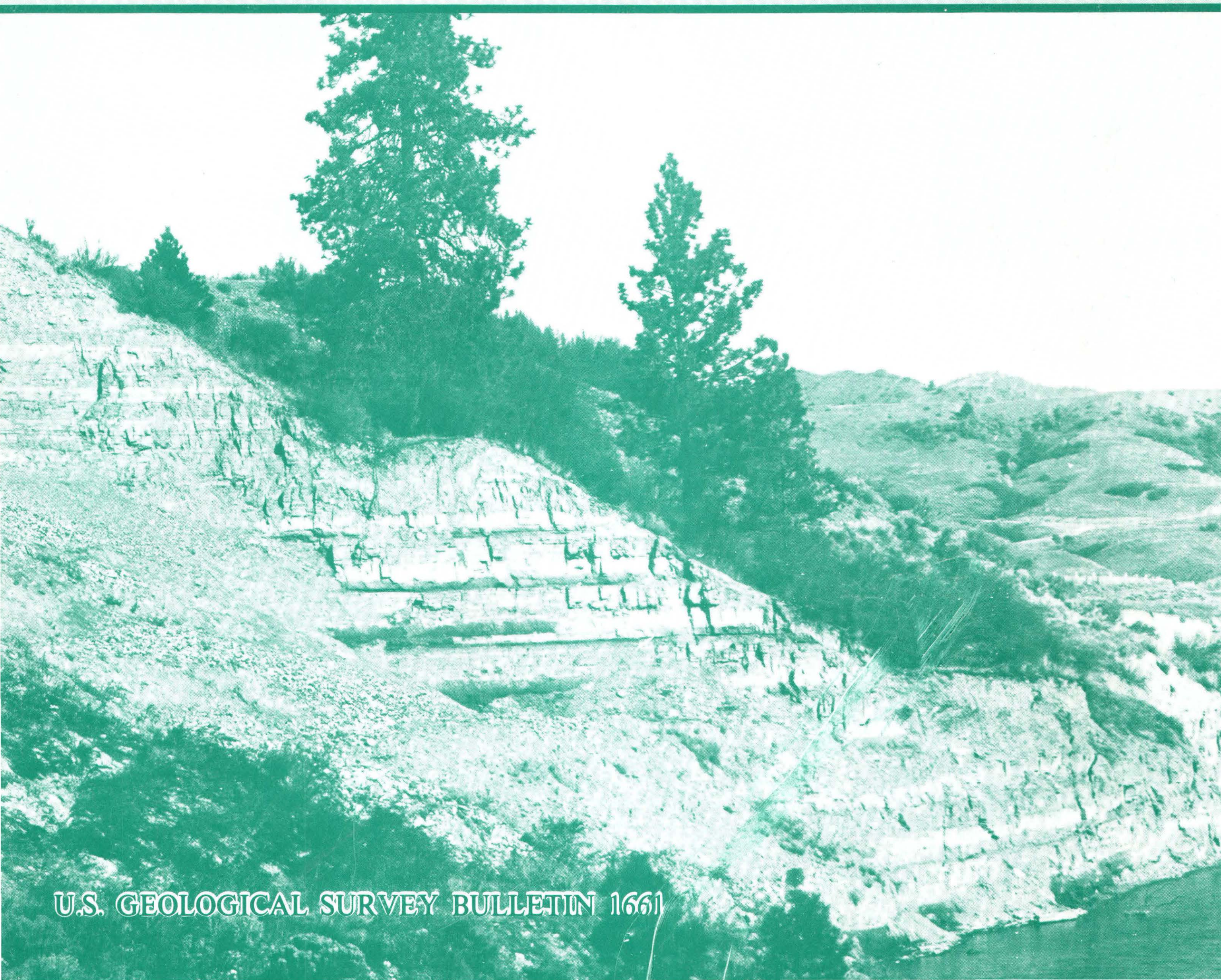
# Pleistocene Glacial-Lake Deposits of the Sanpoil River Valley, Northeastern Washington

Prepared in cooperation with the Colville Confederated Tribes, the U.S. Bureau of Reclamation, and the Bureau of Indian Affairs



U.S. GEOLOGICAL SURVEY BULLETIN 1661

**PLEISTOCENE GLACIAL-LAKE DEPOSITS OF THE SANPOIL RIVER VALLEY, NORTHEASTERN WASHINGTON**


Satellite mosaic shows Sanpoil River valley in relation to paths of floods from glacial Lake Missoula, Montana. Unstably dammed by the Purcell Trench lobe of the Cordilleran ice sheet, Lake Missoula issued about 100 floods during the last (late Wisconsin) glaciation. At least 89 of these floods found the Columbia River valley blocked by the Okanogan lobe; they flowed into glacial Lake Columbia, which usually had an arm in the Sanpoil River valley. Some floods were so large that they probably engulfed Lake Columbia and coursed all major scabland tracts to the south; others may have raised Lake Columbia too little for it to spill through any major scabland except the Grand Coulee, which was Lake Columbia's usual outlet during the last glaciation. Several floods encountered a Lake Columbia that was already swollen from blockage of the Grand Coulee by a maximally advanced Okanogan lobe; several others skirted a maximally advanced Columbia River lobe near the mouth of the Spokane River. Missoula-flood outflow from Lake Columbia discharged into the Columbia River valley between Quincy Basin and Wallula Gap, in southern Washington. ERTS–1 image, 1972; field of view about 350 km wide.

# Pleistocene Glacial-Lake Deposits of the Sanpoil River Valley, Northeastern Washington

By BRIAN F. ATWATER

Prepared in cooperation with the Colville Confederated Tribes,
the U.S. Bureau of Reclamation, and the Bureau of Indian Affairs

A study of rhythmic strata
and their implications
for glacial Lake Missoula,
the Cordilleran ice sheet,
and the Grand Coulee

U.S. GEOLOGICAL SURVEY BULLETIN 1661

DEPARTMENT OF THE INTERIOR
DONALD PAUL HODEL, Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON: 1986

For sale by the
Books and Open-File Reports Section
U.S. Geological Survey
Federal Center, Box 25425
Denver, CO 80225

**Library of Congress Cataloging-in-Publication Data**

Atwater, Brian F.
Pleistocene glacial-lake deposits of the Sanpoil
River valley, northeastern Washington.

U.S. Geological Survey Bulletin 1661
"Prepared in cooperation with the Colville Confederated
Tribes, the U.S. Bureau of Reclamation, and the Bureau of
Indian Affairs."
Bibliography
Supt. of Docs. No.: I 19.3:1661
1. Geology, stratigraphic—Pleistocene. 2. Lake
sediments—Washington (State)—Sanpoil River valley.
3. Glacial epoch—Washington (State)—Sanpoil River
valley. 4. Glacial epoch—Washington (State)—Grand
Coulee region. 5. Missoula, Lake. I. Title.
II. Series.
QE75.B9 no. 1661 557.3 s 86-600064
[QE697] [551.7'92]

# CONTENTS

TABLES

# Pleistocene Glacial-Lake Deposits of the Sanpoil River Valley, Northeastern Washington

*By* Brian F. Atwater

**Abstract**

Late Wisconsin (last-glacial) lacustrine deposits near Manila Creek, in Washington's Sanpoil River valley, alternate rhythmically between sets of varves (varved intervals) and at least 89 graded beds each attributable to a flood from glacial Lake Missoula, Montana (flood beds). The number of varves per varved interval has a broad maximum of 45–55 low in the section and parallels trends in the varved bottom sediments of Lake Missoula itself. Just 1 or 2 varves underlie the highest flood bed near Manila Creek; about 200–400 varves succeed that bed. The total number of varves in the Manila Creek section is 2,000–3,000. Flood beds show overall upsection decrease in thickness, maximum grain size, and erosiveness. These trends coincide approximately with the overall upsection decrease in varves per varved interval; in general, the magnitude of flood effects varied directly with flood frequency, as one might expect for floods from a self-dumping Lake Missoula. Chief exceptions to this rule are two sets of anomalously thin flood beds low in the section. Varves between these flood beds are about as numerous as varves between normally thick flood beds above and below each set; probably the anomalous floods were large at their source but were damped or deflected on the way to the Sanpoil River valley. Additional Lake Missoula floods may be unrecorded in the section because of erosion and nondeposition, particularly at a possible buttress unconformity at the section's base. Detrital wood in a varved interval in the middle of the section yields a $^{14}C$ age of 14,490 ± 290 yr B.P. (USGS–1860). There being no proof of major hiatus within the section, varves allow this radiocarbon control to be extended throughout the section. Resulting age estimates, used without qualification in the next paragraph, may err on the old side because the wood could be as much as 2,500 years older than the deposits containing it.

The Manila Creek section provides a proxy last-glacial history for three lobes of the Cordilleran ice sheet and for the Grand Coulee. The Purcell Trench lobe advanced far enough to dam Lake Missoula sometime before 15,550 ± 450 yr B.P., the age of the lowest flood bed in the known Manila Creek section. Between 15,200 ± 400 and 14,750 ± 375 yr B.P., the Purcell Trench lobe reached its terminus, indicated by a broad maximum in varves per varved interval; the lobe probably withdrew from Clark Fork valley at 13,350 ± 550 yr B.P., the age of the highest flood bed in the Manila Creek section. The Okanogan lobe dammed glacial Lake Columbia from 15,550 ± 450 to 13,050 ± 650 yr B.P., the age range of the known Manila Creek section, and may have been at its terminus astride the upper Grand Coulee for about 200 years near 14,800 ± 375 yr B.P, the age of the upper set of anomalously thin flood beds. The thinness and gray color of these beds are consistent with enlargement of Lake Columbia by glacial blockage of the lake's Grand Coulee outlet, and thick varves among and bracketing these beds suggest a near-terminal position for the Okanogan lobe's appendage in the Sanpoil River valley. The lower set of anomalously thin flood beds, which date from 15,350 ± 400 yr B.P. and differ from the upper set in being brown and interbedded with thin varves, may represent flood attenuation by a fully extended Columbia River lobe. The absence of additional thin flood beds in the lowermost part of the section seems to preclude attenuation of the earliest last-glacial floods by a high-level Lake Columbia. Therefore, it is likely that Lake Columbia's Grand Coulee outlet approached its present depth before the last glaciation.

## INTRODUCTION

Rhythmic alternation between varves and sandy graded beds is common in deposits of ice-age lakes along the path of floods from glacial Lake Missoula, Montana. Some who describe this rhythmic bedding offer no interpretation of its cause (Jones and others, 1961, p. 20, 43); others speculatively attribute the sandy graded beds to drainage of the host lake (Flint and Irwin, 1939, p. 671; Walker, 1967) or to local turbidity currents (McKenzie, 1980, p. 46; McKenzie and Stemen, 1983). Another explanation, in which the sandy graded beds are attributed to periodic floods from other lakes, has been mentioned by some geologists (Flint and Irwin, 1939, p. 671; McKenzie, 1980, p. 47; McKenzie and Stemen, 1983) and best fits sedimentologic evidence recently found by Waitt (1984) and Atwater (1984). The likely source of the inferred floods is Lake Missoula (Waitt, 1984, 1985; Atwater, 1984), which drained dozens of times during the last glaciation (Chambers, 1971; Waitt, 1980, 1985).

An unusually complete late Wisconsin (last-glacial) section of alternating varves and flood beds is located near Manila Creek in the lower reach of the Sanpoil River valley, northeastern Washington (fig. 1). Most of this section formed in glacial Lake Columbia, the largest lake in the path of floods from Lake Missoula (pl. 1). Varves in the section total about 2,000–3,000 and probably register most of Lake Columbia's last-glacial lifespan. Beds herein attributed to floods indicate no fewer than 89 Lake Missoula outbursts during the last glaciation. The composite section of varves and flood beds also indicates changes in the frequency and erosiveness of the floods. Some of these changes, dated by varve-count extrapolation from a $^{14}C$ age, may gauge the advance and retreat of three major lobes of the Cordilleran ice sheet. The section also provides evidence that the upper Grand Coulee, a large scabland channel commonly supposed to have been cut during the last glaciation, had approached its present configuration before the last glaciation began.

## Acknowledgments

Boreholes described in this report were financed by the U.S. Bureau of Reclamation and drilled by Bureau staff, particularly Kayti Didricksen, Phillip Hansen, John Krieger, Anthony Muzzall, and David Peterson. Exposures in the Manila Creek valley were logged with help from Vicki L. Hansen. My fieldwork was funded by the Bureau of Indian Affairs and facilitated by the Colville Confederated Tribes and by Sandy Arrieta, the Jannot and Kuehne families, and Bruce and Sherrel Siegmond. In preparing this report I have benefited from discussions with Derek B. Booth, Kenneth F. Fox, Jr., N. King Huber, Peter J. Mehringer, Jr., Kenneth L. Pierce, C. Dean Rinehart, Peter H. Stauffer, Byron D. Stone, Julia Ann Thomas, William C. Utterback, Richard B. Waitt, Jr., Carl M. Wentworth, Jr., and James C. Yount.

## LAST-GLACIAL SETTING OF THE LOWER SANPOIL RIVER VALLEY

The known Quaternary history of the lower Sanpoil River valley begins with the last continental glaciation (Wisconsin glaciation). The valley appears to lack deposits from previous glaciations, with the possible exception of a few erratic cobbles above altitude 1,000 m between Louie and Iron Creeks (pl. 2*A*; fig. 2).

During the last glaciation the lower Sanpoil River valley was profoundly affected by the Okanogan and Purcell Trench lobes of the Cordilleran ice sheet and may also have been

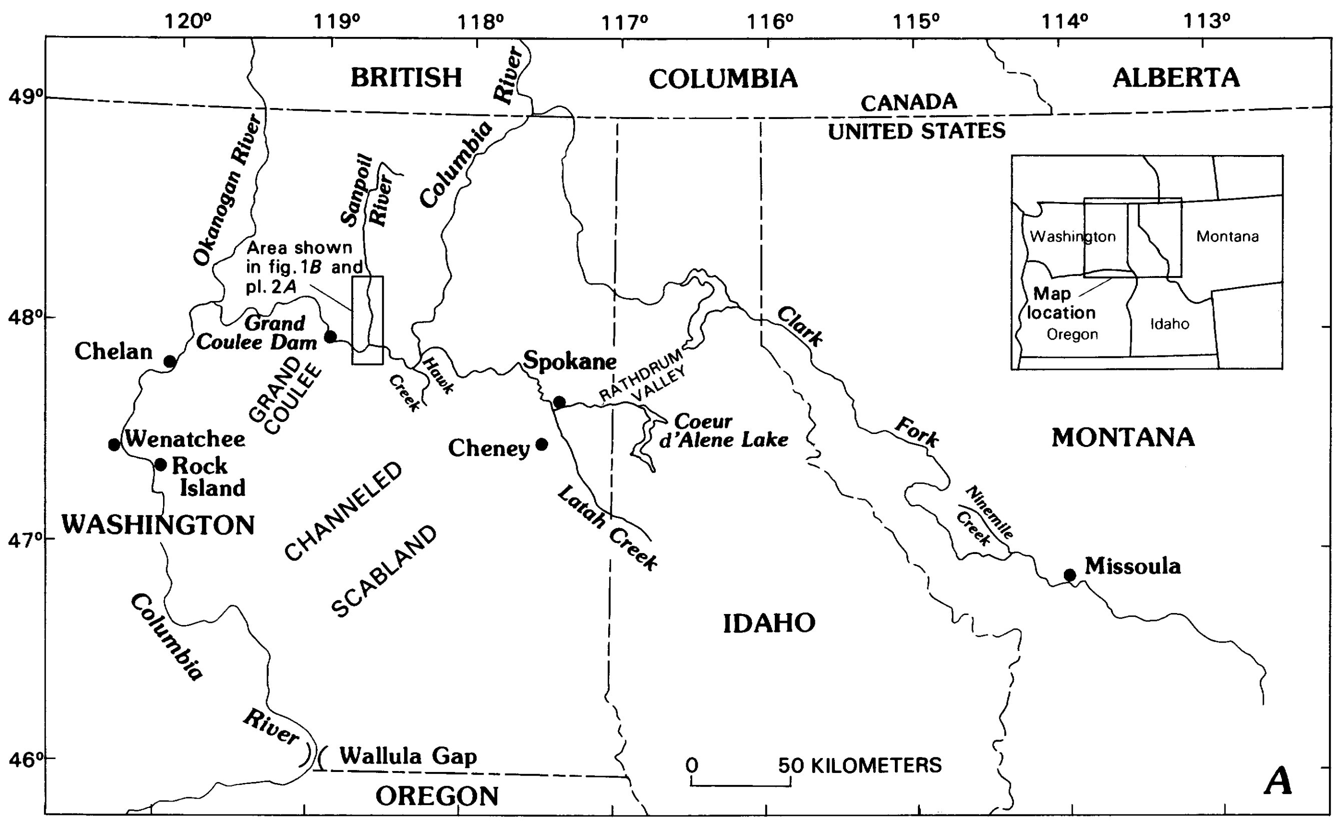



**Figure 1.** Regional (*A*) and local (*B*) index maps for the lower Sanpoil River valley and surrounding areas. The map areas correspond to those in plates 1 and 2*A*, respectively, which show glacial-age paleogeography. Crosses in 1*B* show locations of stratigraphic sections.

affected by the Columbia River lobe of that ice sheet (pl. 1; frontispiece). The Okanogan lobe sent an appendage (the Sanpoil sublobe) into the Sanpoil River valley, and the main part of the lobe dammed the Columbia River downstream of the Sanpoil River, forming a lake (Lake Columbia) that drowned the valley's lower reach. Far east of the Sanpoil River, the Purcell Trench lobe dammed a Columbia River tributary (Clark Fork) to produce a lake (Lake Missoula) whose outburst floods periodically ascended the lower Sanpoil River valley and could have lowered the interflood level of Lake Columbia by eroding scabland divides used as outlets by Lake Columbia. A maximally extended Columbia River lobe may have deflected Lake Missoula floods running toward the Sanpoil River valley from the Spokane area. The lower Sanpoil River valley was thus well situated to record histories of ice lobes, lakes, and divides outside the valley itself, and such histories are inferred in the final parts of this report. Those inferences rest partly on certain presumptions: that the Sanpoil sublobe extended into the lower Sanpoil River valley without long occupying the Manila Creek area; and that the surface of Lake Columbia typically stood near altitude 500 m but reached 715 m during glacial blockage of the Grand Coulee and rose as high as 750 m during floods from Lake Missoula.

