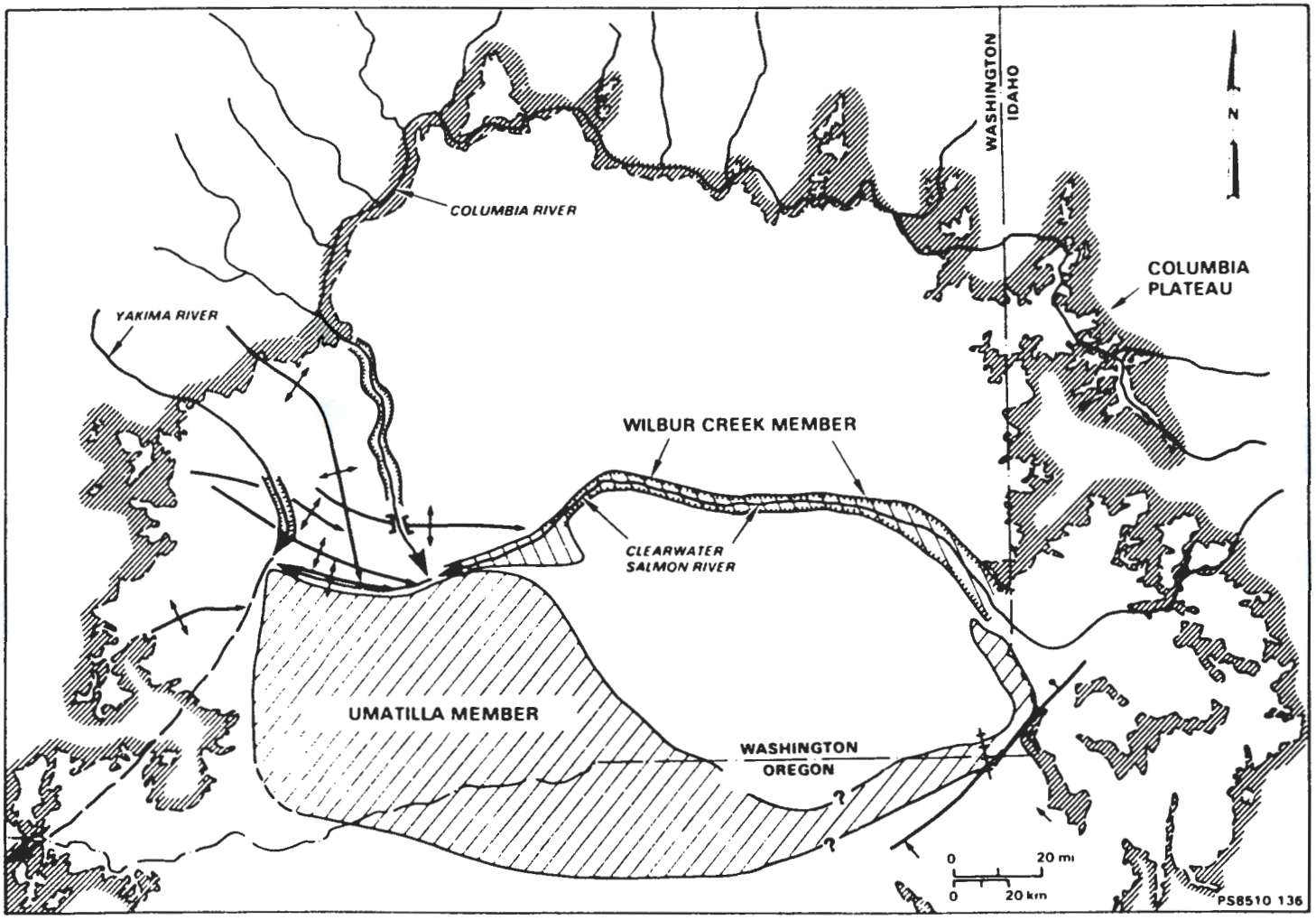

Figure 6. Stream Drainage on the Northern Part of the Columbia Plateau during the Middle to Late Miocene, Post-Umatilla Interval. (See figure 1, sheet 2 for symbol legend.)

On the western Columbia Plateau, the Yakima River and its tributaries began forming an integrated drainage system after the position of the Columbia River was established east of the Hog Ranch structure. Eastward-flowing streams in the Yakima River drainage developed as they were able to overcome the constructional topography of basalt flows that had ceased encroaching on the northwestern plateau. Ellensburg sediments were deposited in the developing Kittitas Basin primarily by eastward-flowing streams that were laden with volcaniclastic sediments from the ancestral Cascade Range. South of the Kittitas Basin, between Ellensburg and Yakima, the Yakima River, which apparently meandered over an ancestral lowland, began entrenching a course across the rising structural ridges of the Yakima Fold Belt (see fig. 6). The antecedence of the Yakima River to the fold belt has long been recognized (Smith 1903; Calkins 1905; Waters 1955). Apparently, the entrenchment of the Yakima River resulted from the combined effect of uplift of ridges and subsidence of basins in the western plateau.

The remaining discussion of middle to late Miocene time will be primarily directed to the Yakima Valley and Pasco Basin areas, where the emplacement of flows and deformation of the plateau has had a pronounced influence on drainage development. The discussion is based on the intervals between eruptions of Saddle Mountains Basalt. Intervals are used in this paper for convenience rather than formally and informally named interbeds, primarily because flows are not as areally extensive as the sedimentary deposits.

Post-Umatilla Interval

Stream drainage on the Columbia Plateau in southern Washington following emplacement of the Umatilla Member is reconstructed from (1) the remnants of the canyon-filling Wilbur Creek Member, (2) the position of the established courses of the Columbia and Yakima Rivers in the northern plateau, and (3) the distribution of Ellensburg sediments along the margin of the Umatilla Member in the Yakima Valley. The Wilbur Creek Member was a relatively small-volume eruption that was confined to an ancestral stream canyon in Washington State and, therefore, defines the position of that stream (see fig. 6). Wilbur Creek lava was erupted from fissures in the North Fork area of the Clearwater River in Idaho and flowed down canyons of the ancestral Clearwater drainage into the Lewiston Basin (Camp 1976, 1981). Stream gravels occur beneath the Wilbur Creek Member in the Clearwater Embayment (Camp 1981). Wilbur Creek lava flowed out of the Lewiston Basin in a northwesterly direction and onto the Uniontown Plateau around the rising Blue Mountains, and then westward down the Palouse Slope filling the ancestral Clearwater-Salmon River canyon (Swanson et al. 1979b, 1980). At Warden, the intracanyon remnants of the Wilbur Creek Member trend southwestward across the northern Pasco Basin and westward to Yakima (Bentley 1977; Myers/Price et al. 1979; Reidel et al. 1980). In the Pasco Basin, this ancestral river was controlled within the structural low of the developing Wahluke syncline and between the rising Saddle Mountains to the north and the thick (>45 m) flow-front of the Umatilla Member to the south (Reidel

et al. 1980; Reidel and Fecht 1981). The Columbia River, flowing south through the Saddle Mountains at Sentinel Gap, apparently joined the ancestral Clearwater-Salmon River in an area southeast of Priest Rapids Dam (see fig. 1 and 6). The course of the combined rivers between the Pasco Basin and Yakima continued to be controlled on the south by the flow-front of the Umatilla Member and to the north by the rising Yakima Ridge. In the Yakima area the combined Columbia/Clearwater-Salmon River joined the ancestral Yakima River to flow in a southwesterly course possibly through the Grayback Mountain paleocanyon to the Columbia River Gorge area where the streams occupied the Bridal Veil channel of Tolan and Beeson (1984). The southwesterly stream course was generally controlled by the western margin of the Umatilla Member to the east and the syncline of the northeast-southwest-trending Yakima folds of this area.

Post-Wilbur Creek Interval

The position of major stream courses during the post-Wilbur Creek interval (fig. 7) is very similar to that of the post-Umatilla interval (see fig. 6). The similarity of positions is due to (1) lack of sufficient volume of lava in the Wilbur Creek eruption to disrupt drainage development, (2) the maintenance of the same structural and constructional controls during both intervals, and (3) the short period between the two intervals. Stream courses during the post-Wilbur Creek interval are mainly defined by the canyon-filling and minor valley-filling flows of the Asotin Member (Swanson et al. 1979b, 1980; Myers/Price et al. 1979; Reidel et al. 1980). The Asotin Member erupted from a source area in the Clearwater drainage (Camp 1981) and flowed down the ancestral Clearwater-Salmon River canyon from the Lewiston Basin across the Palouse Slope to the Pasco Basin (see fig. 7). In the topographic and structural lows of the Lewiston and Pasco Basins, the Asotin lava overflowed the river channel and spread laterally, partially filling the basins (Camp 1981; Reidel et al. 1980; Reidel and Fecht 1981). The thickest section of Asotin basalt in the Pasco Basin (~67 m) is located just north of the approximate margin of the Umatilla Member. The thick section of Asotin Basalt is interpreted to correspond with the former position of the ancestral Clearwater-Salmon River, although no extensive sedimentary deposits are known to be associated with the post-Wilbur Creek interval. The courses of the Columbia, Clearwater-Salmon, and Yakima Rivers from the central plateau into the present-day Columbia River Gorge area remained essentially unchanged from the post-Umatilla interval (see fig. 7).