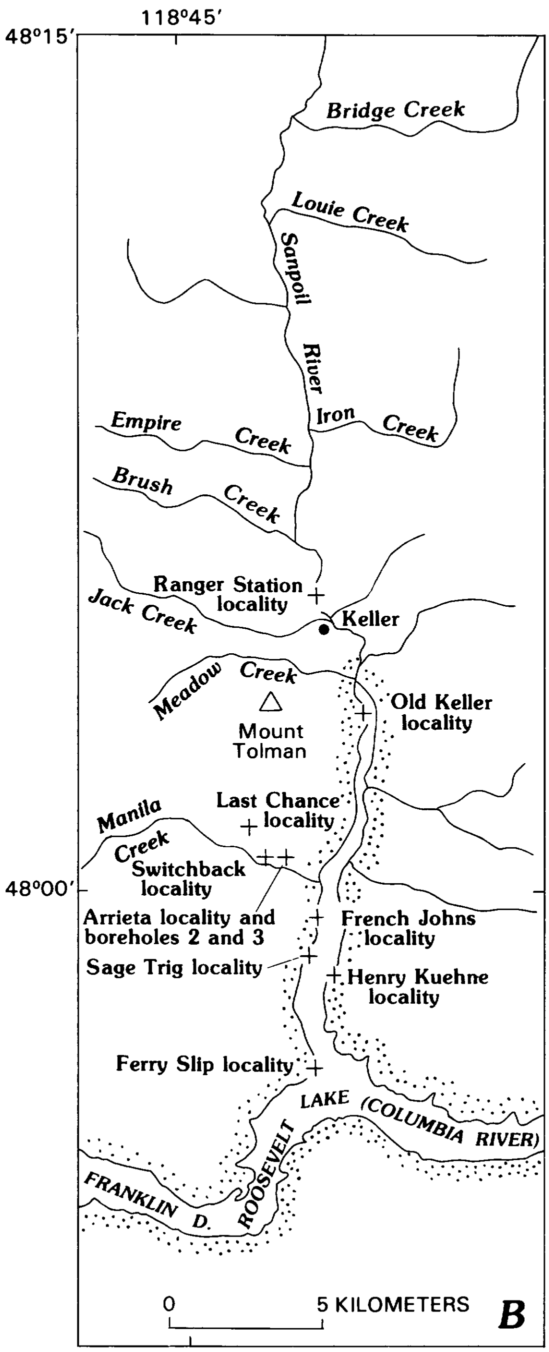



**Figure 1.** Continued.

## Extent of the Sanpoil Sublobe

Flint and Irwin (1939, p. 675-676), citing deposits now covered by reservoir, inferred that glacial ice extended down the Sanpoil River valley to the Sanpoil's confluence with the Columbia River. But other geologists have placed the terminus no farther south than Manila Creek and as far north as Empire Creek (Pardee, 1918, p. 52; Richmond and others, 1965, p. 235; McKenzie and Stemen, 1983). A terminal position at Empire Creek, 22 km north of the Sanpoil-Columbia confluence (pl. 2*A*), is consistent with an ice-surface reconstruction fitted to moraines and to erratics above altitude 750 m (fig. 2). This reconstruction depends on the assumption that the glacier flowed over a rigid substrate. If the substrate was easily deformed, as must have been the case when the glacier advanced into Lake Columbia, then the upper surface of the ice could have sloped more gently than shown in figure 2, and the terminus could have been farther south (compare Boulton and Jones, 1979). But even in this case, discussed further in the section entitled "Diamictons," the Sanpoil sublobe probably did not linger in the Manila Creek area for more than a few decades during the last glaciation.

## Levels of Lake Columbia

Two chiefly lacustrine units separated by till at Grand Coulee Dam indicate that the Okanogan lobe first blocked the Columbia River some distance downstream from the Grand Coulee, then spread upstream to the Grand Coulee, where it formed its last-glacial terminus, and finally withdrew from the Grand Coulee but continued damming the Columbia River downstream for some time before disappearing altogether (Flint and Irwin, 1939). The ambient level of the resulting lake was limited chiefly by the altitudes of divides between the Columbia River valley and the northeastern Channeled Scabland (see pl. 1). The lowest of these divides is

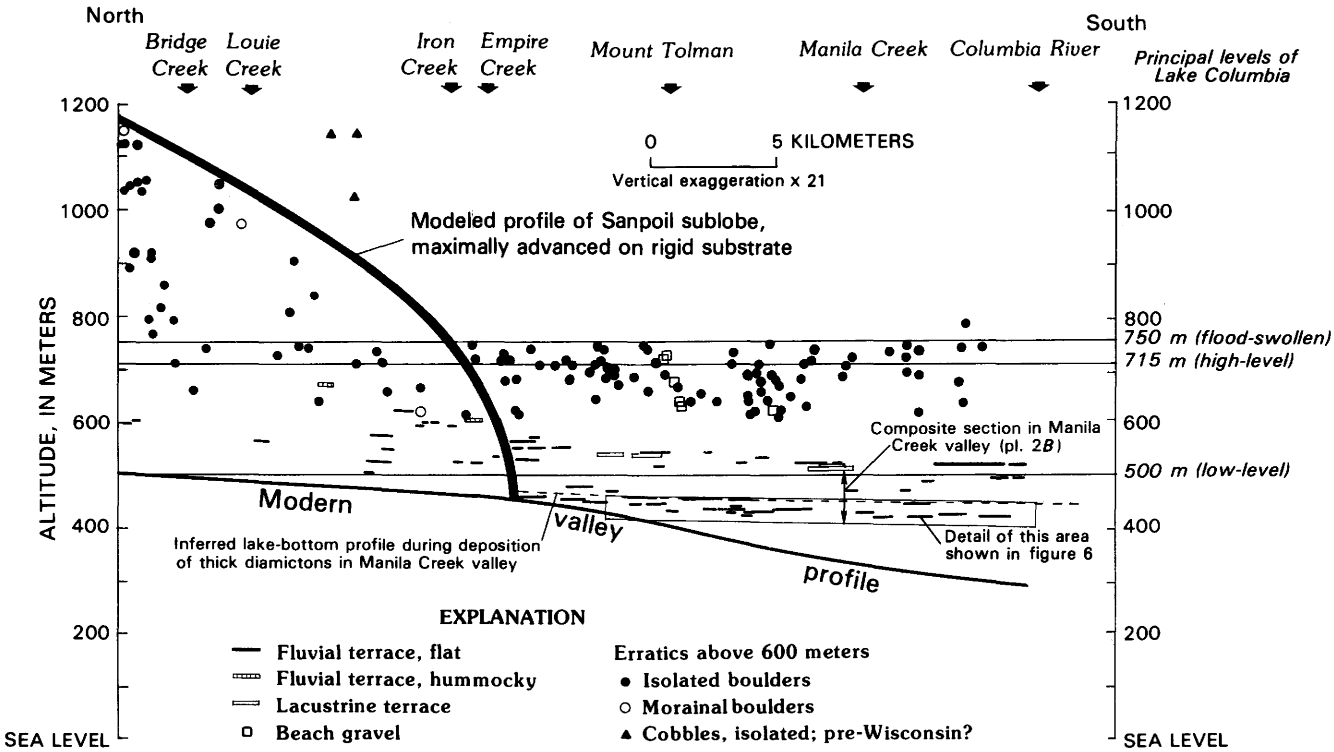



**Figure 2.** Last-glacial features (pl. 2*A*) projected onto a longitudinal profile of the Sanpoil River valley. Profile of Sanpoil sublobe, modeled by J.C. Yount, gives best fit of a theoretical valley-glacier profile (Schilling and Hollin, 1981) to the distribution of erratic boulders above 750 m; it is also consistent with the distribution of kettled terraces. Assumptions built into the modeled profile include: a rigid substrate; a shape factor of 0.6 (at 0.5 the ice would be treated as a semicylinder, at 1.0 an infinite sheet); and an average basal shear stress of 80 kPa (at 100 kPa ice flows rapidly). If the substrate was easily deformed, as in the case of glacial advance over lacustrine deposits, then the profile could have been flatter (Boulton and Jones, 1979) and consequently the snout below 750 m could have been farther south. Base level for modern Sanpoil River is that recorded by Flint (1936, pl. 6) before the river mouth's inundation behind Grand Coulee Dam.

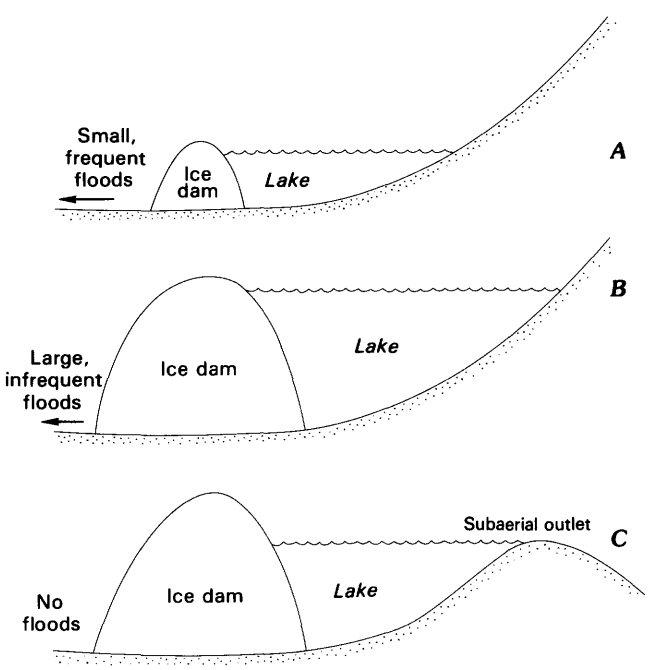



**Figure 3.** Schematic diagrams of ice-dammed lakes. *A* and *B*, Self-dumping lakes. Having no outlet other than an ice dam, the lakes drain as a consequence of buoyant lifting of the dam each time the lake depth reaches about nine-tenths the height of the dam. Resulting outburst floods are smaller and more frequent when the dam is low (*A*) than when the dam is high (*B*), provided there is little change in inflow between floods or in the proportion of the lake drawn down during floods. Adapted from Thorarinsson (1939). *C*, Stable lake. The subaerial outlet prevents self-dumping by keeping lake level well below the crest of the dam.

located at the south end of the upper Grand Coulee and is today at altitude 465 m. Flint and Irwin (1939) gave two arguments for viewing the 465-m Grand Coulee divide as Lake Columbia's chief last-glacial outlet: (1) the Grand Coulee contains till and glacial striations probably formed after the coulee had approached its present depth (Bretz, 1932, p. 35-37), so the coulee became available to serve as Lake Columbia's outlet no later than the last glacial maximum; and (2) the Grand Coulee had surely become Lake Columbia's outlet by late-glacial time, because the lake's highest wide-

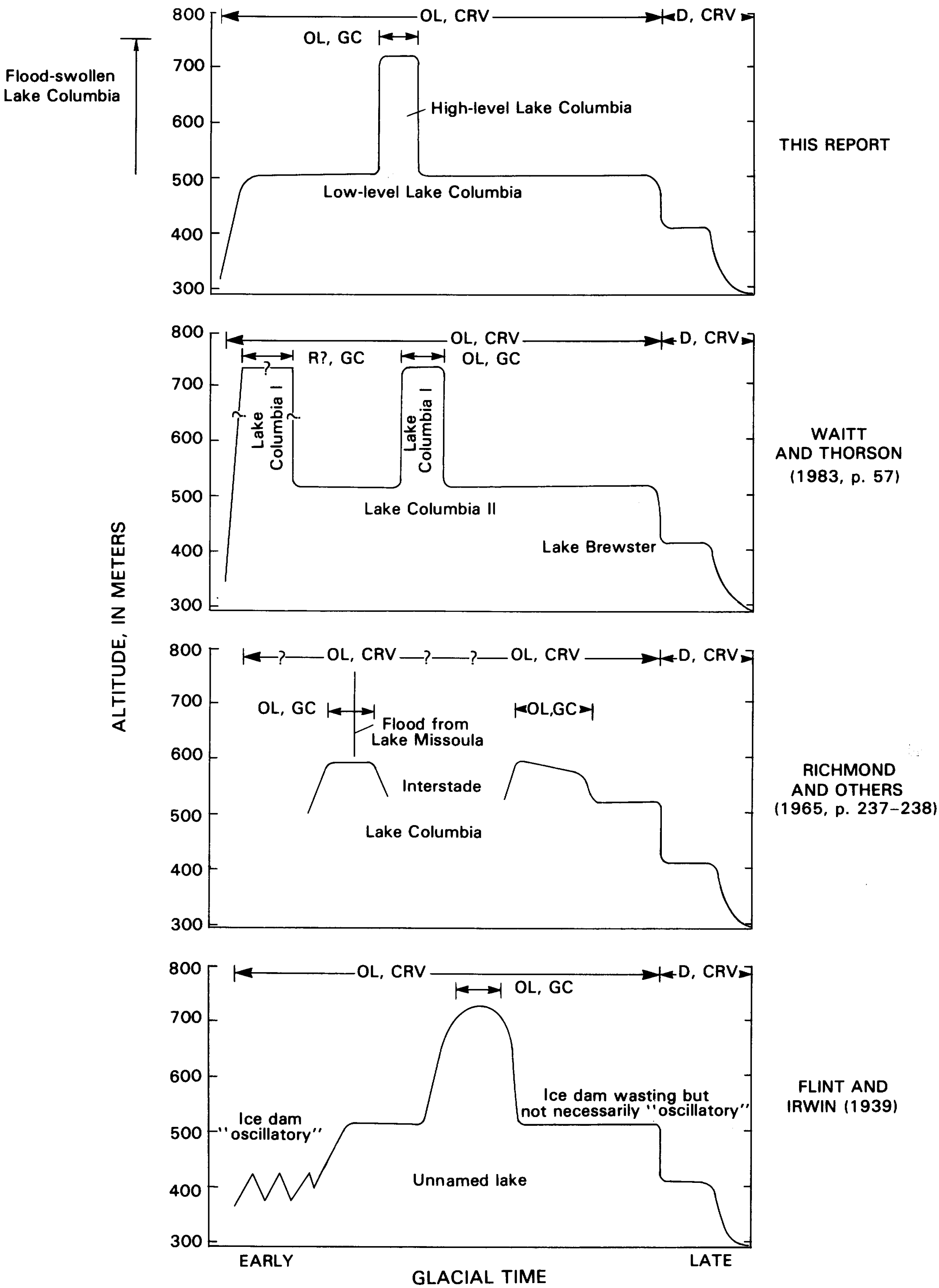



**Figure 4.** Schematic summaries of four histories proposed for the last-glacial levels of Lake Columbia. Abbreviations above graphs denote the kind of dam (D, drift or stagnant ice; OL, Okanogan lobe; R, rock-forming flood-cataract alcove in the Grand Coulee before the intersection of that alcove with the Columbia River valley) and the dam's location (CRV, Columbia River valley; GC, Grand Coulee).

spread terraces (altitude near 515 m) in unglaciated parts of the Columbia River valley appear graded to glaciolacustrine terraces in the Grand Coulee (altitude 480–500 m) (Bretz, 1932, p. 76). At times, however, Lake Columbia apparently used substantially higher outlets, for the lake left strandlines at altitudes above 600 m near the mouth of the Sanpoil River (Flint, 1935, p. 189; 1936, p. 1857). Probably these outlets were located farther east, near Cheney (present altitude 702 m) or near Hawk Creek (present altitude 710 m), or on the scabland just east of the Grand Coulee (pl. 1). Flint (1935) attributed the high-level lake to full-glacial blockage of the Grand Coulee by the Okanogan lobe.