Post-Asotin Interval

Following the eruption of the Asotin Member, the ancestral Clearwater-Salmon River reestablished a course on the Palouse Slope ~25 km south of the river canyons formed during the post-Umatilla and post-Wilbur Creek intervals (fig. 8). The ancestral Clearwater-Salmon River incised a canyon into the Palouse Slope that is now preserved by the Esquatzel intracanyon flow (Swanson et al. 1980). The new course was located near the present-day

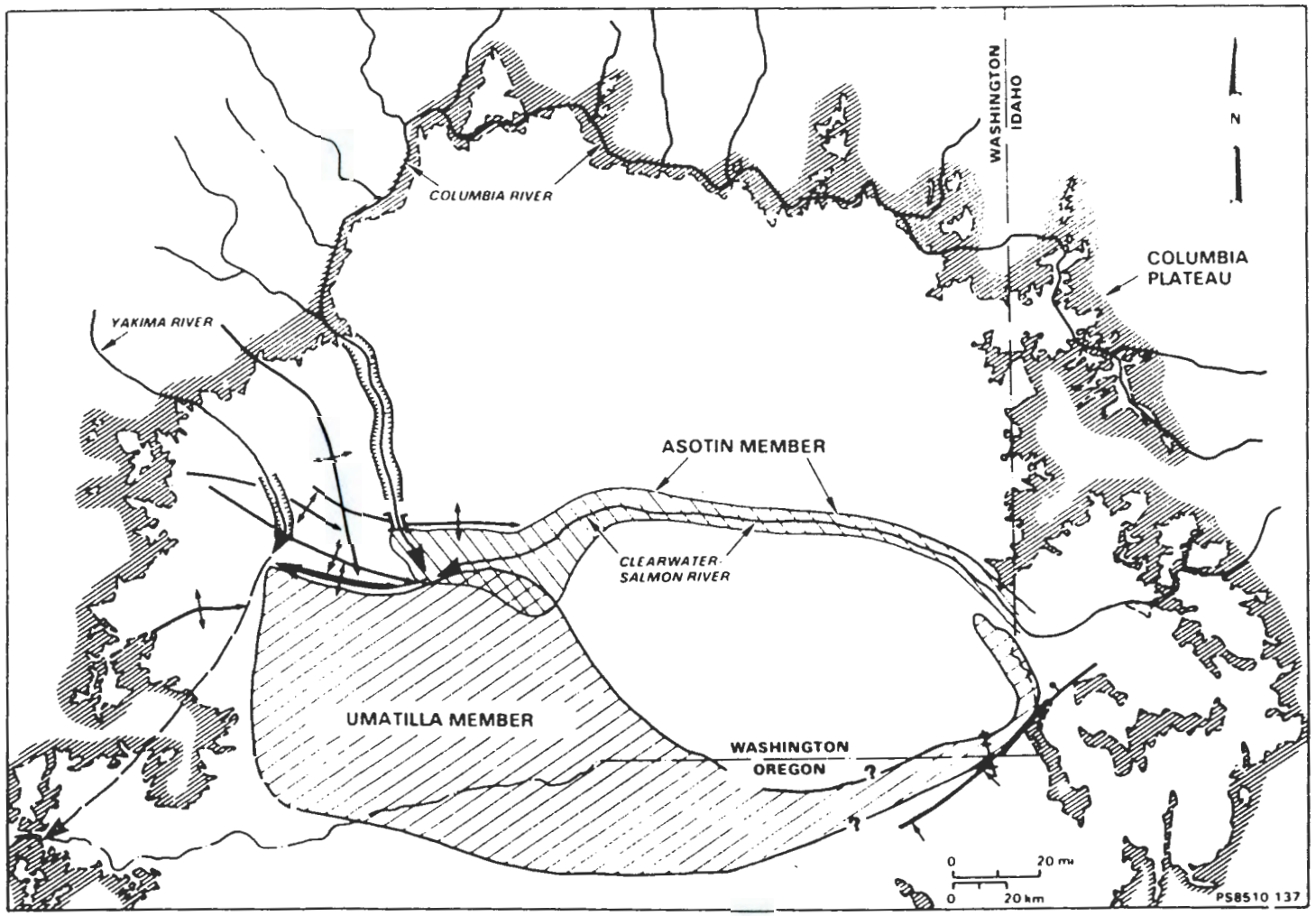

Figure 7. Stream Drainage on the Northern Part of the Columbia Plateau during the Middle to Late Miocene, Post-Wilbur Creek Interval. (See figure 1, sheet 2 for symbol legend.)

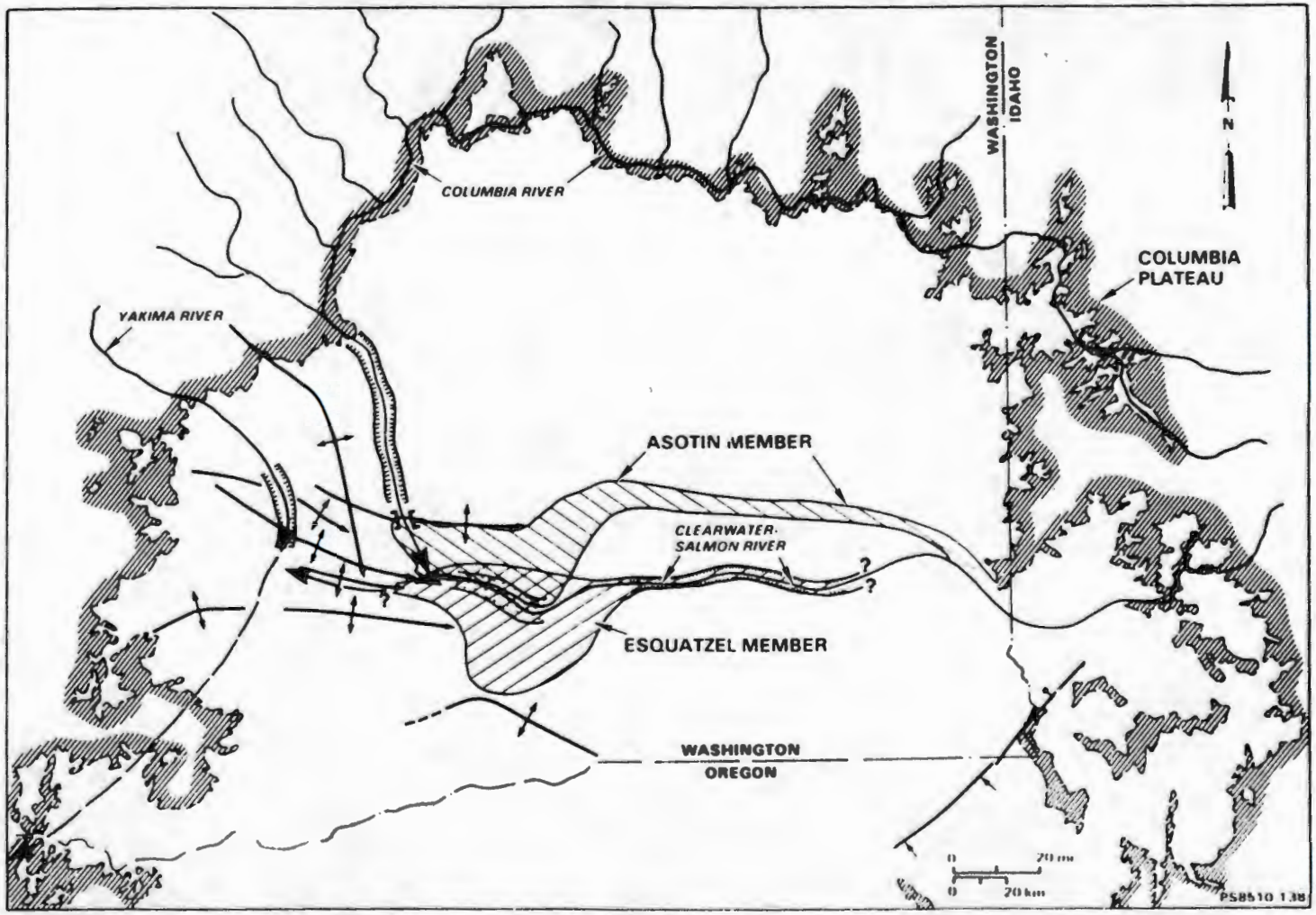

Figure 8. Stream Drainage on the Northern Part of the Columbia Plateau during the Middle to Late Miocene, Post-Asotin Interval. (See figure 1, sheet 2 for symbol legend.)

Snake River between the Lewiston Basin and Lower Monumental Dam. Following the post-Asotin interval, the ancestral Clearwater-Salmon River continued to reestablish and entrench its course within a few kilometers of the present-day Snake River (Swanson et al. 1980) as the central plateau continued to subside.

The course of the ancestral Clearwater-Salmon River, as determined by the distribution of the Esquatzel Member, loses definition as Esquatzel lavas spread laterally and ponded in the subsiding Pasco Basin. However, the course can be defined by clastic sediments underlying the Esquatzel Member. These form part of the Cold Creek interbed of the Ellensburg Formation and are divided into two distinct textural facies: (1) a fine-grained, tuffaceous and arkosic sandstone and mudstone facies and (2) a coarse-grained sandstone and conglomerate facies (Myers/Price et al. 1979; Reidel and Fecht 1981). The coarse-grained facies follows an arcuate trend across the basin that is subparallel to the flow front of the Asotin Member. The coarse-grained facies is interpreted to represent the main-channel deposits of the ancestral Clearwater-Salmon River with the fine-grained facies mainly representing overbank and early post-Asotin fluvial deposits. The course of the ancestral Clearwater-Salmon River in the Pasco Basin was controlled within the topographic and structural low along the southern margin of the Asotin flow front.

At the western margin of the Pasco Basin, the ancestral Clearwater-Salmon and Columbia Rivers in post-Asotin time joined in a poorly defined area, probably near the east end of the present-day Yakima Ridge, to flow westward out of the basin. The combined-river course to the west is defined by remnants of the Esquatzel Member that at least partially filled the eastern portion of Black Rock Valley between the rising Yakima Ridge and Rattlesnake Hills (Myers/Price et al. 1979). Esquatzel flows have not been mapped west of about long. 120° W., but since the Yakima Ridge and Rattlesnake Hills were emerging, the combined course of the Columbia/Clearwater-Salmon Rivers was probably confined between these basaltic ridges to the vicinity of Yakima. At Yakima, the combined ancestral Columbia/Clearwater-Salmon Rivers joined with the ancestral Yakima River to flow southwestward to the present-day Columbia River Gorge area in a course similar to that of earlier intervals in middle to late Miocene time (see fig. 8).

Post-Esquatzel Interval

The course of the ancestral Clearwater-Salmon River during the post-Esquatzel interval is defined by the canyon-filling Pomona Member (Swanson et al. 1979b, 1980). The position of the river was essentially coincident with its former position during the post-Asotin interval (fig. 9). Within the Pasco Basin, Pomona lavas spread laterally and inundated the basin. Beneath the Pomona Member in the basin, extensive sedimentary deposits occur that form the Selah Member of the Ellensburg Formation (Myers/Price et al. 1979). The Selah Member is composed of volcaniclastic and arkosic sediments that range in size from clay to gravel. The Selah gravels are known to occur in three areas of the Pasco Basin and are important in defining the

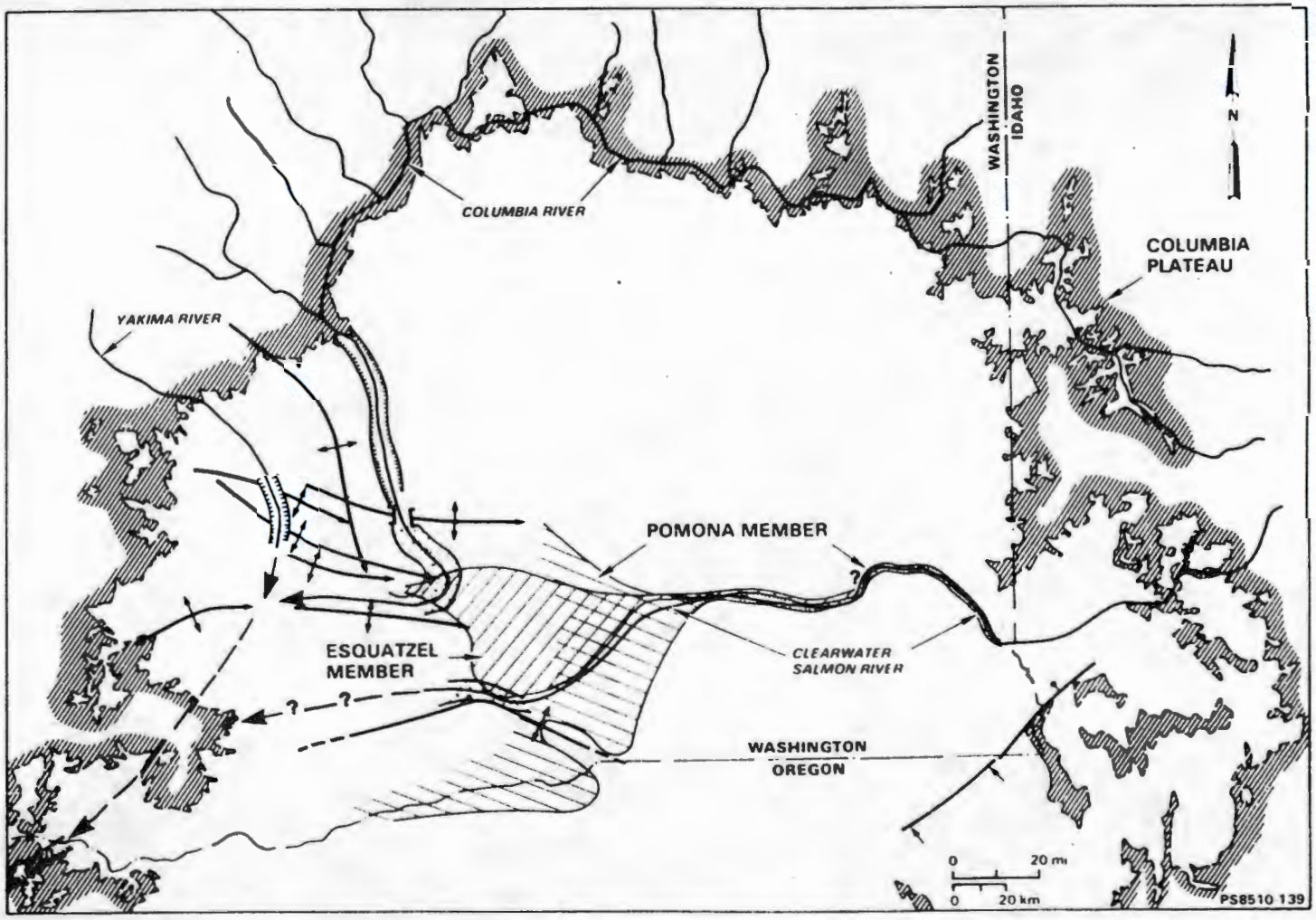

Figure 9. Stream Drainage on the Northern Part of the Columbia Plateau during the Middle to Late Miocene, Post-Esquatzel Interval. Only the eastern portion of the Pomona Member is shown. (See figure 1, sheet 2 for symbol legend.)

courses of main through-flowing streams. In the northwest portion of the basin, a gravel train can be defined from Sentinel Gap in the Saddle Mountains, southeasterly around the east end of Umtanum Ridge, and then westerly over the east end of Yakima Ridge. The Selah gravels are mainly composed of basaltic, plutonic, and metamorphic clasts. In the southwestern portion of the Pasco Basin, Selah gravels are exposed on the north flank of the Horse Heaven Hills and lie beneath a thick (>60 m) Pomona Member (Bond et al. 1978). These gravels lie between the Umatilla and Pomona Members and are mainly composed of basaltic clasts. The small nonbasaltic fraction consists of a variety of metamorphic and plutonic clasts including a few metabasalt clasts. In the southeastern Pasco Basin, an outcrop of basaltic Selah gravels is exposed immediately northeast of Wallula Gap (Gardner et al. 1981). These gravels also lie between the Umatilla and Pomona Members.

All three Selah gravel deposits differ sufficiently in composition to suggest deposition by three separate streams. The distribution of the northern gravel train corresponds closely with former courses of the ancestral Columbia River during middle to late Miocene time (see fig. 7-9). The composition of these northern gravels also appears similar to other deposits of the ancestral Columbia River. The ancestral Columbia River during this interval flowed essentially in the same course as during the post-Asotin interval. This course was probably controlled by the northern margin of the Esquatzel Member.

Gravel deposits in the southwestern Pasco Basin are composed of different lithologies than the gravels in the northern Pasco Basin and are interpreted to have been deposited by the ancestral Clearwater-Salmon River. The course of the ancestral Clearwater-Salmon River is believed to have flowed from the Devil's Canyon area southwest across the southern Pasco Basin, through the Chandler area, and westward into the lower Yakima Valley. In the Pasco Basin, the ancestral Clearwater-Salmon River was forced south to a position apparently controlled by the southern flow front of the Esquatzel Member and in the Chandler area by the rising Horse Heaven Hills.

The basaltic Selah gravels that were deposited in the southeastern Pasco Basin are suggestive of a stream that originated on the Columbia Plateau. It is speculated here that these gravels represent the ancestral Walla Walla River which flowed westward along the front of the Horse Heaven Hills or along the series of rising brachyanticlines that now form the southeastern portion of the Rattlesnake Hills.

Post-Pomona Interval

The ancestral Columbia and Clearwater-Salmon Rivers that joined in the Pasco Basin in the earlier intervals of middle to late Miocene time appear to have diverged during the post-Pomona interval. The course of the ancestral Columbia River through the Pasco Basin during this interval is well defined by a gravel train that is preserved in the Rattlesnake Ridge Member of the Ellensburg Formation (fig. 10). The gravel train is present from Sentinel Gap southeast around the east end of Umtanum Ridge and southwest

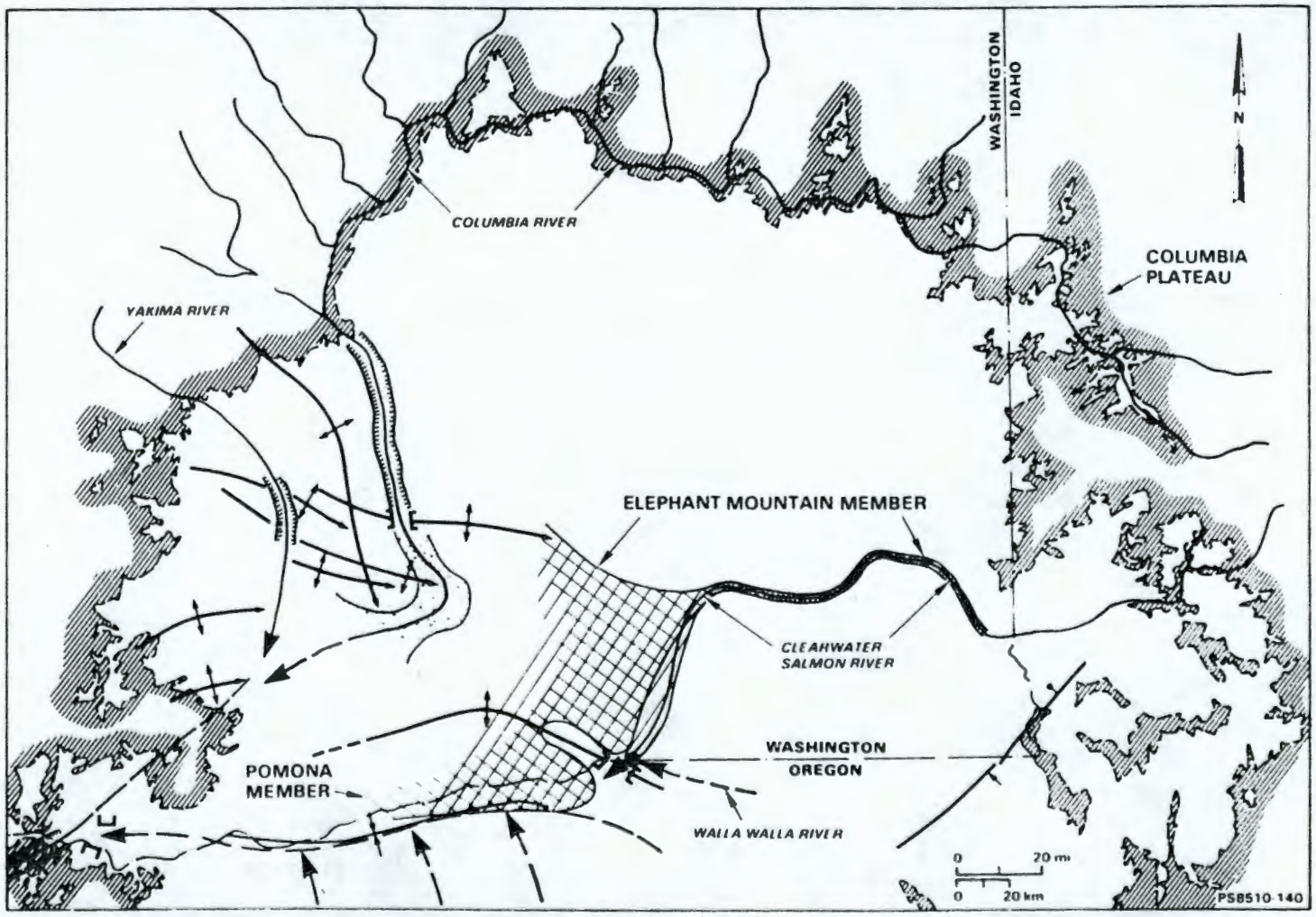

Figure 10. Stream Drainage on the Northern Part of the Columbia Plateau during the Middle to Late Miocene, Post-Pomona Interval. Only the eastern portion of the Elephant Mountain Member is shown. (See figure 1, sheet 2 for symbol legend.)

across the east end of Yakima Ridge. The gravel train is flanked by fining-upward cycles of sandstone and mudstone that thin and grade to mainly sandy mudstone, and mudstone on to the eastern and southern margins of the Pasco Basin.