Subaerial outlets such as the Grand Coulee gave Lake Columbia a stability not shared by all ice-dammed lakes. A lake having no outlet other than its ice dam (figs. 3*A*, 3*B*) may drain through subglacial tunnels each time the lake makes the dam buoyant by rising to about nine-tenths the dam's height (Thorarinsson, 1939, p. 221-222; Nye, 1976). Such periodic drainage has been observed for modern lakes (for example, Thorarinsson, 1939; Mathews, 1965; Post and Mayo, 1971) and has also been inferred for Lake Missoula (Waitt, 1980, 1985; Clarke and others, 1984). But periodic drainage is unlikely if a subaerial outlet lies well below the altitude of the ice dam; the subaerial outlet serves as a safety valve, preventing self-dumping (fig. 3*C*; Clarke, 1982, p. 7). Thus Lake Columbia should have avoided routine self-dumping because its subaerial outlets were usually lower than the top of the Okanogan-lobe dam. Possible exceptions were those early- and late-glacial times when the Okanogan lobe lay within but not across the Columbia River valley; in addition, the elevated full-glacial Lake Columbia inferred by Flint (1935) could have drained periodically, though only to the altitude of the Grand Coulee outlet, when the Okanogan-lobe dam in the Grand Coulee was not much higher than the scabland outlets near Cheney and Hawk Creek. Flint and Irwin (1939, p. 671) and McKenzie (1980, p. 46) invoked periodic drainage of Lake Columbia to explain rhythmic alternation of varves with sandy graded beds at Grand Coulee Dam and in the Sanpoil River valley, respectively. But as argued below in the section entitled "Selection and Assembly of the Manila Creek Section," these sandy graded beds were deposited by periodic floods from Lake Missoula. Moreover, as discussed in the section entitled "Varved Intervals," the varves that alternate with these beds suggest interflood stability for Lake Columbia; varves of the Sanpoil River valley typically lack the very properties that, in varves of the Clark Fork valley, indicate periodic drainage of Lake Missoula.

The lake-level history inferred by Flint (1935, 1936) and Flint and Irwin (1939) was partly adopted, partly amended, and partly abandoned in review articles by Richmond and others (1965) and Waitt and Thorson (1983) (fig. 4). The most durable amendment is the hypothesis that flood water from Lake Missoula briefly raised the level of Lake Columbia to 750 m or more (Richmond and others, 1965, p. 239). Richmond and others (1965, p. 237-238) abandoned Flint's lake-level history by deducing that the Okanogan lobe entered the Grand Coulee twice during the last glaciation, once during each of two alpine-glacial stades, and by asserting that Lake Columbia stood near altitude 550 m during both these stades. Waitt and Thorson (1983, p. 57) largely returned to Flint's lake-level history by designating a Lake Columbia I, with a surface altitude of 730 m and an outlet across a scabland beside the Grand Coulee, and a Lake Columbia II, with a surface altitude of 515 m and an outlet through the Grand Coulee; and they reiterated Flint's (1935) view that full-glacial lake level must have risen well above 515 m when the Okanogan lobe blocked an already-cut Grand Coulee. But unlike Flint and Irwin (1939, p. 679), Waitt and Thorson (1983, p. 57, 67) allowed a last-glacial age for lowering of the divide at the Grand Coulee from 730 m to the present 465 m. They noted that such last-glacial erosion could have caused Lake Columbia to drop from an early-glacial level near 730 m to a late-glacial level near 515 m.

Strata and landforms in the Sanpoil River valley record both a *low-level Lake Columbia* and a *high-level Lake Columbia,* similar to the lake stands proposed by Flint and Irwin and by Waitt and Thorson. In addition, erratics in the Sanpoil River valley mark a *flood-swollen Lake Columbia* that probably resulted from Lake Missoula outbursts (fig. 4).

Low-level Lake Columbia is represented in the Sanpoil River valley by the highest widespread deposits of lacustrine silt and by fluvial terraces descending past these deposits. The silt forms terraces near altitude 515 m (Pardee, 1918, p. 15), chiefly in the recesses of Manila, Meadow, and Jack Creeks (terraces near altitude 1,700 ft, pl. 2*A*). In the section below entitled "Varved Intervals" I argue that these recessed terraces were completed in isolated lakes impounded to levels slightly above low-level Lake Columbia by a late-glacial outwash plain of the Sanpoil River (fig. 2, fluvial terraces descending toward 500 m). If this argument is valid, then low-level Lake Columbia was slightly lower than altitude 515 m, probably near the 500-m altitude of Bretz's (1932, p. 76) late-glacial terrace near Grand Coulee Dam. All these altitudes may have a component of isostatic rebound (Flint, 1935, p. 189; 1936, p. 1873), not only from the Cordilleran ice sheet but also from Lake Columbia. The only logical outlet of low-level Lake Columbia was the Grand Coulee divide at or near its present 465-m altitude (pl. 1).

High-level Lake Columbia is recorded chiefly by strata of wave-winnowed sand and gravel (fig. 5) near 715 m on the north side of Mount Tolman (pl. 2*A;* Cochran and Warlow, 1980, p. 40). These deposits are too scanty to represent a lake as long-lived as low-level Lake Columbia, but they nonetheless indicate a lake that persisted long enough to form beaches. Probably this was the lake having a dam of ice (Flint's view) or rock or both (options mentioned by Waitt and Thorson) at the Grand Coulee; in the section below entitled "Age of the Grand Coulee," I present evidence in support of Flint's (1935) hypothesis that the high-level Lake Columbia of last-glacial age formed only by glacial blockage of an already-cut Grand Coulee. The lake's likely outlets were the Cheney and Hawk Creek divides (pl. 1). Planimetry on 1:250,000-scale maps indicates an area of about 6,000 km$^2$ for the high-level Lake Columbia shown on plate 1. By comparison, Lake Missoula at its highest level covered about 9,650 km$^2$ (Clarke and others, 1984, p. 290), and low-level Lake Columbia covered no more than about 900 km$^2$.

Raising of Lake Columbia to levels near 750 m is implied by ice-rafted erratics in the lower Sanpoil River valley (pl. 2*A*; fig. 2). Most of these erratics are granitoid rocks whose slight degree of weathering suggests a last-glacial age. A few of the erratics near the Columbia River appear to be derived from the Proterozoic Belt Supergroup (pl. 2*A*), which is exposed chiefly to the east, in Idaho and Montana. These probable Belt erratics, together with the lack of well-winnowed beach deposits above those assigned to high-level Lake Columbia, suggest that the 750-m level was reached only during floods from the vicinity of Lake Missoula.

## SELECTION AND ASSEMBLY OF THE MANILA CREEK SECTION

Varve-bounded graded beds suggesting floods into Lake Columbia from Lake Missoula are abundantly exposed in the axial part of the lower Sanpoil River valley (Atwater, 1984). These beds (hereafter termed flood beds) typically have the following properties in valley-axis exposures: (1) thickness equal to that of tens of adjacent varves (figs. 6, 7); (2) upward fining from sand to clay (figs. 7, 8*A*), and local interruption of this fining by turbidites probably derived from upslope equivalents of the sand (figs. 8*B*, 8*C*, 9); (3) maximum sand size greater than that in adjacent varves (fig. 9); (4) upvalley decrease in average grain size (fig. 9); (5) upvalley decrease in the amount of erosion into underlying varves (figs. 6, 9); (6) upvalley dip of ripple foresets (if any) near the base of the bed (pl. 2*A*); (7) downvalley dip of ripple foresets (if any) in middle and upper parts of the bed (pl. 2*A*); (8) redder clay (Munsell hues 2.5Y and 10YR) and more

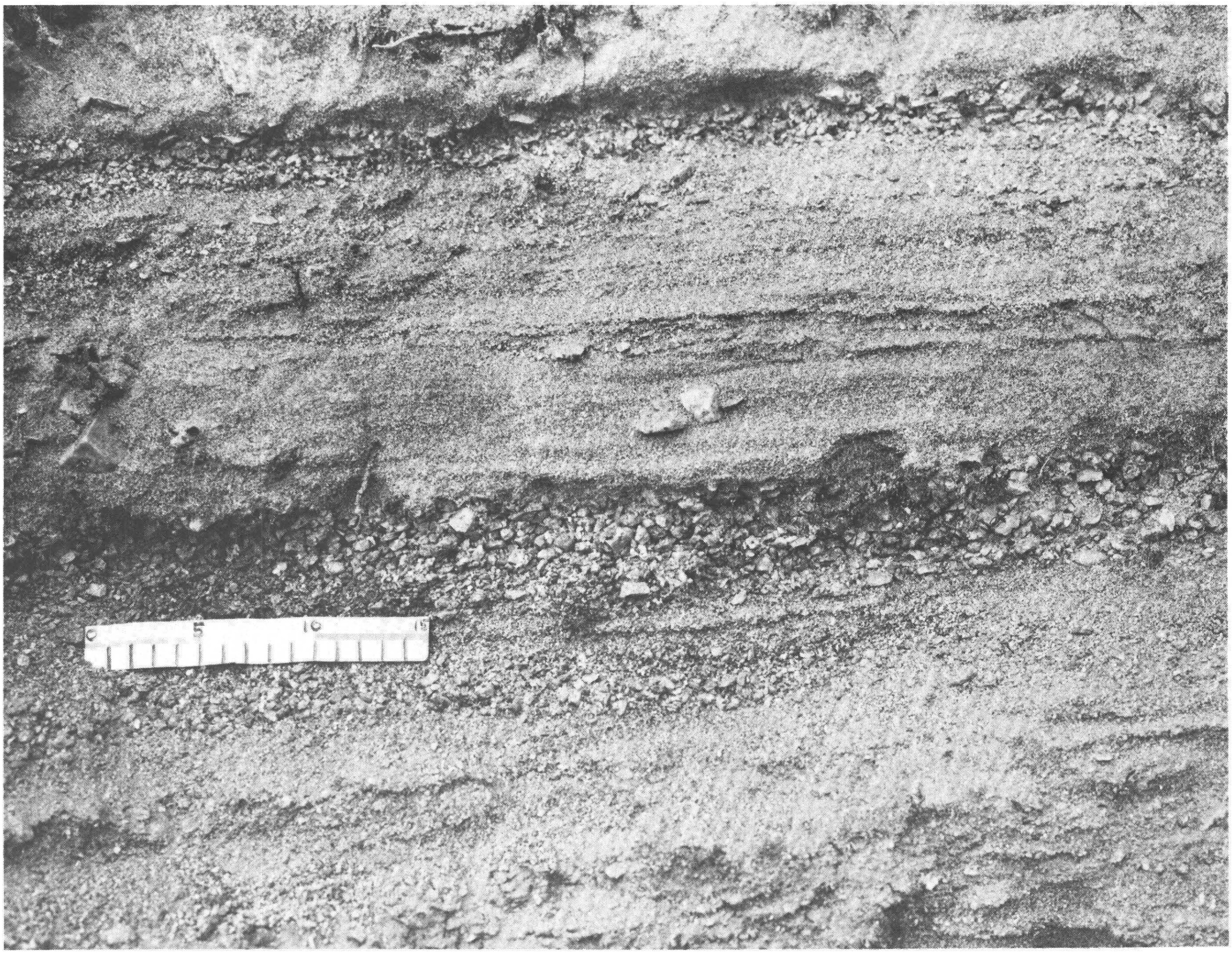



**Figure 5.** Lacustrine sand and gravel at altitude 710 m on north side of Mount Tolman (pl. 2*A*). The lack of interstitial sand in the gravel beds suggests winnowing by waves. Scale in centimeters.

orange-stained sand grains than in adjacent varves (hue 5Y); and (9) bracketing by two varved intervals each containing about 35–55 varves (tables 1, 2). Properties 1–3 indicate currents of greater velocity and sediment load than those depositing the varved intervals. These currents ascended the Sanpoil River valley from the Columbia River valley (properties 4–6), then became reflected flows or return drainage (7). The currents typically carried more well-weathered detritus than ordinary inflow to Lake Columbia (8); the currents typically resulted from floods that incorporated oxidized soil and sediment on the way to or around Lake Columbia. The regular period of the floods (9) befits outbursts from a self-dumping ice-dammed lake. That this lake was Missoula is indicated chiefly by the floods' age and frequency (see section entitled "Frequency and Number of Floods from Lake Missoula"), and by the regionality of Missoula-flood effects (Waitt, 1985).

The axial part of the Sanpoil River valley does not, however, expose more than a partial record of Lake Missoula floods. Most valley-axis glaciolacustrine deposits were

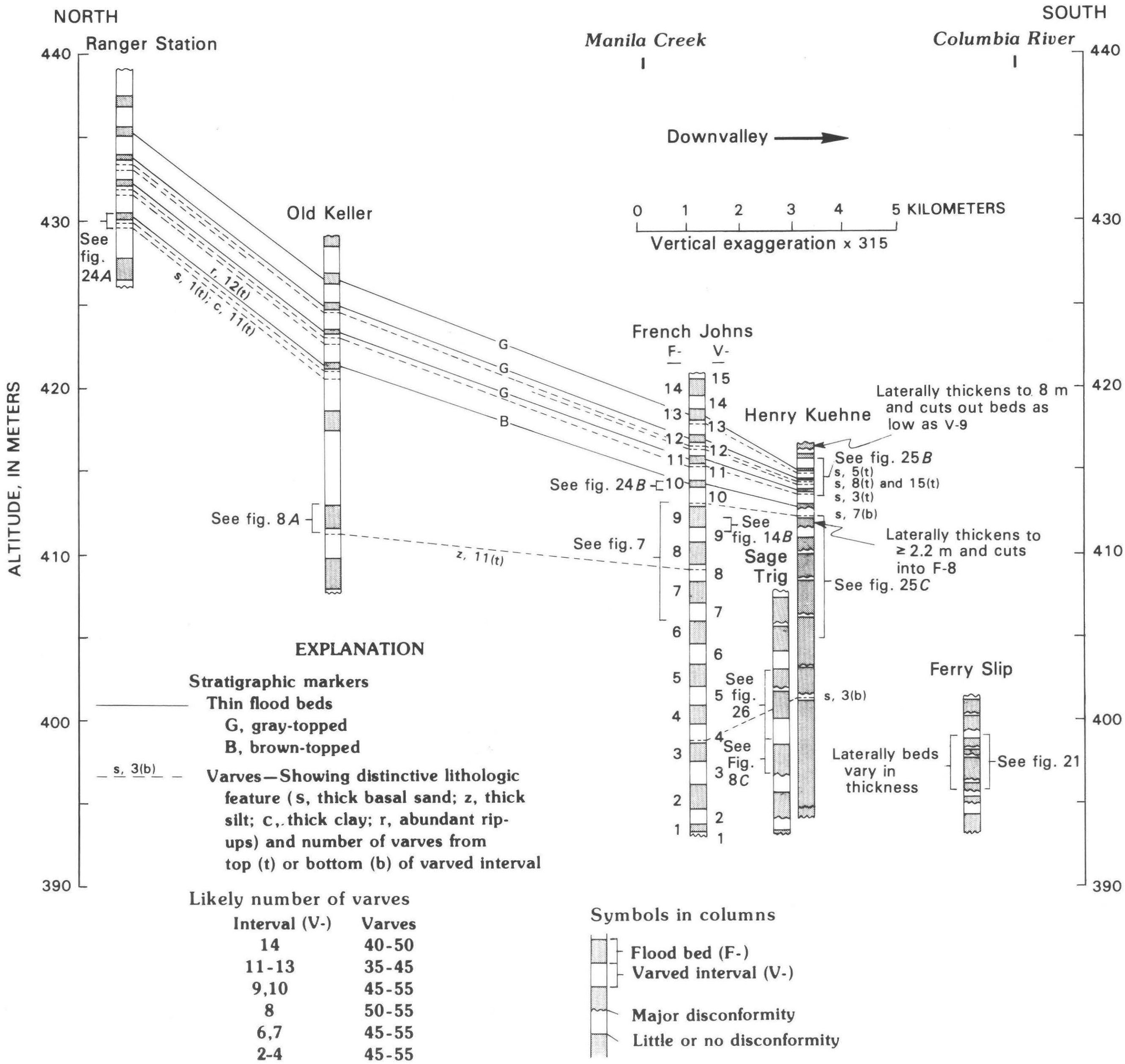



**Figure 6.** Correlation of skeletal columnar sections along the axis of the lower Sanpoil River valley. Sections at Sage Trig and Ferry Slip localities (pl. 2A) probably lie below flood bed F–10, but otherwise their stratigraphic position is unknown. Varve counts and stratigraphic markers summarized from tables 1 and 2.