Southwest of the Pasco Basin, the course of the ancestral Columbia River shifted widely across the Rattlesnake Hills based on the widespread occurrence of gravels mapped in the Rattlesnake Ridge interbed by Schmincke (1967a). The ancestral Columbia River joined the Yakima River in the present upper Yakima Valley between about Union Gap and Toppenish Ridge and then flowed across the eastern part of the Yakima Indian Reservation (Bentley et al. 1980). The combined course of the rivers apparently flowed southwest in the paleocanyon and into the Bridal Veil channel of Tolan and Benson (1984). These paleocanyons have been partially filled by Pomona lava.

The main course of the ancestral Clearwater-Salmon River has been only tentatively defined in the central Columbia Plateau during the Post-Pomona interval. Based on examination of borehole samples and surface exposures of the Rattlesnake Ridge interbed in the Pasco Basin, there has been no evidence found to establish the ancestral Clearwater-Salmon River from the Palouse Slope westward across the Pasco Basin. Lithologies of gravel clasts of the ancestral Columbia River west of the Pasco Basin were also examined to determine if the ancestral Clearwater-Salmon River may have joined the ancestral Columbia in the central plateau of Washington State. Key lithologies of the ancestral Clearwater-Salmon River (e.g., metabasalts) are absent, suggesting that the ancestral Clearwater-Salmon River did not flow across the central plateau. It is believed that the course of the ancestral Clearwater-Salmon River may have been diverted south of the Pasco Basin through Horse Heaven Hills, probably at Wallula Gap.

The course of the Clearwater-Salmon River through Wallula Gap is, in part, based on the occurrence of a gravel unit exposed near the crest of the Horse Heaven Hills on the west side of the Gap. The gravels are composed of a mixture of basaltic, metamorphic (including metabasalts), and plutonic rocks, in similar proportions to gravel deposits in the ancestral Clearwater-Salmon River drainage on the eastern Columbia Plateau. These gravels are main-channel deposits of the ancestral Clearwater-Salmon River. At Wallula Gap, the gravels form an unnamed interbed of the Ellensburg Formation that partially fills a canyon eroded into the Umatilla Member and are capped by the Ice Harbor Member (basalt of Martindale) of the Saddle Mountains Basalt (ARHCO 1976). The age of the gravels is not well constrained. Field mapping in the Wallula Gap area on the north flank of the Horse Heaven Hills has not revealed the presence of exotic gravels within interbeds beneath the Ice Harbor, Elephant Mountain, or Pomona Members at other localities (Gardner et al. 1981). However, gravels in the same stratigraphic position and of similar composition occur 10 km northeast of Wallula Gap along the present-day Walla Walla River. The occurrence of basaltic gravels in the Selah Member immediately northeast of Wallula Gap (see post-Esquatzel interval) suggests that the unnamed interbed is probably post-Selah in age.

If the gravels at Wallula Gap are in part, post-Pomona interval in age, then the westerly flowing ancestral Clearwater-Salmon River was probably diverted to a southwesterly course along or very near the flow front of the Pomona Member in the southeastern Pasco Basin (see fig. 10). Diversion of the ancestral Clearwater-Salmon River across the Horse Heaven Hills at Wallula Gap may have been in response to constructional topography built by the emplacement of the Pomona Member. The river course through the Horse Heaven Hills was apparently controlled by the southern flow-front of the Pomona Member on the west side of Wallula Gap and by a structural low in the Horse Heaven Hills at the Gap, based on field mapping of Gardner et al. (1981).

Southwest of Wallula Gap, the ancestral Clearwater-Salmon River probably flowed southwest into the forming Umatilla Basin where the river was captured by a river system draining north-central Oregon. In the Umatilla Basin, the major river was probably controlled in the forming Umatilla syncline south of the southern margin of the Pomona Member. This course is based on the occurrence of fine-grained sediments in the Rattlesnake Ridge interbed within the Umatilla basin (Shannon and Wilson 1972, 1975). No coarse-grained clastics associated in the Umatilla Basin with the river system of the post-Pomona interval have been observed that contain lithologies diagnostic of the ancestral Clearwater-Salmon River. The lack of these sediments may be due to erosion and reworking of fluvial sediments in the area over the past 10.5 to 12 m.y. The major river of the north-central Oregon system is assumed to have flowed west, parallel to the axis of the forming Umatilla-Dalles syncline and through the Columbia Hills at the present-day Columbia River water gap. The water gap is interpreted to have been an active major stream course through the Columbia Hills since at least the beginning of middle to late Miocene time. This interpretation is based on the absence of erosional features, intracanyon flows, or coarse-grained clastics of late Miocene age elsewhere across the Columbia Hills. This ancestral river joined the ancestral Columbia-Yakima River between the Columbia Hills Water Gap and Hood River, Oregon, to flow through the ancestral Cascade Range.

Post-Elephant Mountain Interval

Following the Elephant Mountain volcanic episode that inundated much of the central Columbia Plateau, the major ancestral rivers reestablished courses in about the same position as the courses of the major rivers in the Post-Pomona interval.

The presence of the ancestral Columbia River in the post-Elephant Mountain interval is defined by the widespread occurrence of stream gravels that overlie the Elephant Mountain Member from the Sentinel Gap area southwest to the Columbia River Gorge. The gravels include the quartzite gravels of Warren (1941), Snipes Mountain conglomerate of Schmincke (1967a), and "gravels of the ancestral Columbia River" of Campbell (1979) and Rigby et al. (1979). These ancestral Columbia River gravels are composed of quartzitic clasts as well as plutonic, basaltic, and other metamorphic

clasts. Russell (1893) and Waring (1913) first described the occurrence of quartzitic pebbles in the southwestern Columbia Plateau. Warren (1941) suggested that the gravels marked the former course of the Columbia River from Sentinel Gap southwest through Satus Pass and into the Columbia River Gorge. Waters (1955) demonstrated that Satus Pass resulted from local stream capture and not from a course incised by an ancestral Columbia River. The relatively broad course of the ancestral Columbia River south and east of Satus Pass in the Goldendale area was determined by Schmincke (1967a) and Rigby et al. (1979) based on the widespread occurrence of quartzitic gravels.

The general course of the ancestral Columbia River during the post-Elephant Mountain interval can be defined by the distribution of "quartzitic" gravels from Sentinel Gap area southeast around the east end of Umtanum Ridge and southwest in a broad path over the Rattlesnake Hills to Snipes Mountain (fig. 11). The course of the river over the central Columbia Plateau was not controlled by flow margins as occurred in many of the earlier Saddle Mountains intervals. Near the center of the path of "quartzitic" gravels, an erosional canyon has been cut in and through a structural low across the Rattlesnake Hills. It is speculated here that an ancestral Columbia River may have cut a channel into the ridge forming "Sunnyside Gap" during uplift of the hills after emplacement of the Elephant Mountain Member (see fig. 11).

During this interval, the ancestral Yakima River was flowing south from Yakima through Union Gap in Ahtanum Ridge and southeastward into the upper Yakima Valley (Toppenish Basin) (see fig. 11). Sediments deposited by the ancestral Yakima River were mainly composed of volcanic debris. Immediately south of Snipes Mountain, the gravel train is composed of a mixture of volcanic, plutonic, and metamorphic clasts, which represents the combined courses of the ancestral Yakima and Columbia Rivers (Schmincke 1964). The combined rivers flowed southwesterly toward Goldendale and into the present-day Columbia River Gorge area along a course suggested by Warren (1941). This is consistent with the southwestern current directions measured by Schmincke (1964) and the mixed lithologies of the gravels.

The westerly flowing ancestral Clearwater-Salmon River on the Palouse Slope was flowing in a southwesterly course along or very near the flow front of the Elephant Mountain flows to Wallula Gap (see fig. 11). The river course through the Horse Heaven Hills was apparently controlled by the flow front of the Elephant Mountain Member on the west side of Wallula Gap and by a structural low in the Horse Heaven Hills at the Gap, based on field mapping of Gardner et al. (1981). South of the Horse Heaven Hills in north-central Oregon, the major stream of this region flowed west parallel to the axis of the Umatilla-Dalles syncline and through the Columbia Hills Water Gap as during the post-Pomona interval.

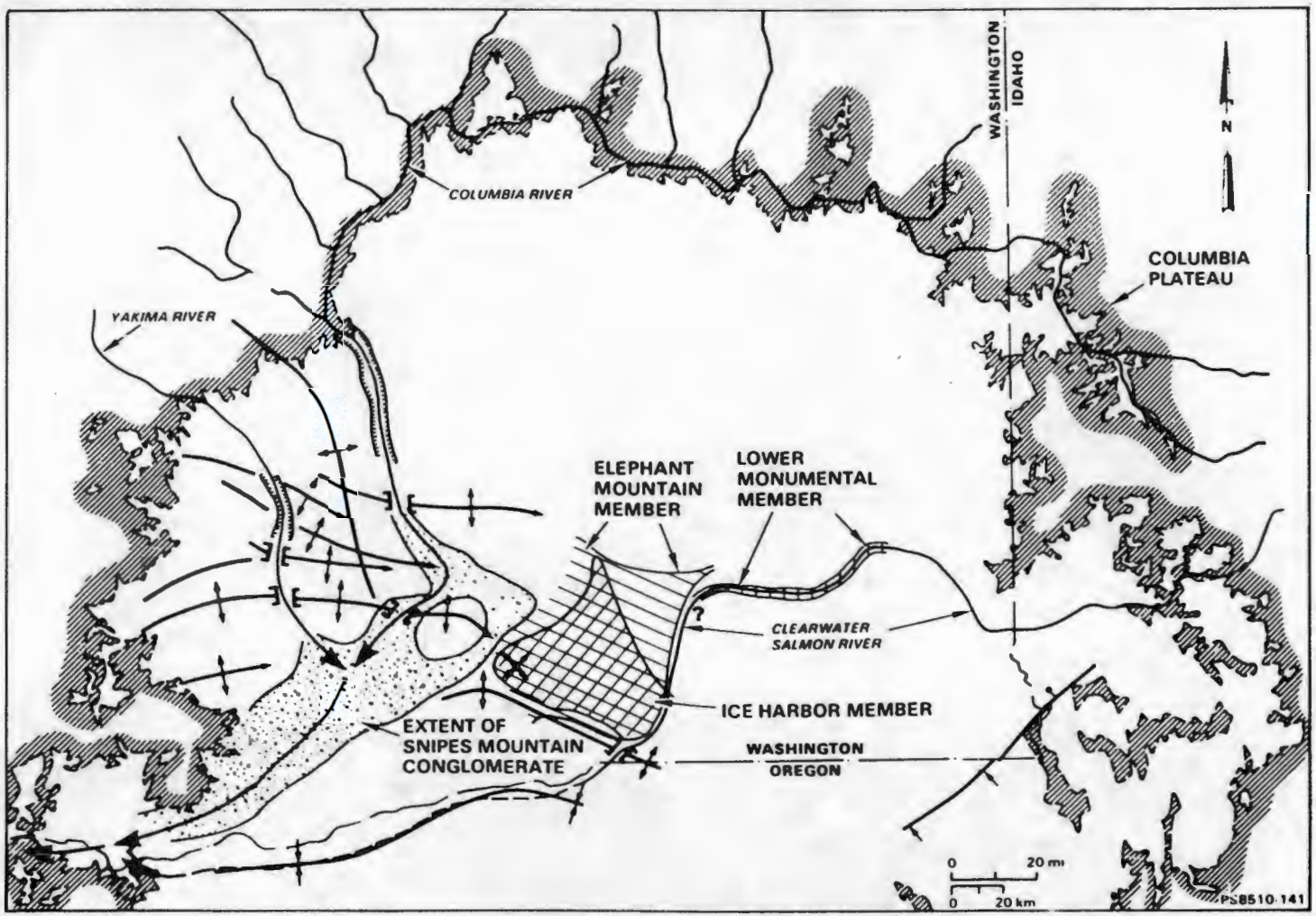

Figure 11. Stream Drainage on the Northern Part of the Columbia Plateau during the Middle to Late Miocene, Post-Elephant Mountain Interval (Early Snipes Mountain). Only the central portion of the Elephant Mountain Member is shown. (See figure 1, sheet 2 for symbol legend.)

LATE MIOCENE TO MIDDLE PLIOCENE

The ancestral Clearwater-Salmon River apparently continued to flow through Wallula Gap during the late Miocene to middle Pliocene (fig. 12), although sediments indicative of an ancestral Clearwater-Salmon River course have not been found west of the Palouse Slope. The composition of gravel clasts indicative of the ancestral Clearwater-Salmon River are rarely found in the Snipes Mountain conglomerate. The absence of the clasts in the Snipes Mountain conglomerate suggests that the course of the ancestral Clearwater-Salmon River was probably maintained across the southeastern Pasco Basin through Wallula Gap. The course was probably controlled by the constructional topography built by the Ice Harbor Member (Myers/Price et al. 1979; Gardner et al. 1981).

The course of the ancestral Columbia River was restricted to the structural lows of the Pasco Basin and lower Yakima Valley and was controlled by the structural topography of rising ridges and constructional topography of the Ice Harbor Member. The southwesterly course of the ancestral Columbia River across the Yakima Ridge and Rattlesnake Hills was apparently diverted by combined uplift of these ridges and subsidence of the Pasco Basin. Compared to the post-Elephant Mountain interval (see fig. 11), the new course of the ancestral Columbia River was shifted eastward around the east end of Umtanum Ridge and into the central Pasco Basin (see fig. 12). Extensive gravel deposits that overlie the Elephant Mountain Member have been encountered in drill holes in the central Pasco Basin (Fecht and Lillie 1982) and mark the course of the river in the central basin. These gravels are over 30 m thick (Brown and Brown 1961; Routson and Fecht 1979) and are lithologically similar to gravels found along the former course of the ancestral Columbia River over the Yakima Ridge and the Rattlesnake Hills. These gravels form the basal Ringold unit (Routson and Fecht 1979; Tallman et al. 1979; Myers/Price et al. 1979) and mark the beginning of deposition of the Ringold Formation in the Pasco Basin.

Within the central Pasco Basin, the basal Ringold gravels essentially terminate north of the Ice Harbor Member margin (see fig. 12). In the southern Pasco Basin, the basal Ringold gravels are only locally present and attain a maximum known thickness of ~2 m (Brown 1979). The basal Ringold gravels have been considered to be, in part, equivalent to the Levey interbed of the Ellensburg Formation that lies beneath the Ice Harbor Member (Brown and Brown 1961). The Levey consists of the arkosic sandstones and mudstones that do not coarsen near the margin of the Ice Harbor flows. The basal Ringold gravels are probably not a lateral equivalent to the Levey interbed, but were deposited after emplacement of the Ice Harbor Member. The age of the basal Ringold gravels must be less than the age of the Ice Harbor Member, which has been dated at 8.5 m.y. (McKee et al. 1977) and which also marks the general end of Columbia River basalt volcanism.

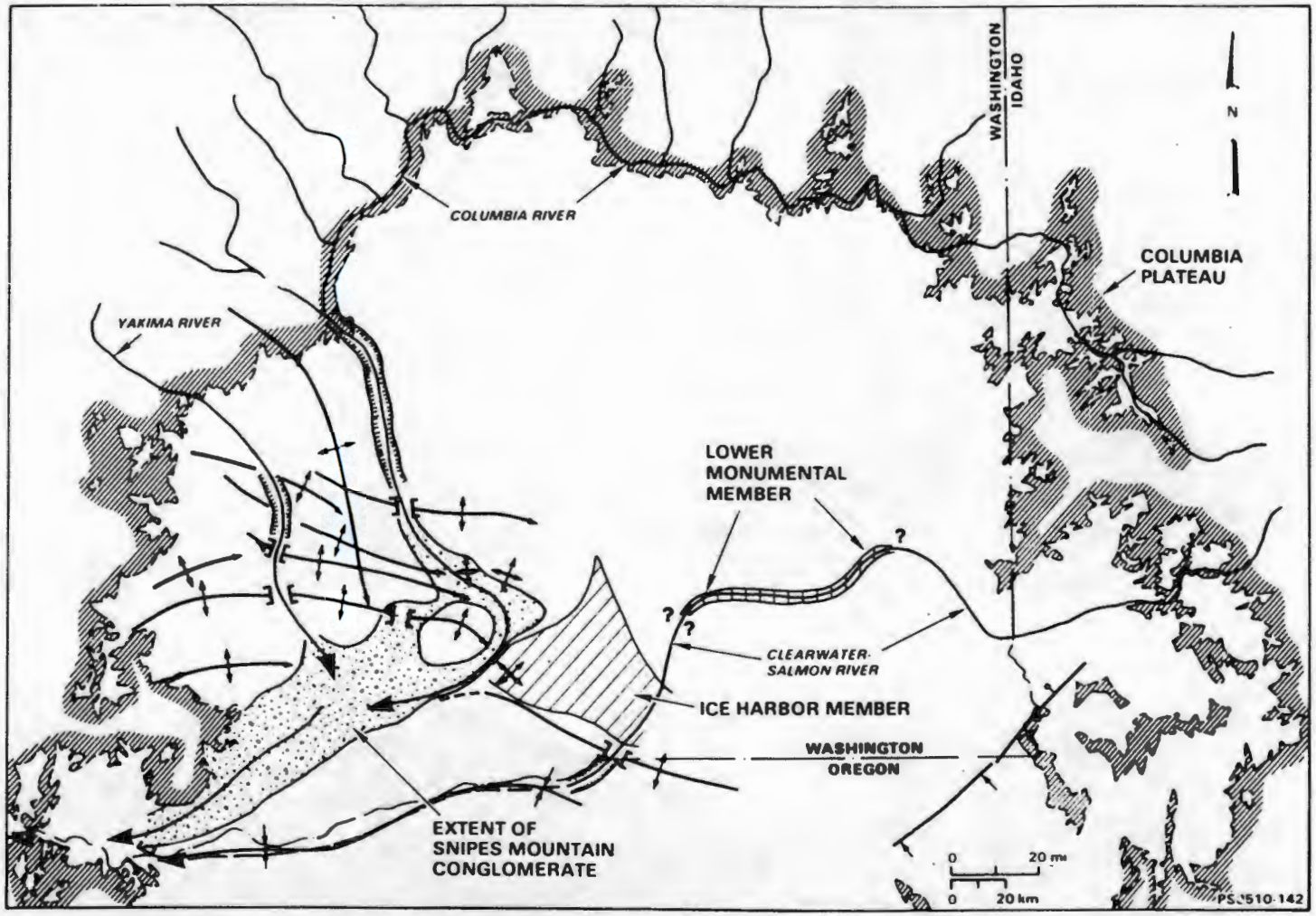

Figure 12. Stream Drainage on the Northern Part of the Columbia Plateau during the Late Miocene to Middle Pliocene, Late Snipes Mountain Time (Basal Ringold Time). (See figure 1, sheet 2 for symbol legend.)

The course of the ancestral Columbia River southward from the central Pasco Basin is defined by a series of thin remnant gravel deposits exposed on the southeastern slope of Rattlesnake Mountain and on the north flank of the Horse Heaven Hills near Prosser. These gravels overlie the Elephant Mountain Member and are lithologically similar to the "quartzitic" gravels on nearby ridges and in the central Pasco Basin. Based on the trend and similarity in composition of these gravel deposits, the ancestral Columbia River is interpreted to have flowed from the central Pasco Basin southwest into the lower Yakima Valley (Brown 1966; Fecht et al. 1982) (see fig. 12).

In the lower Yakima Valley, the ancestral Columbia River joined the ancestral Yakima River in the same approximate location as during the post-Elephant Mountain interval, which was between Sunnyside and the east end of Toppenish Ridge (see fig. 12). The combined course of the ancestral Columbia-Yakima River to the Columbia River Gorge area was similar to that of the previous interval (see fig. 11).

The shift of the Columbia River to a course flowing through the Horse Heaven Hills at Wallula Gap has long been debated by geologists. Warren (1941) thought that uplift of the Horse Heaven Hills defeated the former course of the Columbia and Yakima Rivers and that the courses of the rivers shifted eastward to a lower path across the ridge at Wallula Gap. Waters (1955) argued that the Columbia River was defeated by accelerated deposition of volcaniclastic sediments from eastward-flowing streams draining the Cascade Range that forced the ancestral Columbia River to the east. Schmincke (1964) observed that "quartzite-bearing" gravels stratigraphically overlie the volcaniclastic sediments and therefore, volcanic debris could not have diverted the ancestral Columbia River eastward. Waters (1955) observed flows of olivine-rich basalt of the Simcoe lavas erupting in the area of the Simcoe Mountains (see fig. 1), that had filled former stream valleys and eroded into the Columbia River basalts and the Ellensburg Formation. The presence of the widespread gravels of the Snipes Mountain conglomerate over the Horse Heaven Hills and the absence of a canyon that was typical of earlier river channels suggests that channel incision by the ancestral Columbia-Yakima River across the Horse Heaven Hills was interrupted. Whether the Simcoe lavas repeatedly blocked the Columbia-Yakima River drainage across the Horse Heaven Hills and forced a more easterly course needs further study. However, we have evidence to propose that continued subsidence of the central Columbia Plateau centered in the Pasco Basin and uplift of the Yakima folds, specifically the Horse Heaven Hills, were important components in the diversion of the Columbia River. Field mapping and borehole studies have demonstrated continued subsidence of the central Columbia Plateau since at least the early Miocene to about the middle Pliocene (Routson and Fecht 1979; Myers/Price et al. 1979; Reidel et al. 1980; Reidel and Fecht 1981; Tallman et al. 1981; PSPL 1982). Once the ancestral Columbia River overcame the constructional topography of the Ice Harbor Member, it apparently flowed southeast in the trough of the Pasco syncline of Newcomb et al. (1972). South of Pasco, the river was captured by the ancestral Clearwater-Salmon River channel. The Yakima River was also diverted from a southwesterly course across the Horse Heaven Hills to a southeasterly course down the lower Yakima Valley and into the Pasco Basin

through Badger Coulee (fig. 13). The diversion of the Yakima River occurred at about the same time as the Columbia River, based on the absence of sediments consisting of distinctly volcaniclastic material in the area where the former combined Columbia-Yakima River crossed the Horse Heaven Hills.