**Table 1.** Ranges of varve counts from last-glacial (late Wisconsin) deposits along the axis of the lower Sanpoil River valley

[Range for a given bed at a given locality obtained by making two counts, one treating as simple varves nearly all silt-and-clay couplets thicker than 5 mm, the other lumping selected sets of non-rhythmic couplets into composite varves. Underscored numbers denote count made incomplete by erosion at contact with overlying flood bed; all other counts presumably complete. Intervals not counted: i, exposed but mostly inaccessible; e, mostly eroded; c, covered]

| Interval (See fig. 6) | Locality (see fig. 1B and pl. 2A) | | | | Likely range |
|---|---|---|---|---|---|
| | Ranger Station | Old Keller | French Johns | Henry Kuehne | |
| V-14 | 35-46 | 48-56 | 35-44 | i | 40-50 |
| V-13 | 41-52 | 44-46 | 34-41 | 34-36 | 35-45 |
| V-12 | 40-52 | 45-49 | 40-47 | 36-38 | 35-45 |
| V-11 | 40-51 | 36-48 | 39-46 | 37-47 | 35-45 |
| V-10 | 51-73 | 47-55 | 50-59 | 29-38 | 45-55 |
| V-9 | c | 53-59 | 39-49 | 32-40 | 45-55 |
| V-8 | c | 56-62 | 48-54 | e | 50-55 |
| V-7 | c | c | 44-52 | e | |
| V-6 | c | c | 50-57 | e | |
| V-5 | c | c | i | e | 45-55 |
| V-4 | c | c | 47-51 | e | |
| V-3 | c | c | 48-55 | e | |
| V-2 | c | c | 44-48 | e | |

**Table 2.** Varves used to correlate between localities along the axis of the lower Sanpoil River valley

[Localities, shown in figure 1B and plate 2A: Ranger Station (RS), Old Keller (OK), French Johns (FJ), and Henry Kuehne (HK)]

| Varved interval | Varve: Distinctive lithologic feature | Stratigraphic position, as number (a, approximate number) of varves from top (t) or bottom (b) of interval | Lateral variation (if any) and known distribution |
|---|---|---|---|
| V-13 | Thick base of very fine sand. | 5 (t) | Not distinctive at OK and RS owing to abundance of sandy varves at these localities. |
| V-12 | Thick base of very fine sand. | 8 (t) | Thins from 2-3 cm at RS to 0.8 at HK. |
| | Thick base of very fine sand. | 15 (t, a) | Not distinctive at OK owing to abundance of sandy varves at this locality. |
| V-11 | Thick base of of very fine sand. | 3 (t) | Thins from 8 cm at RS to 0.2-0.5 cm at HK; overlying varves eroded at FJ and partly detached at HK. |
| | Structureless coarse silt and very fine sand with tabular clasts of varves. | 12 (t, a) | Recognized only at RS and OK. |
| V-10 | Thick base of very fine sand. | 1 (t), of which the marker forms the base. | Recognized only at RS and OK. |
| | Exceptionally thick (10 cm) clayey part of varve. | 11 (t) | Recognized only at RS and OK. |
| | Exceptionally thick (5-7 cm) clayey part of varve. | 7 (b, a) | Recognized only at RS and OK. |
| V-8 | Silt, 10 cm thick------ | 11 (t, a) at OK | Recognized only at OK and FJ: covered, if present at all, at RS; cut out by erosion HK. At FJ 3-5 of the overlying varves have probably been removed by erosion. |
| V-4 | Very fine sand--------- | 3 (b, a) | Recognized only at FJ and HK: covered, if present at all, at RS and OK. |

deeply eroded in late-glacial or early post-glacial time by the Sanpoil River (Flint, 1936, p. 1873-1874), whose terrace-forming gravel at altitude 400–450 m (fig. 10) disconformably overlies all glaciolacustrine deposits shown in figure 6. Vertically extensive exposures of Sanpoil-arm deposits above altitude 440 m are restricted to tributary valleys harboring 515-m terraces. The best of these exposures are in the valley of Manila Creek, 7 km north of the Columbia River.

I composited the Manila Creek section from four surface exposures and two boreholes (pls. 2, 3). Deposits low in the section are exposed at the French Johns locality, 1 km south of the mouth of Manila Creek. The upper half of the section comprises exposures at three localities to the northwest, up the Manila Creek valley: Arrieta, topographically the lowest of the three; Switchback; and Last Chance, the only one reaching a 515-m terrace. The remainder of the section is known from two boreholes at the Arrieta locality (fig. 11). The boreholes, 3 m apart, were cored continuously through depths of 2–67 m (borehole 2) and 13–38 m (borehole 3) from a ground-surface altitude of 466.5 m. Individual cores were 10 cm in diameter (fig. 12) and as much as 3.0 m long. Borehole 2 apparently bottomed in weathered granite; borehole 3 provided sample from intervals of poor recovery in borehole 2.

Distinctive varved intervals and flood beds allow assembly of a 120-m composite section from these surface exposures and boreholes. Both the French Johns locality and the boreholes contain sandy varved interval V–9, a thick clayey varve in varved interval V–10, and two sets of thin flood beds (pls. 2*B*, 3; figs. 12–14). The tops of the boreholes are located within the Arrieta exposure (fig. 11). Most of the Switchback exposure is higher stratigraphically than the Arrieta exposure: a distinctively reddish (7.5YR 6/4) clayey layer, present in the lowermost part of a varved interval near the top of Arrieta, appears also to be present near the base of Switchback (approximate altitude 485 m; labeled RC in pl. 2*B*); in addition, notably thick and sandy varved intervals above the reddish layer at Switchback are totally absent from Arrieta (SS, pl. 2*B*). All but the lowermost deposits at Last Chance are less rhythmic than the uppermost deposits at

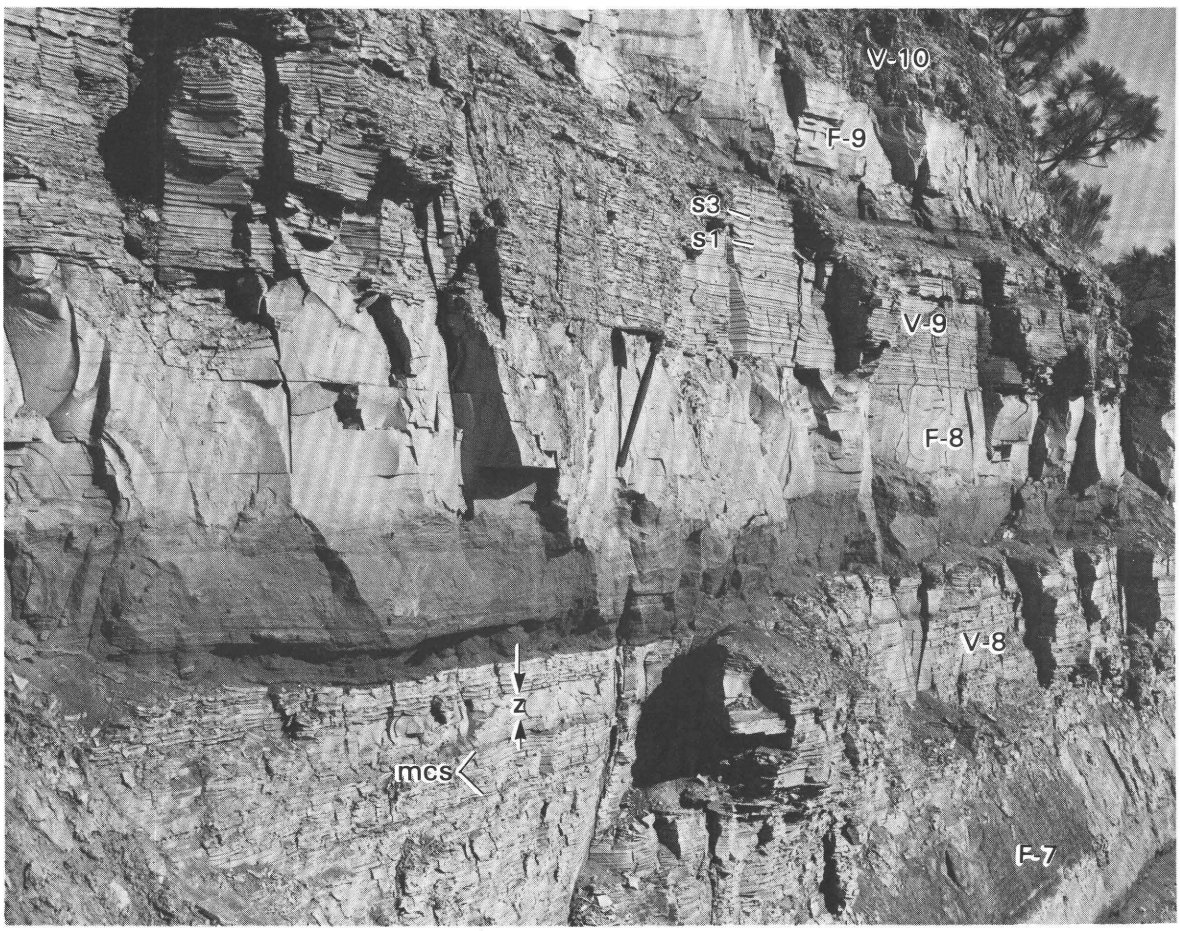



**Figure 7.** Typical flood beds and varved intervals at French Johns locality (pl. 2*A*). Flood bed F–8 displays typical upward gradation from sand (dark) in the lower part to silt and clay (light) in the upper part. Varved intervals V–8 and V–9 each contain about 50 varves (table 1). Prominent sand layers s1 and s3 in V–9 are shown in more detail in figure 14. The exceptionally thick silt (z) in the uppermost part of V–8 is exposed also at the Old Keller locality, 7 km upvalley (fig. 6; table 2). Varves below this silt are intercalated with layers of medium and coarse sand (mcs) that resembles sand in the lower parts of the flood beds. Shovel handle is 0.5 m long.

Switchback and probably belong above them.

The correlations between the French Johns locality and the boreholes are especially important because they show that the section along the Sanpoil River valley axis is not inset into the section in Manila Creek valley. The most secure of these correlations involve the sandy varved interval (V–9) and the upper set of thin flood beds (F–10 through F–13). Distinctive for at least 13 km along the Sanpoil River valley axis (figs. 6, 9), these strata also stand out in core from Manila Creek valley (figs. 12, 14). In contrast, I have not seen the lower set of thin flood beds outside the Manila Creek area. These beds are so low in the section (pl. 2*B*) that they should be mostly concealed.

## STRATIGRAPHY

The composite Manila Creek section contains at least 89 different flood beds separated by varves. Rhythmic alternation between flood beds and varved intervals pervades all but two parts of the section: at altitude 443–451 m, where gravelly diamicton predominates; and the section's top 9 m, in which flood beds are absent and varves predominate (pls. 2*B*, 3).

### Varved Intervals

Varved intervals in the Manila Creek section are characterized by internal rhythmicity but vary greatly in the degree of that rhythmicity. Some intervals consist mostly of simple, regularly repeating couplets of silt and clay (figs. 12, 13, 15). As shown below, regional ice-sheet chronology provides evidence that each of these couplets represents one year—that each is a varve in the sense of DeGeer (1912). But other varved intervals, especially sandy ones, have less internal rhythmicity (figs. 14, 16).

Nearly all varved intervals contain enough arhythmic laminae to warrant both a stingy count, in which many couplets are grouped into compound varves, and a generous count, in which most couplets are treated as simple varves. The generous counts probably err on the high side, as shown in the axial part of the Sanpoil River valley by a downvalley decrease in apparent varve counts from widely correlated varved intervals (table 1) that coincides with downvalley decrease in the abundance of sand in the varved intervals (fig. 9). Because I wish to emphasize the imprecision of my varve counts, the counts are reported as the full stingy-to-generous ranges (figs. 13–17; pl. 3). The ranges are given as limiting minima where the base of the succeeding flood bed is noticeably disconformable (for example, the upper flood bed in fig. 13).

The Manila Creek varve counts plotted in fig. 17 total 1,586–2,291. To this range I add the following estimates: (1) 100–200 varves removed during deposition of flood beds; (2) 200–300 varves in nine intervals for which I made no counts but assume ranges similar to those in neighboring varved intervals; and (3) 200–400 varves in the mostly arhythmic deposits at altitude 503–515 m, to which I apply the average sedimentation rate of 3 to 6 cm/yr that is implied by varves at altitude 503–506 m and at altitude 510 m. These additions bring the rough total to 2,000–3,000 varves.

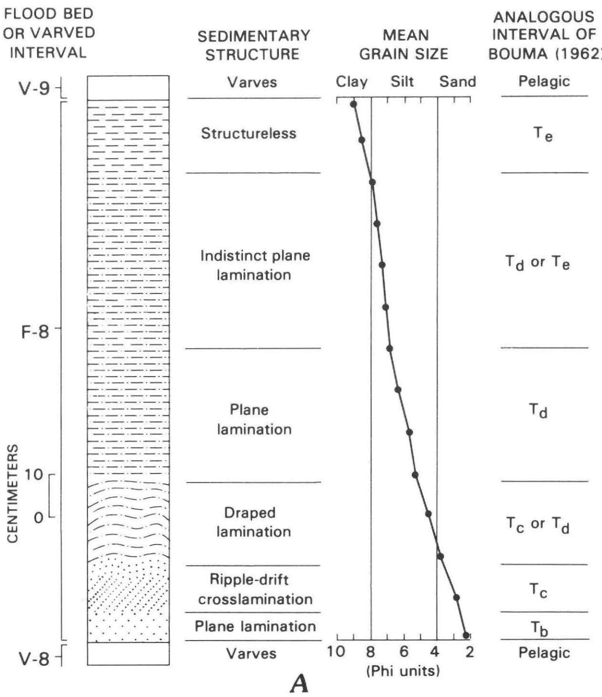
The Manila Creek section shows little or no systematic upward decrease in grain size and varve thickness within individual varved intervals (figs. 7, 13, 15). This is significant because upward decrease in grain size and varve thickness is characteristic of individual sets of varves (varved rhythmites of Chambers, 1971) in the bottom sediments of Lake Missoula at Ninemile Creek, Montana (Chambers, 1971, p. 36, 46; Waitt, 1980, p. 673-674). Chambers (1971) and Waitt (1980) interpret each of Lake Missoula's varved rhythmites as indicating a cycle in which Lake Missoula progressively deepened (causing the upward decrease in grain size and varve thickness), then abruptly drained (causing a commonly disconformable contact with the succeeding varved rhythmite). By the same token, the scarcity or absence of upward fining and thinning within individual varved intervals of the Sanpoil River valley is consistent with the deduction made above (in the section entitled "Levels of Lake Columbia") that Lake Columbia did not ordinarily undergo cyclic emptying and filling.

Although systematic vertical variation is slight or lacking *within* varved intervals, two properties of varves vary conspicuously and systematically *among* varved intervals of the Manila Creek section. One is the number of varves per uneroded varved interval (fig. 17). From about 20 to 40 in the lowermost part of the section (borehole 2), this number increases to a maximum of 45–55 (intervals V–2 through V–10), then declines gradually, with one or two slight reversals (labelled R in fig. 17), to only 1–2 beneath the highest flood bed (fig. 16). A puzzling departure from these overall trends is an apparently complete varved interval at altitude 437 m in borehole 3 that has one-quarter the number of its neighbors' varves (pl. 3). Below, in the section entitled "History of the Cordilleran Ice Sheet," I ascribe the overall trends to variation in the thickness of Lake Missoula's ice dam.

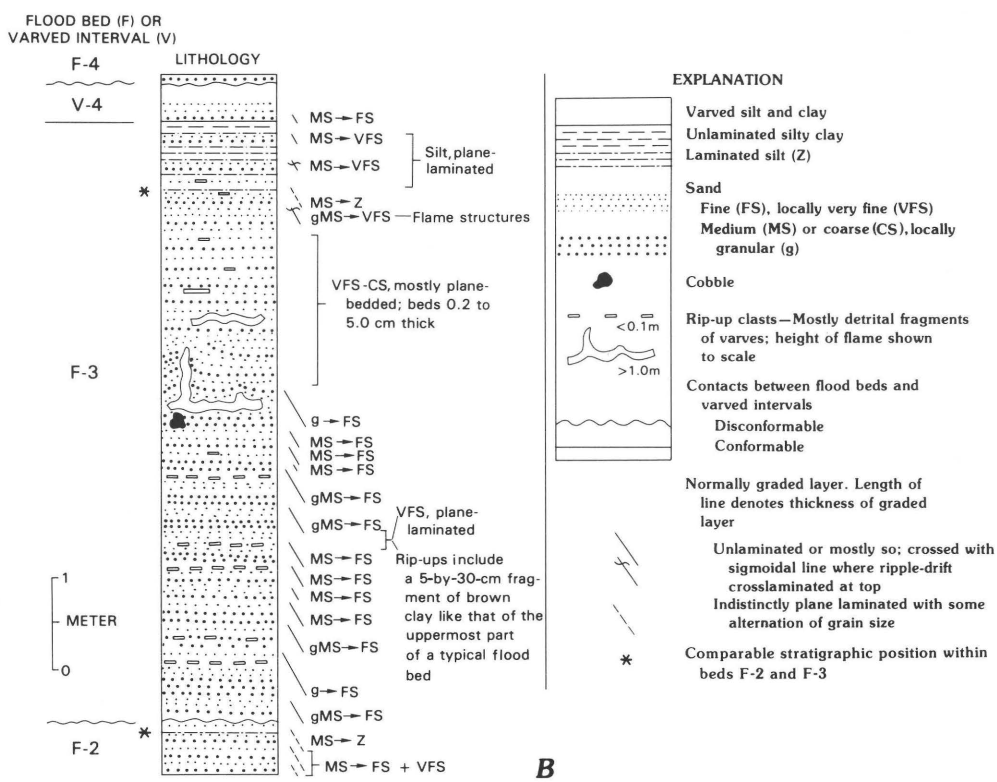
Varve thickness, the other property varying systematically among varved intervals, has a broad maximum near the middle of the composite Manila Creek section and reaches still greater values high in the section (fig. 17). Typical varve thickness in Manila Creek valley increases upsection from 0.5 cm in the lowermost part (fig. 18) to 3–4 cm at altitude 430–450 m; similarly, in partly correlative section at the French Johns locality, varves thicken from about 1 cm near the base of the exposure (fig. 13) to 2–3 cm in intervals V–2 through V–14 (fig. 14). Farther upsection in Manila Creek valley, typical varves are 1–2 cm thick at altitude 470–485 m (fig. 15) but at least 2 cm and as much as 5–17 cm thick above altitude 486 m (figs. 16, 19).

The varve-thickness maximum at 430–450 m in Manila Creek valley probably correlates with maximal advance of the Sanpoil sublobe, and the thickening of varves above 486 m

**Figure 8.** Vertical trends in grain size and sedimentary structures within flood beds in the axial part of the Sanpoil River valley (see pl. 2*A* and fig. 6 for locations). ***A***, Simply graded flood bed (F-8) at Old Keller locality. Analogy with marine turbidites refers to intervals of Bouma (1962, p. 49). Sand was sieved, silt and clay measured with an electroresistance particle-size analyzer, and mean size calculated with moment statistics (Griffiths, 1967, p. 87-88). ***B***, Complexly graded flood bed (F–3) at Henry Kuehne locality (see fig. 25*A*). Mostly unlaminated, normally graded sand layers, similar to those shown in figures 8*C* and 9, make up most of bed F–3 at this locality. The bed does, however, show overall upward fining in its upper half, where there is gradation, despite interruption by turbidites, from bedded sand through laminated silt to structureless silty clay. Varved interval V–3 and the uppermost part of flood bed F–2 are missing below bed F–3, but they may be sources of the rip-up clasts of varves and flood-bed clay within bed F–3. ***C***, Complexly graded flood bed at Sage Trig locality. Graded, mostly unlaminated sand layers, probably derived upslope from this flood bed and deposited by high-density turbidity currents (compare Lowe, 1982, p. 286, 291, 292), interrupt both the normal grading of laminated parts of the flood bed (F) and the sequence of varves in the overlying varved interval (V). Tops of several of the turbidites display ripples (r) on which the overlying deposits are draped. Currents indicated by these ripples, and by similar ripples at the Henry Kuehne locality, ran mostly toward the axis of the Sanpoil River valley (pl. 2*A*, stippled paleocurrent wedges). Some turbidites are abundantly invaded by flame structures (f) from laminated silt of the flood bed, and some contain detrital fragments of varves (d). The boulders (b) were probably dropped from bergs. Total thickness of the flood bed is 2.0 m; shovel blade is at top of the bed. Shovel handle is 0.5 m long.




*A*




***B***

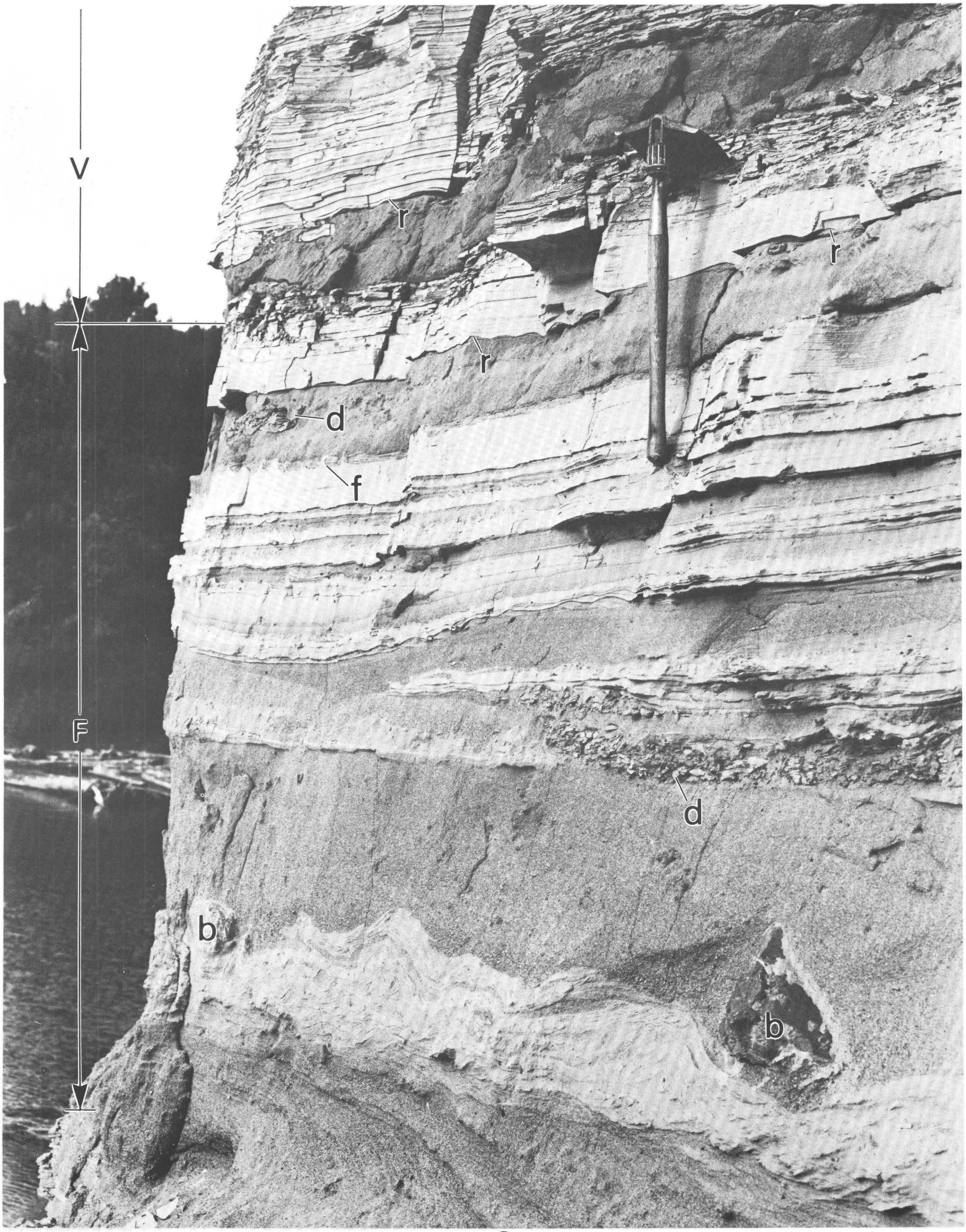



Figure 8. Continued.

probably correlates with progradation of a Sanpoil River outwash plain past the mouth of Manila Creek. These correlations are based on the premise that varve thickness increases with nearness to sediment source, as revealed in the Sanpoil River valley by upvalley thickening and coarsening of varved intervals (figs. 6, 9) and shown elsewhere by Ashley (1975) and Gustavson (1975, p. 260-261). The correlations are also based on two lines of evidence from Manila Creek valley: (1) Diamictons in the composite Manila Creek section are concentrated at 443–451 m (pls. 2*B*, 3). As interpreted below in the section entitled "Diamictons," the diamictons at 443–451 m were probably deposited from floating ice or from ice-front debris flows while the Sanpoil sublobe was maximally advanced. Thus the thick varves at 430–450 m overlap a stratigraphic interval from which there is independent evidence of maximum glacial advance. (2) With Lake Columbia at 500 m, varves above 486 m could not have formed in water deeper than 14 m, whereas the thick varves at 430–450 m must have formed in at least 50 meters of water. Consequently, a Sanpoil River outwash plain (Flint, 1936, p. 1873; Cochran and Warlow, 1980, p. 55) prograding into Lake Columbia near Manila Creek valley more probably correlates with the thick varves above 486 m than with the thick varves lower in the section. Because this outwash plain probably aggraded faster than did the lake bottom in Manila Creek valley, Lake Columbia's Manila Creek arm was probably tranformed into an isolated, outwash-dammed lake whose direct backflooding by the Sanpoil River produced the thick varves above altitude 500 m.

Other aspects of varved-interval sedimentology include the following:

(1) Does the typical rhythmic couplet really represent one year? Treating couplets as varves, I infer a 2,000- to 3,000-year lifespan for Lake Columbia (see section below entitled "Okanogan Lobe"). This inferred lifespan is about one-third the maximum allowed by the history of advance and

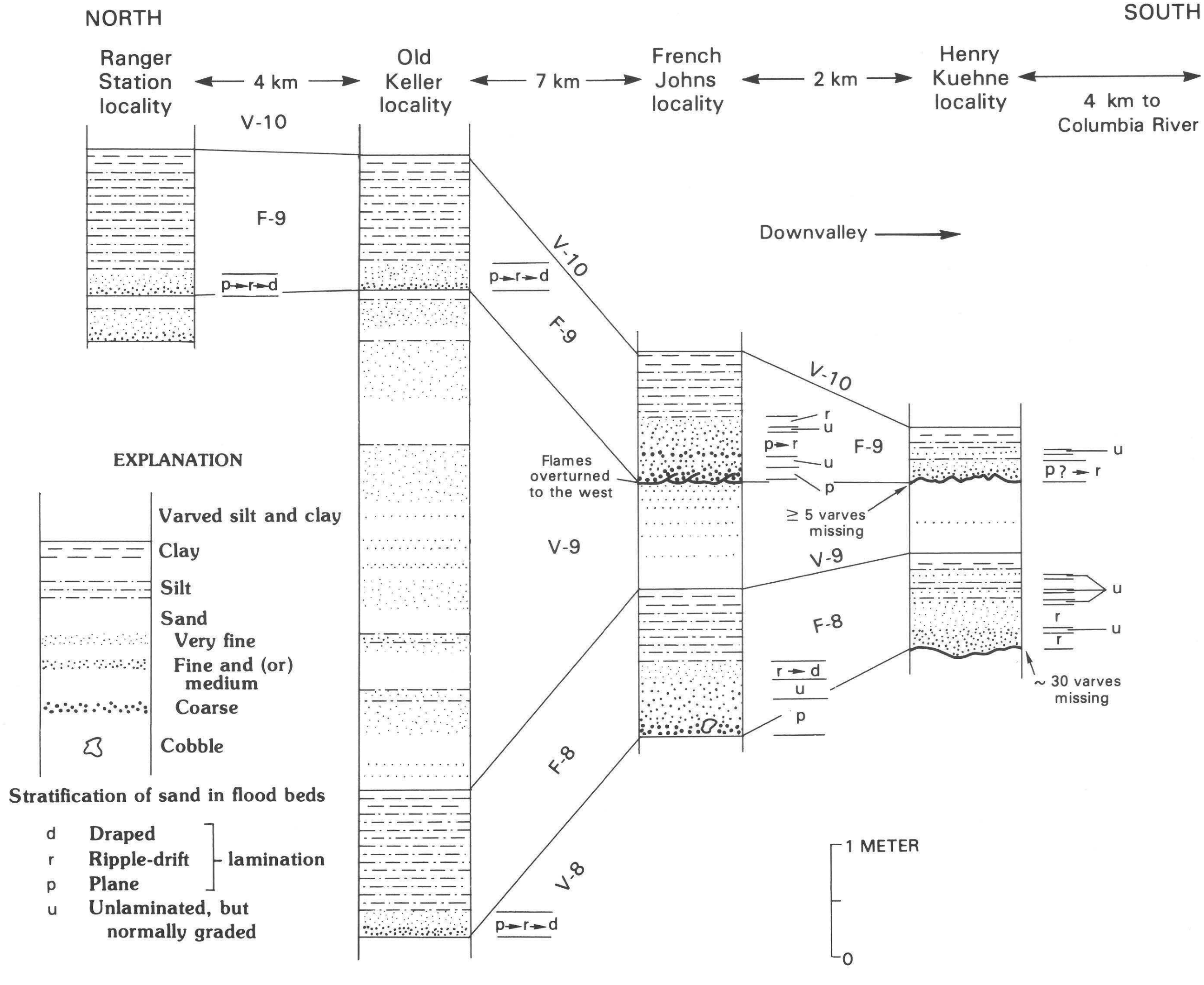



**Figure 9.** Changes in the grain size and thickness of flood beds F–8 and F–9 and varved interval V–9 in the axial part of the Sanpoil River valley. Though not shown this way in the figure, bed F–9 thickens locally to at least 2.2 m at the Henry Kuehne locality, with nearly all additional thickness taken up by sand and accommodated by erosion into V–9 and F–8 (fig. 6).