Following the capture of the Columbia and Yakima Rivers, the rivers on the plateau continued to aggrade sediments in the developing synclinal troughs and basins and to scour ever-deepening gorges through rising basaltic ridges. Deposition of sediments in structural basins continued on the plateau until about the middle Pliocene. The continued aggradation of the sedimentary sequences is due to a high relative base level that resulted from (1) the absence of Columbia River basalt volcanism that formed constructional topography on the plateau except in the area of the Clearwater Embayment (Swanson et al. 1979a; Camp 1981), (2) continued subsidence and folding of the plateau (Caggiano and Duncan, 1983), (3) uplift of the Cascade Range, and (4) possibly volcanism in the Columbia River Gorge area that repeatedly choked the Columbia River with hyaloclastic debris and lava flows (Tolan and Beeson 1984).

In the western Columbia Plateau the Yakima River and its tributaries deposited the Pliocene Thorp Gravel of Waitt (1979) that unconformably overlies the Ellensburg Formation in the Kittitas Basin. South into the Toppenish and Satus Basins, the Yakima River and its tributaries deposited sediments similar to those in the Kittitas Basin. Here the volcanic sediments of the Ellensburg Formation are unconformably overlain by these gravel deposits, which formed fluvial terraces and fans along the basin margins. These gravels may be equivalent to the Thorp Gravel (Bentley 1977; Rigby et al. 1979; Campbell 1983).

In the eastern Columbia Plateau, the ancestral Clearwater and Salmon Rivers deposited the North Lewiston Gravel, Clearwater Gravels, Clarkston Heights Gravel, and perhaps the Clarkston Gravels in the Lewiston Basin (Kuhns 1980; Waggoner 1981). On the Palouse Slope the ancestral Clearwater-Salmon River deposited gravels that are found below the Lower Monumental Member of the Saddle Mountains Basalt (see fig. 12). The Walla Walla River and its tributaries deposited an "old gravel and clay" unit with gravel clasts derived from Columbia River basalt (Newcomb 1965). The "old gravel and clay" unit is up to ~180 m thick in the Walla Walla Basin.

In the central plateau, the most extensive fluvial deposit of late Miocene to middle Pliocene age is the Ringold Formation (Merriam and Buwalda 1917). The Columbia River and its tributaries from the Palouse Slope deposited mainly fine sands, silts, and clays up to 165 m thick in the Quincy Basin (Grolier and Bingham 1971, 1978). South into the Pasco Basin the Columbia, ancestral Clearwater-Salmon, and Yakima Rivers deposited up to 360 m of Ringold sediments. The sediments are composed of gravel, sand, silt, and clay that can be informally subdivided into four or more units based on texture (Newcomb et al. 1972; Brown 1979; Tallman et al. 1979; PSPL 1982). The upper Ringold unit, exposed at the White Bluffs in the northeast Pasco Basin, is composed of mainly fine sands and silts that contain microtine rodent fossils 3.7 to 4.8 million years old. These ages are consistent

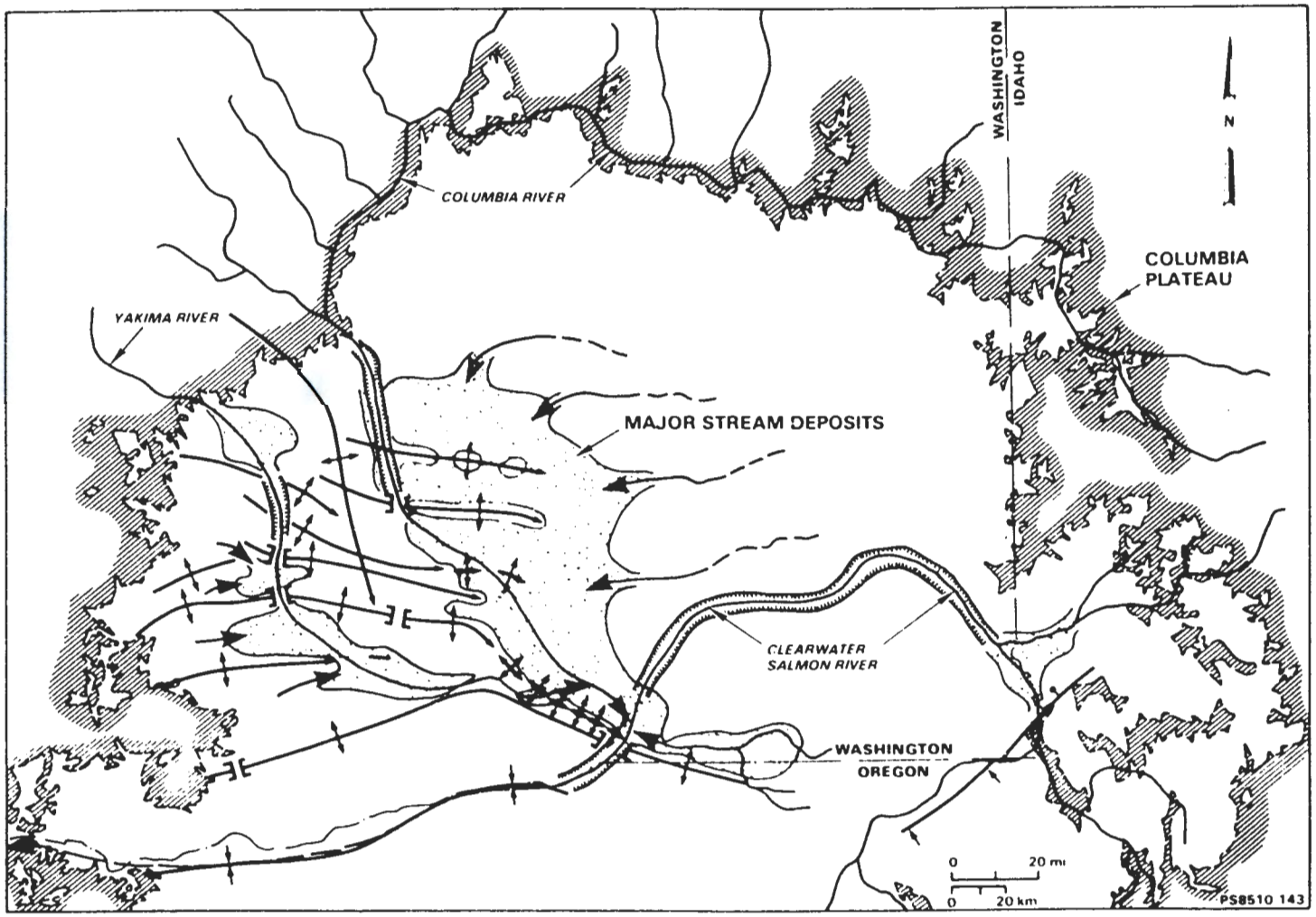

Figure 13. Stream Drainage on the Northern Part of the Columbia Plateau during the Late Miocene to Middle Pliocene, Post-Snipes Mountain Time. (See figure 1, sheet 2 for symbol legend.)

with a long period of reversed magnetic polarity believed to correspond to the Gilbert Magnetic Polarity Epoch (3.4 to 5.12 m.y.B.P.) (LaBrecque et al. 1977; Mankinen and Dalrymple 1979). A rhinocerus belonging to the Hemphillian (>4.8 m.y.B.P.) was identified by Gustafson (1978) in the underlying middle Ringold conglomerate. The basal Ringold gravel, previously discussed, is interpreted to be post-Ice Harbor age (8.5 m.y.B.P.). Thus, the Ringold Formation is concluded to be between ~3.4 and 8.5 million years old.

The age of the other aforementioned sedimentary deposits of the late Miocene to middle Pliocene interval is, in part, time equivalent to the Ringold, based on dates and stratigraphic position (Tallman et al. 1982). The Thorp Gravel in the Kittitas Valley has been dated at 3.64 ± 0.74 and 3.70 ± 0.20 m.y. old (Waitt 1979). Bentley (1977) and Campbell (1983) have interpreted the old gravel deposits in the Yakima Valley to be equivalent to the Thorp Gravel of the Kittitas Basin. The ages of the gravels in the Lewiston Basin and on the Palouse Slope are, in part, constrained by the Lower Monumental Member that is dated at 6.0 m.y. in age (McKee et al. 1977). Therefore, the gravels are, in part, time equivalent to the Ringold Formation (Webster et al. 1984). Finally the "old gravel and clay" unit in the Walla Walla Basin has been interpreted by Newcomb (1965) to be, in part, equivalent to the Ringold Formation.

MIDDLE TO LATE PLIOCENE

The deposition of Ringold sediments in the Pasco Basin ended rather abruptly, based on the major incision of the Ringold Formation by the Columbia River system, the preservation of a largely unmarred Ringold surface in the eastern and northern basin, and the absence of post-Ringold deposition over the top of this Ringold surface (Newcomb 1958). The age of the incision is dated between 2.0 ± 0.22 to 3.4 m.y. The younger age is based on a single thermoluminescent date from the calcrete that caps the Ringold surface on the White Bluffs.

The Thorp and Thorp-like gravels of the western plateau also were deeply incised, based on the remnants of terraces and fans resting high above the Pleistocene and present-day Kittitas and Yakima Valley floors. The gravel deposits in the Lewiston Basin also occur above the present-day basin floor. It is suspected that the timing of incision of Ringold, Thorp, Thorp-like sediments, and possibly the gravel deposits in the Lewiston Basin is related mainly due to the similar magnitude of the incisions and also that by the middle-to-late Pliocene, the Columbia River system in Washington State was well integrated.