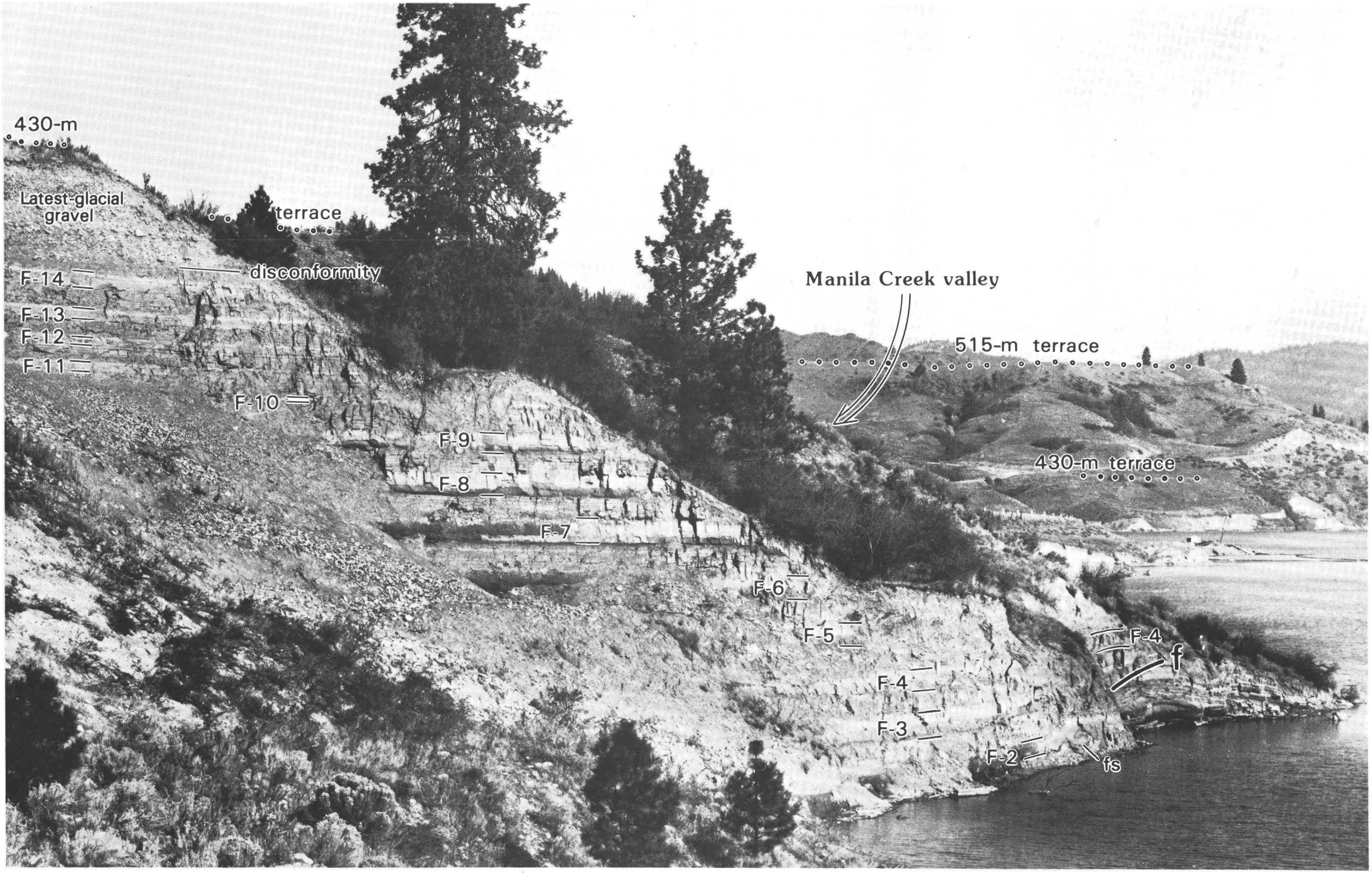



**Figure 10.** Disconformity between latest-glacial gravel (upper left) and full-glacial lacustrine deposits at French Johns locality (pl. 2). View is northward, up the Sanpoil River valley and across the mouth of Manila Creek valley. Bottom of exposure is at altitude 393 m (normal level of Franklin D. Roosevelt Lake, the reservoir at right). The more complete lacustrine section in Manila Creek valley has its base near altitude 400 m (pl. 2*B*) but extends up to about the altitude of the 515-m terrace visible in the distance. The northernmost part of the lacustrine section at French Johns locality is complicated by tilting and partial truncation of beds below F–4 (see also the varves labelled "t" in figure 13 and "d" in figure 20). This tilting and truncation, and also the large flame structure (fs) in bed F–2, resulted at least in part from glacial shove or landslide slip along a low-angle fault (f). The several thin light-colored strata below the fault are the thin, brown-topped flood beds shown in figures 13 and 22.

retreat of the Okanogan lobe: the lobe advanced across the Canada-United States boundary sometime after 19,000 yr B.P. and perhaps as late as about 17,000 yr. B.P. (Clague and others, 1980); the lobe retreated from the Columbia River valley to a point about 15–20 km up the Okanogan River valley by 11,200 yr B.P. (Porter, 1978, p. 39; age as revised by Mehringer and others, 1984); and the lobe vacated at least some areas at altitude 1,000 m near the international boundary by 10,000 yr B.P. (Mack and others, 1979, p. 214-216). Possibly the Okanogan lobe blocked the Columbia River during only one-third of the time that it lay south of that boundary, for only one-third of the lobe's American excursion was south of the Columbia (pl. 1). The time represented by the typical rhythmic couplet in the Sanpoil River valley thus should not exceed three years and may well equal one year.

(2) What is the origin of the layers of medium and coarse sand in varved intervals near Manila Creek (figs. 7, 8*C*, 20; pl. 3)? Most of these layers were probably laid down by high-density turbidity currents (compare Lowe, 1982, p. 286, 291, 292) derived from unstable deposits of flood-bed or deltaic sand (fig. 8*C*, sand layer above shovel). Some thin,

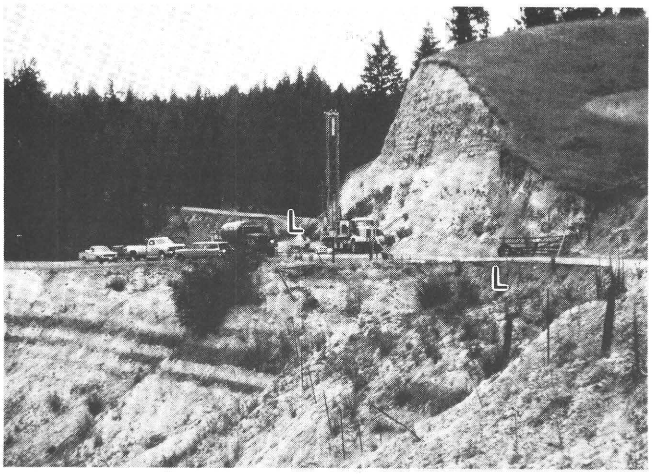



**Figure 11.** Setting of boreholes 2 and 3 and of exposures at Arrieta locality, Manila Creek valley (pls. 2, 3). The upper part of the Arrieta exposure is the roadcut above the drill rig; for a closeup of this roadcut, see Waitt (1985, his fig. 14). The lower Arrieta exposure is the dissected landslide scarp below the other vehicles. Old Manila Creek Road shows damage from landslides (L). Manila Creek itself is out of view to the left, flowing toward camera. Trees conceal Switchback locality, up Old Manila Creek Road about 400 m from the drill rig. August 1983.

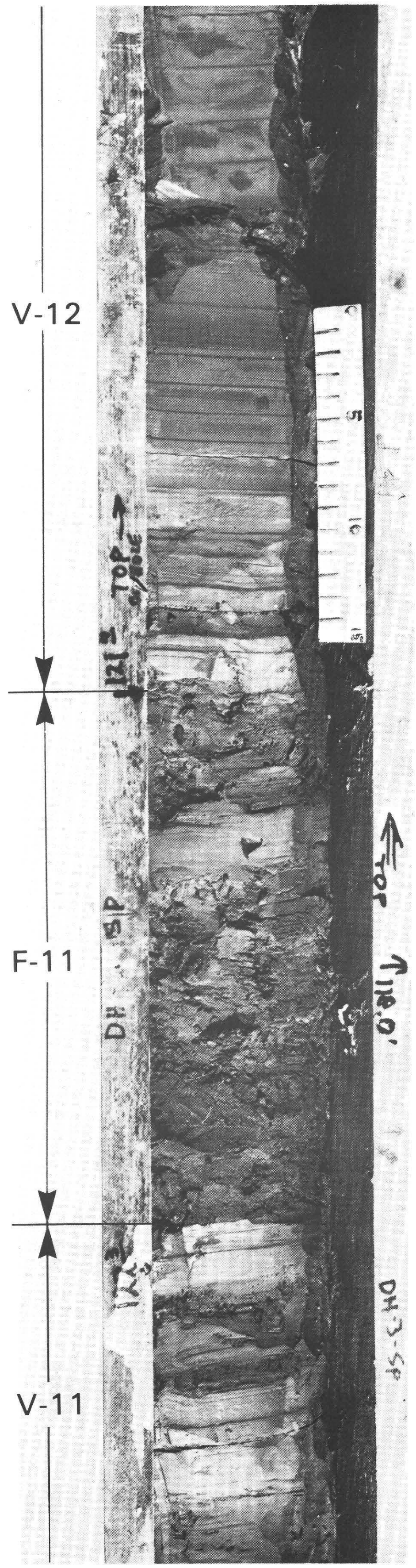



**Figure 12.** High-quality core of flood bed F–11 and bracketing varves, borehole 3, Manila Creek valley. Scale in centimeters.

unlaminated and ungraded layers at the French Johns locality, however, may be sedimentary sills injected during floods, for they lithologically resemble flood-bed sand but appear chiefly in the upper part of varved intervals (pl. 3, intervals V–2, V–6, V–8, V–10, V–13, V–14; see also layers labeled mcs in fig. 7 and s in fig. 20). Such sills disrupt interflood varves of the Latah Creek section, near Spokane (pl. 1; Waitt, 1984, p. 54-57).

(3) Do varved intervals of the Sanpoil River valley contain deposits of periodic floods from sources other than Lake Missoula? Non-Missoula floods may account for the rhythmic intercalation of thick, graded layers between sets of a few varves in a least two places: (a) in varved interval V–9 at the Ranger Station locality (below the lowest deposits shown in figs. 6 and 9); and (b) in four or five successive varved intervals at altitude 486–492 m at the Switchback locality (pl. 3). Absence of such rhythmic interbedding in southerly exposures of interval V–9 indicates that at least some of the inferred non-Missoula outbursts were small floods from the Sanpoil River drainage.

## Flood Beds

Like the varved intervals, flood beds in the Manila Creek section have properties that vary greatly with stratigraphic position (fig. 17). In the lower half of the composite section (at the French Johns locality and below altitude 455 m in the boreholes), most flood beds are at least 1 m thick, most grade from basal fine or medium sand to silty clay at their tops, and erosion at the base of some beds locally cuts deeply

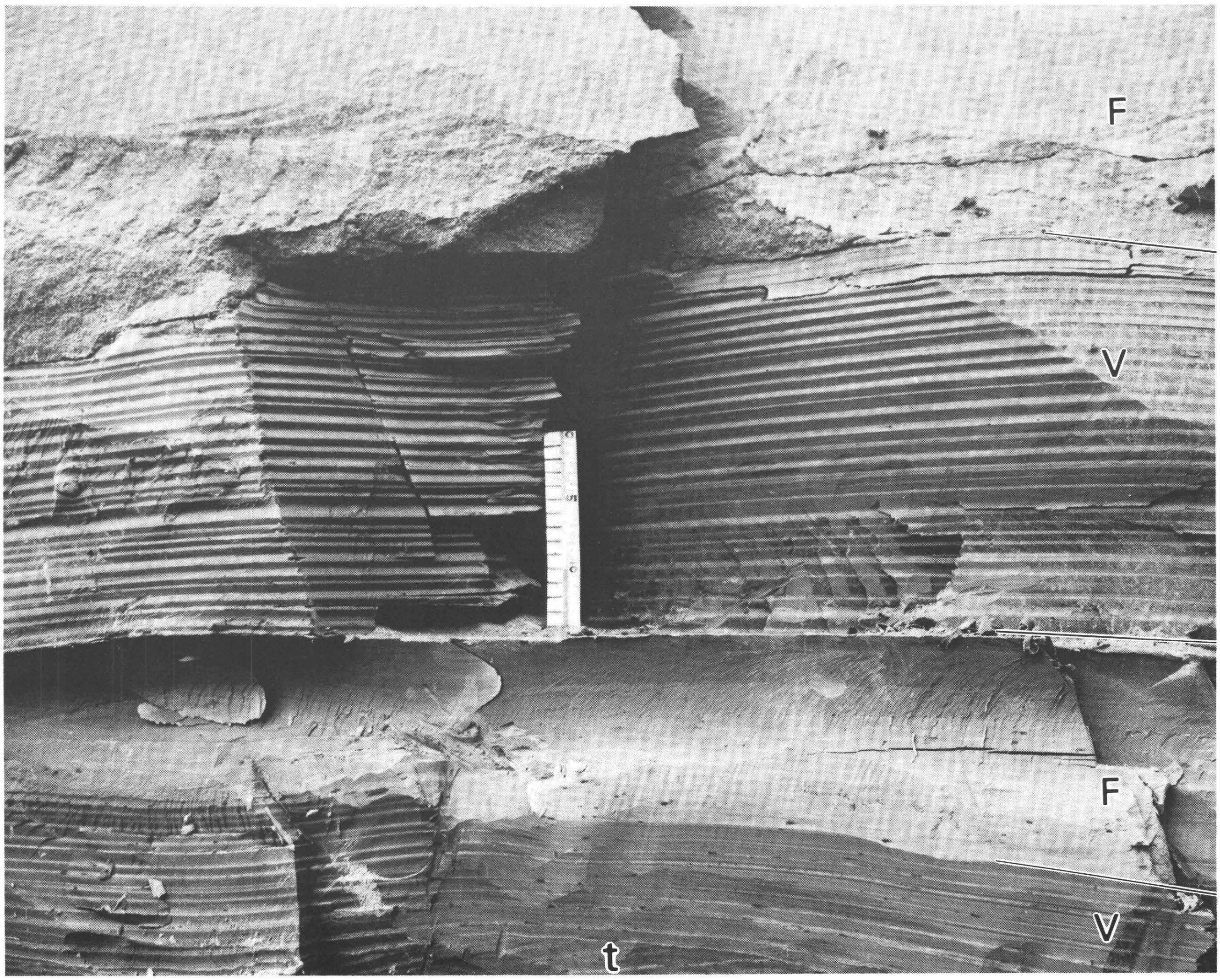



**Figure 13.** Varved intervals (V) and flood beds (F) low in composite Manila Creek section, in northernmost part of French Johns locality. The varved interval in the middle contains 27 or 28 varves; another 4 varves are preserved nearby, higher in the interval. Medium sand of the overlying flood bed not only cuts into this varved interval, it cuts out an entire flood bed and an entire varved interval that intervene nearby (fig. 22). By contrast, the base of the lower flood bed in the picture is only slightly disconformable. Truncated varves (t) indicate low-angle faulting within the lower varved interval. Scale in centimeters.

unto underlying varves and even into underlying flood beds. Such erosion is especially common in the axial part of the Sanpoil River valley south of the Manila Creek area (figs. 6, 9, 21). It is also notable in outcrops at the French Johns locality (figs. 13, 22) and in borehole 2, where erosion at the base of one or more flood beds at altitude 407–423 m has removed at least three varved intervals between interval V-9 and the set of thin, brown-topped flood beds (pls. 2*B*, 3). By contrast, few flood beds above altitude 456 m are thicker than 1 m, few appear to cut deeply into underlying deposits, and most grade upward from interlayered very fine sand and silt to mud (fig. 15) that feels poorer in clay than the uppermost parts of lower flood beds. The highest flood beds are only 5–10 cm thick and consist entirely of such mud (fig. 16).

The overall upsection decrease in thickness, maximum grain size, and erosiveness of flood beds coincides with an overall upsection decrease in number of varves per varved interval (fig. 17; see also fig. 23*A*). This coincidence suggests that flood magnitude varied directly with flood frequency, a logical relation for floods from a self-dumping lake if that lake's inflow is fairly constant (figs. 3*A*, 3*B*). The apparent upsection decrease in clay content of the uppermost parts of flood beds may be due to shoaling; sedimentary filling of Manila Creek valley decreased the thickness of water from which clay could settle after a flood.

Many flood beds depart from the overall trends in thickness, grain size, and erosiveness without necessarily indicating anomalous flood magnitude within the Sanpoil River valley. Some flood beds pinch and swell in outcrop. An extreme example is the flood bed at altitude 474 m: only 5 cm thick where I logged it, this bed swells to 30–50 cm thick a few tens of meters along the outcrop. Such local variation in flood-bed thickness suggests local differences in sedimentation within Manila Creek valley rather than regionally significant differences in flood magnitude. The upsection thickening of flood beds beginning at altitude 490 m (pls. 2*B*, 3; fig. 17) does not appear to be an artifact of my logging. Though accompanied by no great departure from the vertical trends in

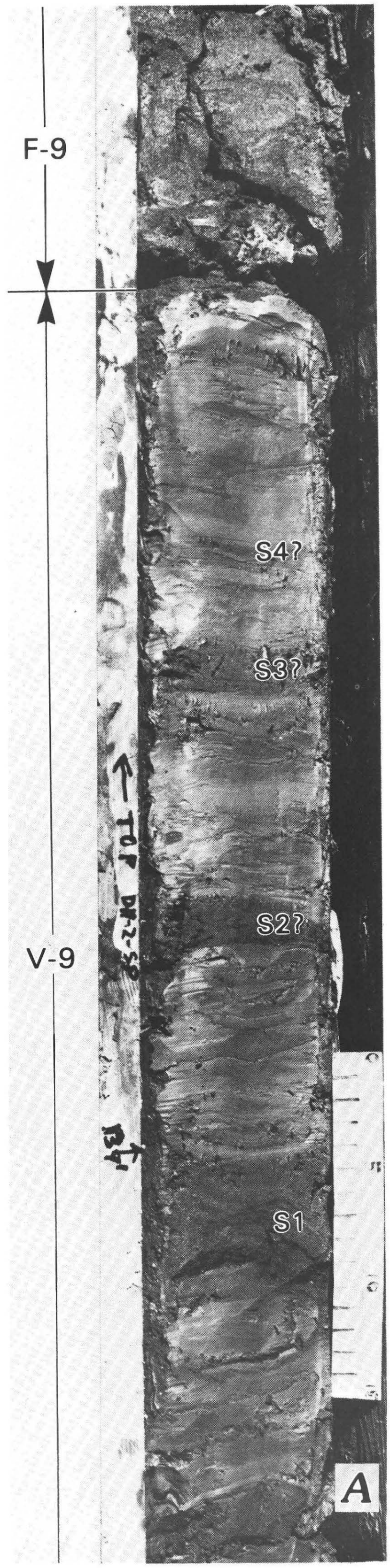



**Figure 14.** Upper part of exceptionally sandy varved interval V–9 low in composite Manila Creek section, as seen in core from borehole 2 (*A*) and in outcrop at French Johns locality (*B*). About 0.9 m thick in the Manila Creek area, V–9 thickens northward to at least 4.5 m, mostly by thickening of sand (fig. 9). The correlated sand layers (numbered) are wet (dark) in the core and dry (light) in the outcrop. Between sand layer s1 and the top of V–9, I counted 10–15 varves in the core, 11–14 varves in the outcrop. Flood bed F–9 is abundantly injected with flame structures (f) from V–9 at French Johns locality. Scale in centimeters.


Figure 14. Continued.


V
F
V
F

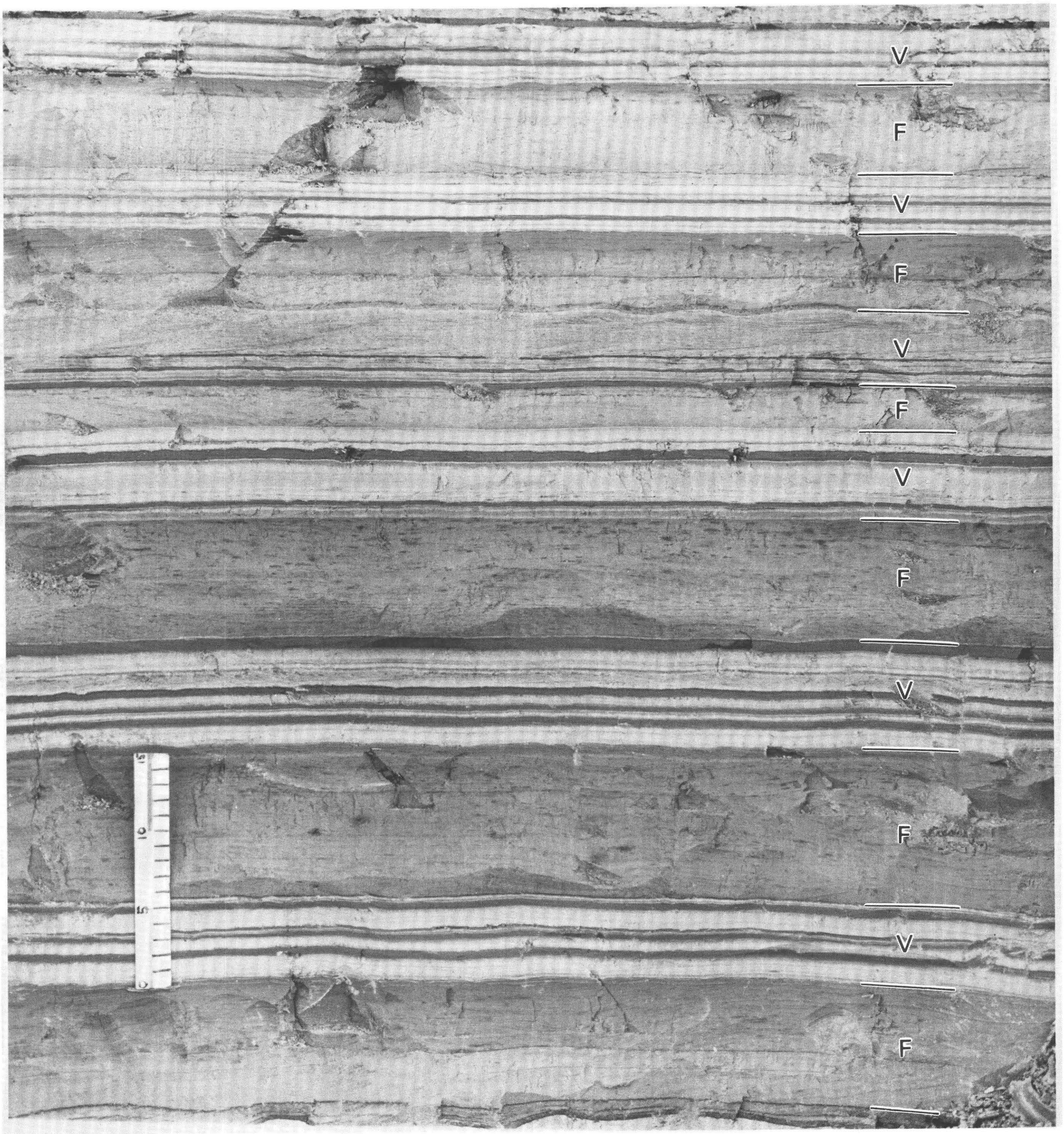



**Figure 16.** Varved intervals (V) and flood beds (F) at Switchback locality, high in composite Manila Creek section (pl. 2). I estimate 3 varves in the lowest fully visible varved interval, 2–4 varves in the next higher varved interval, and 1–2 varves in each of the three succeeding ones. The flood beds closely resemble the upper parts of many flood beds lower in the section, such as the top third of the upper flood bed shown in figure 15. The uppermost flood bed may represent the last late-Wisconsin outburst from Lake Missoula. Scale in centimeters.

**Figure 15.** Varved intervals and flood beds in roadcut at Arrieta locality (fig. 11), near middle of composite Manila Creek section (pl. 2). I counted 20–22 varves in the lower varved interval. The lower two-thirds of the overlying flood bed consists of very fine sand and coarse silt in laminae 0.5–3.0 mm thick; these grade upward into mostly unlaminated medium silt. A shovel blade scraped the lines across varves in the lower varved interval. Scale in centimeters.

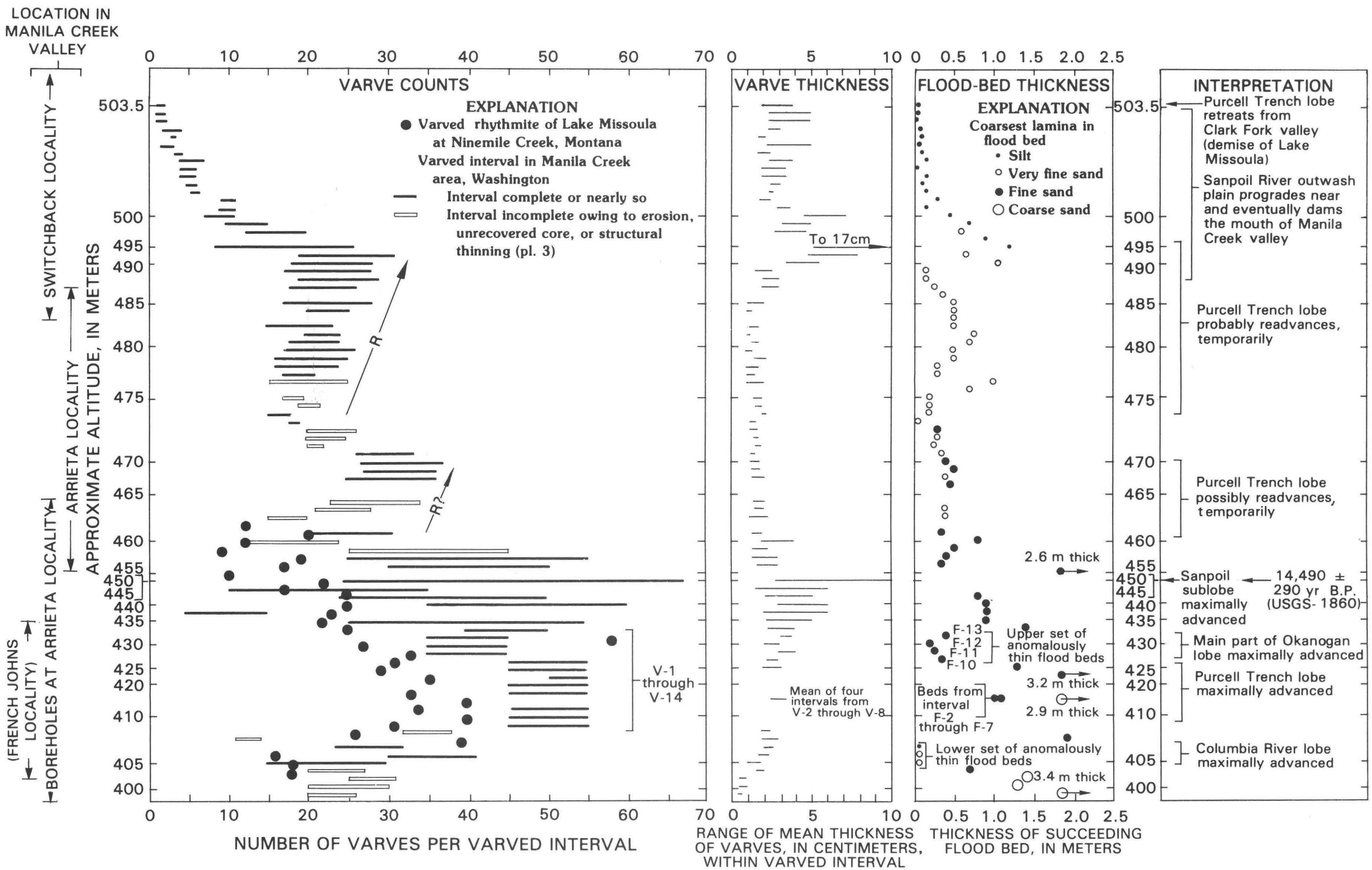



**Figure 17.** Vertical trends in ranges of varve counts, in ranges of mean varve thickness, and in flood-bed thickness near Manila Creek, and some of the glacial, lacustrine, and fluvial events inferred from these data. Ordinate divided into 89 even increments each corresponding to a known or inferred flood bed and to the known or inferred interval of varves beneath that bed. Varve-count ranges for intervals V–1 through V–14 are composited from estimates made in the axial part of the Sanpoil River valley (table 1, "likely range"); all other Manila Creek counts are from boreholes and exposures in Manila Creek valley, as are all the thickness data. The varve-count ranges are compared with varve counts by Chambers (1971, app. III) from bottom-sediment rhythmites of Lake Missoula. The Lake Missoula counts are fitted visually to the Manila Creek counts with presumption that non-deposition and erosion prevent the Lake Missoula data from recording all of interflood time (see Chambers, 1971, p. 30, 59). Arrows labelled R highlight two reversals of overall decline of varve counts in the upper part of the Manila Creek section. See figure 1 or plates 1 and 2 for location of named places.

flood-bed grain size, this thickening does coincide with abrupt thickening of interbedded varves (fig. 17). Perhaps the prograding Sanpoil River outwash plain formed a new sediment source that was tapped by these late floods as they entered Manila Creek valley.

Other anomalous flood effects are present far more widely, probably at least throughout the Sanpoil River valley, as two sets of anomalously thin, fine-grained, scarcely erosive flood beds in the lower half of the Manila Creek section (the correlated flood beds in pl. 2*B*). The lower set is known only from the French Johns locality (four beds, of which the topmost is much eroded; figs. 13, 22) and from the interval 405–407 m in borehole 2 (three beds preserved). Beds of the lower set are 7–15 cm thick at French Johns locality and 2.5–4.5 cm thick at borehole 2. They are mostly sand-free, though the top bed at each locality contains matrix-supported sand grains and granules probably dropped from icebergs. Each bed of the lower set grades upward from silt to silty clay at the French Johns locality; silty clay predominates in borehole 2. In both places the silty clay is browner than clayey parts of adjacent varves. Basal erosion locally cuts into underlying varves but not as much as with flood beds immediately above and below the set.

The four thin flood beds of the upper anomalous set extend at least 13 km along the Sanpoil River valley axis (beds F–10 through F–13; figs. 6, 23–25). In the Manila Creek area, the thickness of individual beds in the upper set ranges from 25 cm (fig. 12) to 60 cm. The lowest bed is brown (2.5Y 5/2 – 10YR 5/4) in its uppermost part, but the other three are mostly gray (5Y 5/2) throughout. Grains coarser than fine sand either are absent or are restricted to basal layers. These basal layers are thinner and more comformable than their counterparts elsewhere in the lower half of the Manila Creek section.

The floods represented by the two sets of thin flood beds probably became attenuated on the way to the Sanpoil River valley rather than at the floods' source. Varves between the thin flood beds are about as numerous as varves between thick flood beds above and below each set (figs. 17, 23). Varve counts thus indicate no substantial change in flood frequency; if the flood source was a self-dumping ice-dammed lake with fairly constant inflow, this implies no great change in flood magnitude at that source. Later in this paper, in proposing a proxy chronology for the Okanogan and Columbia River lobes, I suggest means by which these ice lobes could have caused Lake Missoula floods to become attenuated on the way to the Sanpoil River valley.

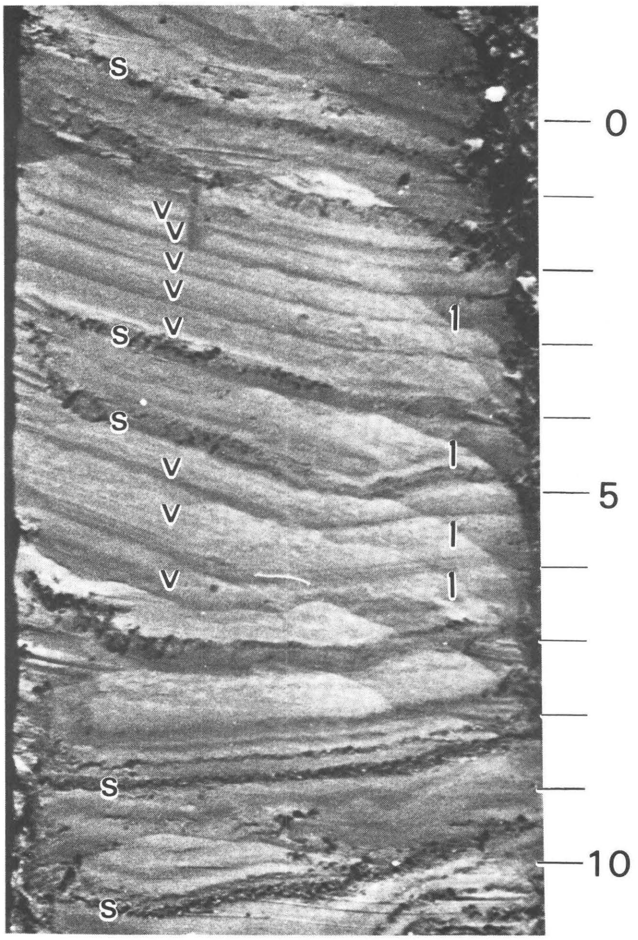



**Figure 18.** Thin varves near bottom of composite Manila Creek section in core from borehole 2 (pl. 2). Simple varves (v) between 0 and 7 on the scale average about 0.5 cm thick, about half as much as the thin varves shown in figure 13. The varves consist of silt and clay whose grainy appearance is due to photographic enlargement. Layers of medium and coarse sand (s) may be turbidites of reworked flood deposits (see figs. 8C and 25). Lines (l) crossing the lamination at right are ridges left by knife. Scale in centimeters.