The cause of the baselevel change that precipitated these major incisions has been speculated on by earlier workers. Flint (1938a) and Newcomb (1958) suggested that waters of the Columbia River were impounded or perhaps periodically impounded behind the rising Horse Heaven Hills and eventually spilled over and incised a path through the structural and topographic low

at Wallula Gap. However, geologic mapping in the Wallula Gap area by Gardner et al. (1981) indicates a relatively slow and continuous rate of uplift of the Horse Heaven Hills since at least middle Miocene time. This rate is consistent with uplift rates in the Rattlesnake Hills and Saddle Mountains (Reidel and Fecht 1981). In addition, there are stratified (i.e., fluvial) sands and silts in the upper Ringold unit of the Pasco Basin that are intercalated with lacustrine facies, which rule out a totally lacustrine origin for the upper unit. It is believed that the Columbia, Clearwater-Salmon, and Yakima Rivers were flowing through Wallula Gap essentially continuously with some temporary ponding since river capture in the late Miocene. Therefore, the cause(s) for the major regional baselevel change must have occurred downstream from Wallula Gap.

Recent work by Tolan and Beeson (1984) in the Columbia River Gorge has demonstrated that the course of the ancestral Columbia River, which is defined based on the occurrence of the canyon-filling Pomona Member and sedimentary lithology of the Troutdale Formation, was continually being inundated by large volumes of high alumina basalts and volcanic debris from the Cascades, which aggraded the Columbia River canyon and forced the Columbia River to a more northerly course through the Cascade Range. The new course of the Columbia River was established in about its present-day position near where the Columbia River basalts lap out against old rocks of the Skamania Volcanic Series as defined by Trimble (1963). The Columbia River eroded a new channel through the Columbia River Basalt Group and rapidly incised into the weathered and altered Skamania Volcanics (Tolan and Beeson 1984). Erosion of the new channel is estimated to have started about two million years ago with the onset of Cascadian uplift (Tolan and Beeson 1984). The entrenchment of the Columbia River is speculated to have caused a lowering of the baselevel and initiated headward erosion upstream into the Columbia Plateau. Although speculative, the geologic events and the apparent timing of the events in the Columbia River Gorge appear to explain the major regional depositional and erosional events on the Columbia Plateau of Washington State in middle-to-late Pliocene time.

By the late Pliocene, the Columbia and Yakima Rivers were established in very near their present positions. Also, in the late Pliocene or early Pleistocene, the Snake River was captured by a tributary of the Salmon River to become a part of the Columbia River system (Wheeler and Cook 1954; Webster et al. 1984). This capture completed the final major shift in the paleodrainage of major streams in the Columbia River system.

PLEISTOCENE

During the Pleistocene epoch, continental glaciers repeatedly advanced and retreated from British Columbia into northern Washington and occasionally impinged on the northern Columbia Plateau (fig. 14). Along the glacier margins, ice temporarily plugged drainages, diverting the Columbia River to more southerly courses and impounding meltwaters in glacial lakes. Plugging and diversion of streams caused by glaciation had minimal and temporary effects on the drainage system in the Kittitas Valley, Waterville Plateau, and Columbia Valley. However, failure of ice dams impounding glacial lakes,

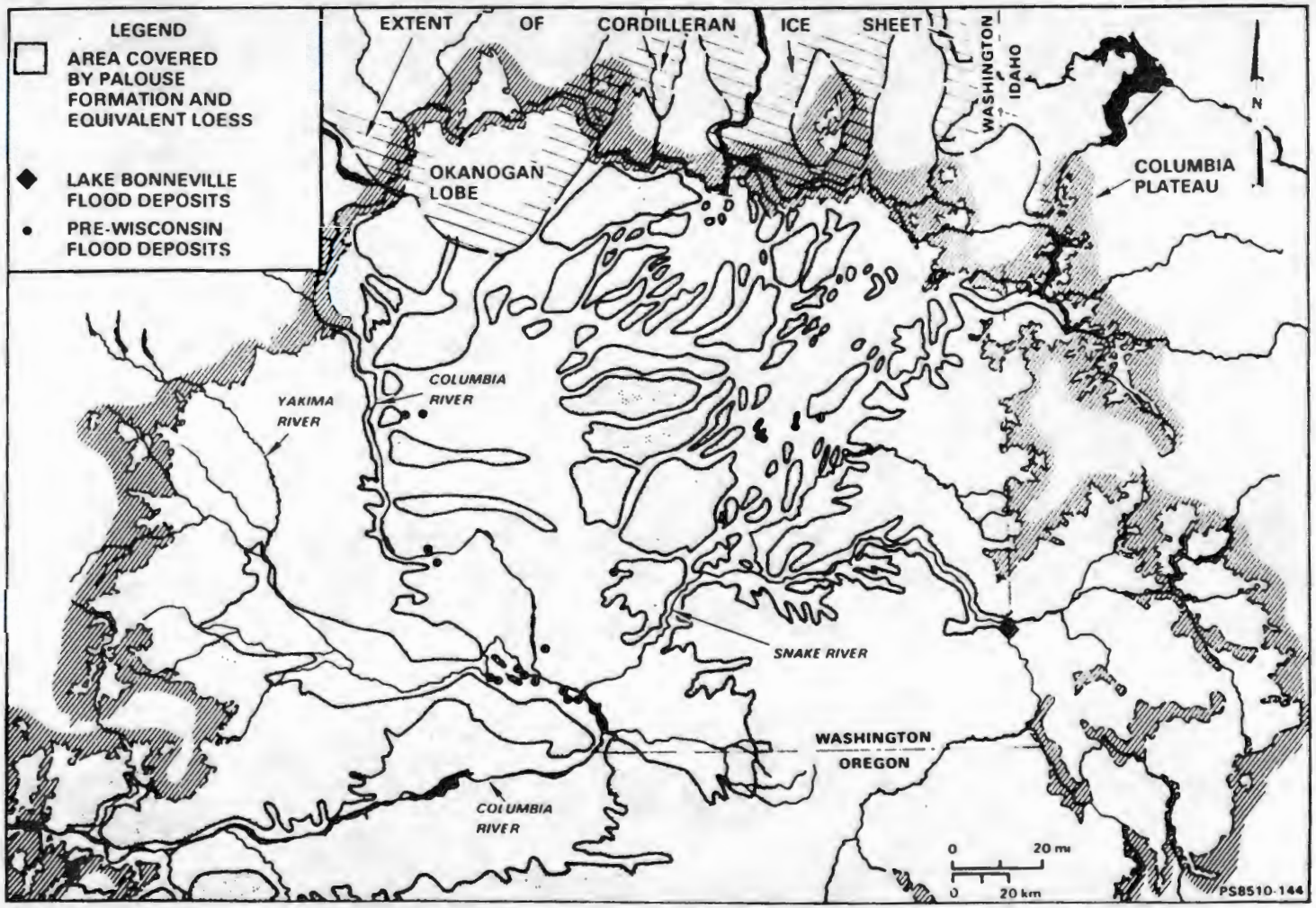

Figure 14. Stream Drainage on the Northern Part of the Columbia Plateau during the Pleistocene. (Compiled after Bretz 1928; Baker and Nummedal 1978; Richmond et al. 1965; and observations of the authors.)

particularly Glacial Lake Missoula, released tremendous volumes of meltwater that catastrophically flooded major portions of the Columbia Plateau of Washington State. The major floods obliterated much of the secondary drainage system of the Palouse Slope and caused minor changes in the course of the Columbia and Yakima Rivers in the Pasco Basin.

In the Kittitas Basin, till and outwash accumulated during three Cascadian alpine glacial events, which are defined as the Lookout Mountain Ranch Drift (pre-Kittitas Drift in age), Kittitas Drift (~130,000 to 140,000 yr in age), and the Lakedale Drift (~10,000 to 20,000 yr in age) (Porter 1976; Waitt 1979). Glaciation in the upper Kittitas Valley and deposition of outwash into the central Kittitas Valley had little effect on the course of the Yakima River on the Columbia Plateau during the Pleistocene.

In the north-central Columbia Plateau, the Okanogan Lobe of the Cordilleran Ice Sheet (see fig. 14) encroached onto the Waterville Plateau (Salisbury 1901; Waters 1933; Flint 1935). The Okanogan Lobe periodically impounded the Columbia River in the Columbia Valley to form temporary lakes (Glacial Lake Columbia) and resulted in the diversion of the Columbia River to a more southerly course through a series of coulees south and east of the Waterville Plateau (Bretz 1923; Hanson 1970). The diversion of the Columbia River was temporary and upon retreat of the Okanogan Lobe north of the Columbia Plateau, the Columbia River reestablished its course along the northern margin of the plateau in its previous channel.

The most significant change to the drainage system on the Columbia Plateau during the Pleistocene resulted from catastrophic floods that emanated from glacial lakes. Failure of ice dams that impounded glacial lakes released large volumes of meltwaters, which flowed across the Palouse Slope and into the central Columbia Plateau. Fluvial erosion associated with the flooding created a spectacular landscape of anastomosing channels, immense cataracts, and deep plunge pools of the Channeled Scabland (Bretz 1923). The flooding also created immense gravel bars in areas marginal to the channels, and deposited thick sequences of glaciofluvial deposits in the basins and major valleys of the Columbia Plateau (see fig. 14) with the exception of the Kittitas Valley.

At least four major catastrophic flooding events have been recorded on the Columbia Plateau: two pre-Wisconsinan events and two Wisconsinan events. Three of the events may include one or more floods. The flooding events have been analyzed using paleomagnetic measurements from fine-grained flood material or capping loess horizons, uranium/thorium radiometric age data from superimposed calcic horizons, and tephra data.

The oldest known catastrophic flooding event occurred prior to 730,000 years ago, based on the reversed magnetic polarity associated with flood deposits at two localities. The first locality is the Marengo site (Patton and Baker 1978) located in the Cheney-Palouse scabland tract. At Marengo, the flood gravels are overlain by a loess that has a measured reversed magnetic polarity (Van Alstine 1982). The flood gravels are

believed to predate the last reversal in magnetic polarity (Matayama Epoch), which ended ~730,000 yr B.P. (Mankinen and Dalrymple 1979). The second locality is along the Yakima Bluffs in the lower reaches of the Yakima River ~9.5 km upstream from the confluence with the Columbia River (see fig. 1). Exposed in the Yakima Bluffs is a rhythmic series of turbidite-like deposits resembling late-Wisconsin Touchet Beds (Flint 1938b) that are underlain by a fluvial sequence of earlier Pleistocene age. Both the "Touchet Beds" and the upper fine-grained unit of the fluvial sequence have reversed magnetic polarity, indicating an age of >730,000 yr. The Marengo and Yakima Bluffs are the only two early flood sites that have an established magnetostratigraphy. Other old flood deposits at Revere, McCall, and Old Maid Coulee in the Cheney-Palouse scabland tract are tentatively included in the early flooding event, based on the correlations of Patton and Baker (1978). The old flood deposits at George and Winchester Wasteway in the western Quincy Basin are also included in this early flooding event, based primarily on the weathered clasts and the superimposed petrocalcic paleosol that caps the flood gravels at both localities. The distribution of old flood gravels suggests that the early flooding event initiated the formation of the Channeled Scabland, but apparently had little effect on the course of major streams during glacial periods.

The second major flooding event includes a series of gravel deposits that are commonly capped by a superimposed calcic paleosol. Two samples of calcic paleosol have been radiometrically (uranium/thorium) dated at 200^{+250}_{-700} thousand and 220^{+380}_{-70} thousand years old (Tallman et al. 1978). Fine-grained silty sand lenses interbedded in the gravel characteristically have a normal magnetic polarity that corresponds to an age of <730,000 yr. The age of the second flooding event is interpreted to be between ~200,000 and 730,000 yr before present. The best exposures of deposits from the second major flooding event occur in the southern Pasco Basin where the gravels form a terrace that unconformably overlies the Ringold Formation. Gravels of this flooding event are also exposed in the northern and eastern portions of the Pasco Basin (see fig. 14).

It is in the Pasco Basin, during the first or second major flooding event, that Pleistocene flooding has had the most pronounced effect on major stream courses on the Columbia Plateau. The Yakima River apparently abandoned its course through Badger Coulee in the southern Pasco Basin to its present course after the Coulee was plugged with a 30-m-thick sequence of flood gravels. A flood origin for these gravels differs from the interpretation of Bunker (1980) who believed the gravels to represent the combined course of the Columbia and Yakima Rivers through Badger Coulee. The gravels are interpreted to be flood deposits, based on the presence of large-scale foreset beds and abundance of many subangular clasts of basalt mixed with a variety of exotic lithologies found in recently excavated gravel pits. Also during one of these flooding events, the Columbia River channel that had been established between Gable Mountain and Gable Butte, east of Umtanum Ridge appears to have been diverted around the east end of Gable Mountain to near its present-day course. The pre-flood river channel is plugged by a large flood bar formed south of Gable Mountain and Gable Butte.

A breach along the northern shoreline of Lake Bonneville at Red Rock Pass near Preston, Idaho, resulted in torrential waters flooding down the Snake River and onto the Columbia Plateau (Malde 1968; Swanson 1984). This was the third major flooding event on the Columbia Plateau. The flood, which occurred ~14,000 to 15,000 yr ago (Scott 1983), must have resulted in the flooding of river courses to the Pacific Ocean. However, sedimentary deposits formed during the Lake Bonneville flood are only known to occur along the southeastern margin of the Columbia Plateau. In the Lewiston Basin, flood debris formed various bars marginal to the present-day Snake River. The Lake Bonneville flood apparently had little, if any, impact on stream courses in the Lewiston Basin or elsewhere on the Columbia Plateau.

The last major flooding event is the classic late-Wisconsin flood or Lake Missoula flood of Bretz (1923) that innundated much of the Columbia Plateau of Washington State (see fig. 14). The flooding resulted in the latest scouring of the Channeled Scabland and widespread deposition of glaciofluvial sediments on the Columbia Plateau (see Bretz 1923; Bretz et al. 1956; Baker 1973; Baker and Nummedal 1978; Waitt 1980). The age of the last major flooding event is ~12,000 yr, based on the occurrence of Mount St. Helens Set "S" ash found within the upper part of the late Wisconsin flood sediments (Mullineaux et al. 1978).

The three proglacial catastrophic flood events referred to here may represent one great flood in each event as Bretz (1923) proposed for the late-Wisconsin flooding or multiple floods as demonstrated by Waitt (1980) for late-Wisconsin flooding. However, flood events and associated glaciation resulted in only temporary or minor changes to major streams on the Columbia Plateau. Catastrophic flooding (except from Lake Bonneville) created the Channeled Scabland and destroyed the pre-Pleistocene secondary drainage network on the Palouse Slope. The Pleistocene events resulted in the latest major sculpturing of the plateau landscape, and essentially the final positioning of major stream courses, with only minor local shifts occurring during the Holocene.

SUMMARY

The evolution of the Columbia River drainage system on the Columbia Plateau of Washington in the last 17 m.y. reflects the geologic history of the plateau. We have updated an interpretation of the evolution of the Columbia River system and defined the geomorphic and structural features that have controlled the position of ancestral streams. The sequence of geologic events and the resulting drainage system for various time intervals in the last 17 m.y. are summarized below.

EARLY TO MIDDLE MIOCENE

Grande Ronde Basalt was repeatedly erupted from fissures in the eastern Columbia Plateau during the most frequent and voluminous episode of Columbia River basalt volcanism. The flood basalts flowing westward down the Palouse Slope inundated the intermontane basin between the Rocky Mountains and the ancestral Cascade Range. Evidence of major streams was located mainly near the margins of the plateau where major streams flowed between the constructional topography built by the accumulation of basalt flows and the surrounding highlands of pre-Columbia River basalt age. Major streams were flowing westward around the margins of the plateau before joining to flow through the ancestral Cascade Range through an area south of the present-day Columbia River Gorge. Because of repeated basaltic volcanism, integrated drainage did not have a chance to develop in the central plateau before succeeding flows covered the area. Drainage in the central plateau was poorly integrated with only minor evidence of small local streams and shallow freshwater lakes, marshes, and bogs.

MIDDLE MIOCENE

The beginning of the middle Miocene is marked by a short time interval of volcanic quiescence over much of the Columbia Plateau, represented by the Vantage interbed. During this interval, continued uplift of Naneum Ridge diverted the ancestral Columbia River to the east near the north-central part of the vast basaltic plain. The diversion of the Columbia River lead to the development of an ancestral Yakima River in the northwest plateau. Renewed Columbia River basalt volcanism resulted in the eruption of Wanapum Basalt that again inundated the Columbia Plateau. Stream drainage during this volcanic episode was similar to that of early Miocene time with major streams confined to the perimeter of the plateau and local streams, lakes, marshes, and bogs in the central plateau area.

MIDDLE TO LATE MIOCENE

Columbia River basalt volcanism continued to wane during the middle to late Miocene with only periodic eruptions of Saddle Mountains Basalt. Subsidence of the central plateau and continuing deformation of portions of the plateau formed topographic features that were not being continuously inundated by basalt flows as during the Grande Ronde and Wanapum volcanic episodes. Saddle Mountains Basalt was erupted from fissures in the eastern plateau, primarily in the Clearwater Embayment, and flowed down ancestral Clearwater-Salmon River canyons. The intracanyon flows define the drainage channels of ancestral streams. The intracanyon flows, in conjunction with gravel trains within the Ellensburg Formation, are used to reconstruct the paleodrainage system in the southern part of the Columbia Plateau of Washington. The ancestral Columbia, Clearwater-Salmon, and Yakima Rivers were controlled by structural relief developing on the plateau and around the constructional topography built by emplacement of flows that spread laterally in the central Columbia Plateau. The ancestral Columbia River

flowing south down the Columbia Slope and the ancestral Clearwater-Salmon flowing westward down the Palouse Slope joined in the central plateau to flow southwestward to the present-day Columbia River Gorge area. The ancestral Yakima River joined the combined Columbia and Clearwater-Salmon in the developing Yakima Valley. Late in the Saddle Mountains volcanic episode, the ancestral Clearwater-Salmon River was diverted into the southern Pasco Basin and through the Horse Heaven Hills at Wallula Gap.

LATE MIOCENE TO MIDDLE PLIOCENE

Columbia River basalt volcanism had essentially ceased, but continued tectonic deformation of portions of the basaltic plain resulted in the development of prominent structural ridges and lows. The major streams flowed within the structural basins and synclinal valleys and in water gaps through structural ridges. Near the beginning of this interval, the ancestral Columbia and Yakima Rivers were captured by the ancestral Clearwater-Salmon River channel to establish the entire Columbia River system through the Horse Heaven Hills at Wallula Gap. The capture may have been the result of plugging of the combined ancestral Columbia and Yakima river channel by the eruption of Simcoe Volcanics in the Goldendale area, and/or continued subsidence of the Pasco Basin and aggradation of a sufficient thickness of sediments to overcome the constructional topography built by emplacement of the Ice Harbor Member. Following the river capture, the ancestral rivers aggraded sediments in the basins of the Columbia Plateau until the middle Pliocene.

MIDDLE TO LATE PLIOCENE

About middle Pliocene time, aggradation of sediments in the structural lows of the central Columbia Plateau ended rather abruptly and the rivers started a period of downcutting. The history of aggradation and erosion of sediments has been previously explained by deformation along the Horse Heaven Hills. However, the slow rate of deformation of the Horse Heaven Hills apparently allowed the Columbia River system to maintain a channel through Wallula Gap during uplift of the ridge. Since deformation along the Horse Heaven Hills appears to explain only a part of a major regional baselevel change observed throughout the plateau, another hypothesis is proposed. As proposed by Tolan and Beeson (1984), the ancestral channel of the Columbia River in the Cascade Range was inundated by high alumina basalts and volcanic debris from the Cascade Range that resulted in a higher base level and regional aggradation of sediments in the Columbia Plateau. This led to the Columbia River establishing a new channel in its present-day position ~2 m.y ago. The incision in the Columbia River Gorge, resulted in a lower base level and incision into sedimentary deposits in the Columbia Plateau. Also, ~2 million years ago, the Snake River that flowed south of the Columbia Plateau was captured to become part of the Columbia River system. The capture essentially linked the final segment into the Columbia River system.

PLEISTOCENE

Glaciation that impinged on the northern Columbia Plateau and catastrophic flooding that resulted from the failure of ice marginal lakes caused only temporary or minor changes to the major rivers on the Columbia Plateau. At least four flooding events resulted in the last major sculpturing of the plateau and essentially the final positioning of major stream courses. Only minor local adjustments in the major streams in topographic lows have occurred during the Holocene.

ACKNOWLEDGMENTS

We are grateful to B. N. Bjornstad, J. A. Caggiano, and T. L. Tolan for critically reviewing earlier revisions of this manuscript. We greatly appreciate discussions with N. P. Campbell, from Yakima Valley College, Yakima, Washington, who contributed to our basic understanding of paleodrainage in the western Columbia Plateau.

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