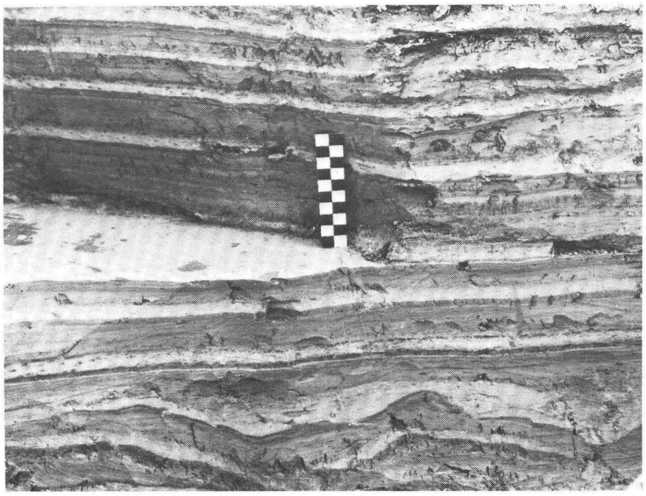


**Figure 19.** Thick varves near top of composite Manila Creek section, Last Chance locality (pl. 2). Light layers are coarse silt, dark layers finer silt and clay. Scale, showing 1-cm increments, rests on contact between two of the varves.

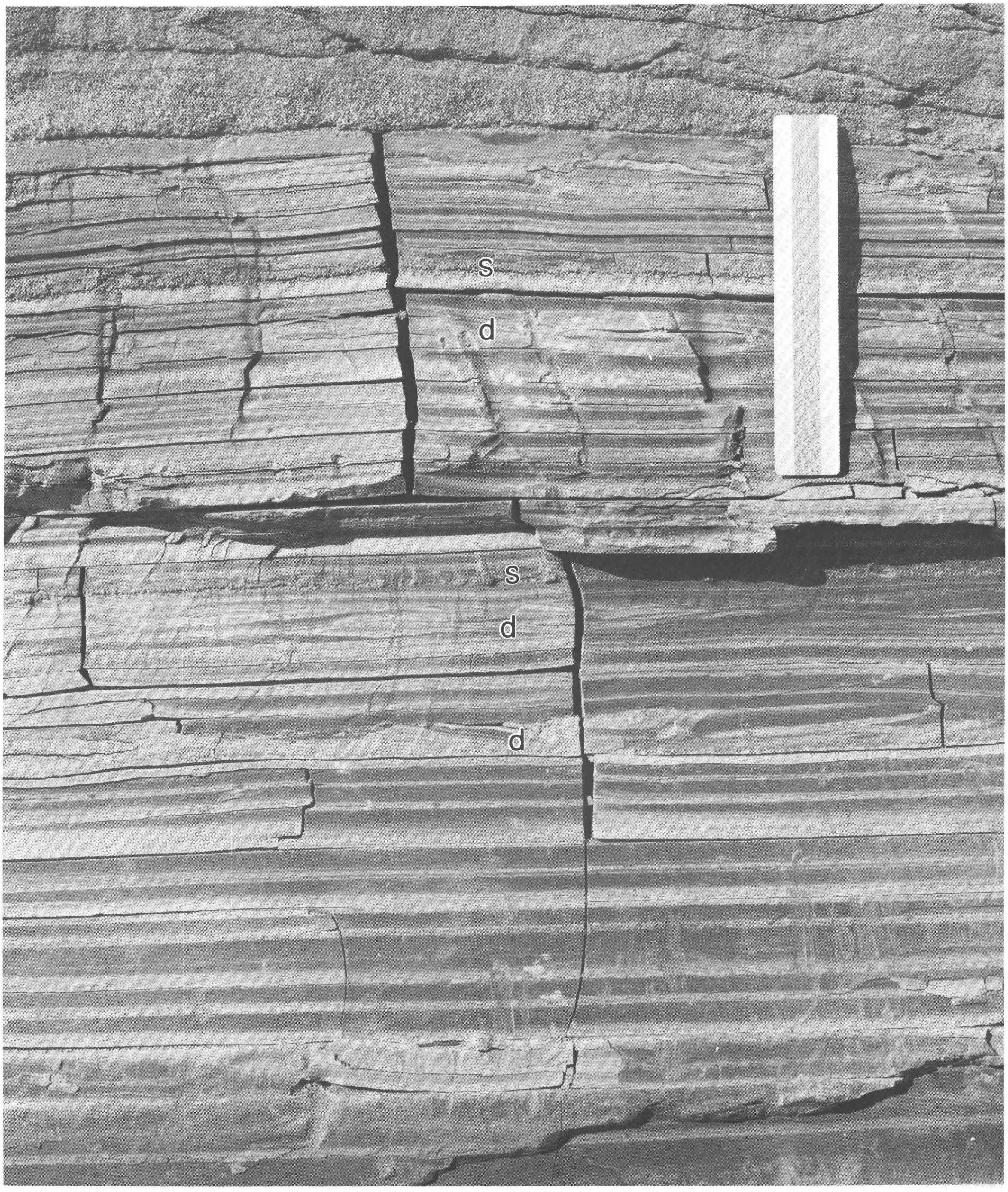



**Figure 20.** Thin layers of medium and coarse sand (s) in upper part of varved interval V–2, French Johns locality. The sand closely resembles the sand in the lowermost part of overlying flood bed F–2. No such sand is present in the lower part of varved interval V–2 at this site (pl. 3). Perhaps these sand layers are sedimentary sills. If so, their injection may have occurred during deposition of F–2, or during the deformation that is indicated by the disrupted varves (d) in this photograph, by the flame structure and low-angle fault shown in figure 10, and by the truncated varves shown in figure 13. Alternatively, the sand layers are turbidites analogous to those identified in figures 8*B*, 8*C*, 18, and 26. Scale is 17 cm long.

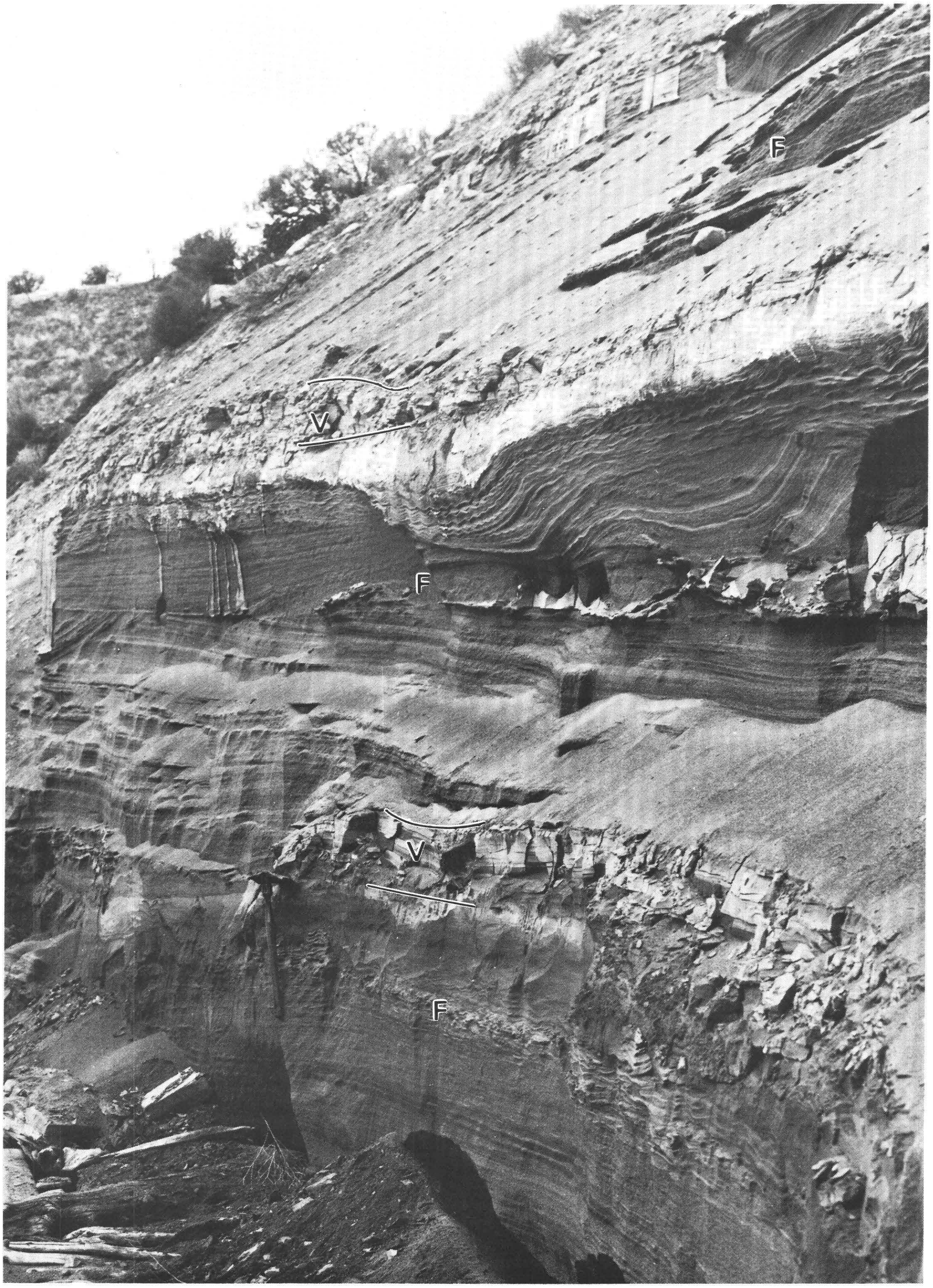



**Figure 21.** Three highly erosive flood beds (F) and erosional remnants of varved intervals (V), Ferry Slip locality (pl. 2*A*, fig. 6). Shovel blade, left of center, marks top of the lowest flood bed, erosive base of the next higher flood bed, and edge of the eroded varved interval that intervenes to the right. A long horizontal rip-up clast from a varved interval appears at right within the middle flood bed. The uppermost flood bed, here mostly covered with colluvial sand, consists largely of cross-stratified coarse sand in sets as thick as 2 m. Foreset laminae in this sand dip west-southwest (basal-sand paleocurrent, pl. 2*A*). Missing here between the middle and uppermost flood beds is a fourth flood bed that, along with some overlying varves, was spared erosion in an area out of view to the right. Shovel handle is 0.5 m long.

Currents depositing flood beds apparently ran both up and down Manila Creek valley (pl. 2*A*). Upvalley-running currents are recorded by ripple-drift crosslamination in the lowermost parts of two flood beds at altitude 469–476 m in the Arrieta exposure. Both these beds contain succeeding downvalley-dipping ripple foresets (pl. 2*B*, beds labeled FUD; pl. 3). Like flood beds in the axial part of the Sanpoil River valley (for example, bed F–10, fig. 24), and like Missoula-flood beds in southern Washington (Waitt, 1980, p. 667) and northern Idaho (Waitt, 1985, p. 1278), these beds register initial ascent and subsequent drainage of a backflooded valley.

Unsolved problems of flood-bed sedimentology include the following:

(1) Were any flood beds in the Sanpoil River valley deposited chiefly by turbidity current? Slackwater deposits of Lake Missoula floods commonly look like turbidites, both in southern Washington (Baker, 1973, p. 46) and in the Sanpoil River valley (fig. 8*A*). However, as shown by Waitt (1980, 1985), floodlaid rhythmites in southern Washington accumulated chiefly from flows in which the water moved the sediment; most of these rhythmites should not be called turbidites, for in a turbidity current the sediment moves the water. The situation seems less clear-cut for flood beds of the Sanpoil River valley. Whereas large floods may have engulfed and entrained low-level Lake Columbia, small floods may have become turbidity currents upon entering the lake. Perhaps all Missoula-flood beds in the Sanpoil River valley are turbidites to some degree. Nevertheless, probably the only pedigreed Missoula-flood turbidites of the Sanpoil River valley are the layers of mostly structureless sand that interrupt the upward fining of flood beds in the lower part of the valley (figs. 8*B*, 8*C*, 9, 26).

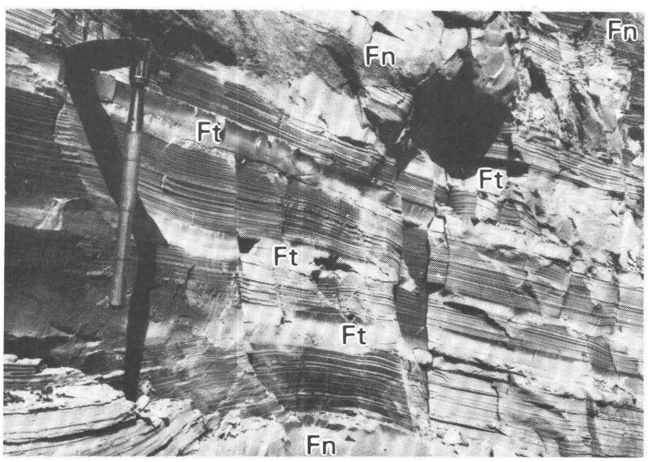



**Figure 22.** Four exceptionally thin, brown-topped flood beds (Ft) in northernmost part of French Johns locality (fig. 10; pls. 2*B*, 3). The topmost of these beds is fully preserved at right but mostly eroded at left. Flood beds of normal thickness (Fn) appear at top and bottom of view. Lines on shovel handle are 10 cm apart.

(2) Why do the flood beds lack reverse grading in their lowermost parts? An outburst flood from a self-dumping lake commonly waxes more slowly than it wanes (Thorarinsson, 1939, p. 227) because subglacial tunnels enlarge during the flood more slowly than they collapse after the ice dam loses buoyancy (Nye, 1976). Therefore the deposit of a glacial-outburst flood might coarsen upward in its lowermost part. Waitt (1984, p. 51–54) describes such upward coarsening in Missoula-flood beds of Latah Creek valley and glacial Priest Lake (pl. 1). In floodlaid deposits of the Sanpoil River valley, however, I have seen no upward coarsening except in the layers at 486–492 m (pl. 2*B*, Switchback locality) that suggest outbursts from a self-dumping lake other than Lake Missoula. The lack of reverse grading in Missoula-flood beds of the Sanpoil River valley could mean that Lake Missoula's tunnels enlarged so rapidly that peak discharge had caught up with lesser, earlier discharge by the time flood water reached the Sanpoil River valley. This speculation is consistent with Bretz's (1969, p. 517) view that the flood front downstream of Wallula Gap (pl. 1) was a "great wall of water, its crested front constantly outrunning and overrunning its basal portion." Alternatively, the lack of reverse grading may signify that high-energy peak flows eroded the deposits of earlier, lower energy flows, or that peak flows were damped in flood-swollen Lake Columbia.

## Diamictons

Beds of mixed clay, silt, sand, and granules, in which the coarse clasts are mostly supported by muddy matrix, are present locally in the lower half of the Manila Creek section (pl. 2*B*, 3). Most of these diamictons are thin: at altitude 406–407 m in borehole 2, two varved intervals and one thin flood bed each contain a flat layer 3–5 cm thick of diamicton with clayey matrix; similar layers crop out in flood beds of partly correlative section at the northern part of the French Johns locality; and higher in the section at borehole 2, interval V–11 contains a granule diamicton with a silty-clay matrix that also forms a flat layer only 5 cm thick.

However, three thick diamicton beds or lenses separated by a few tens of varves apparently form most of the section at altitude 443–451 m in the boreholes. One or more of these may be the "gravelly clay till" found cropping out in Manila Creek valley by McKenzie (1980, p. 38). The coarsest clasts in all three are angular granules and pebbles of quartz and medium-grained biotite granite or granodiorite; the lower two also contain granule-size books of muscovite. These granules and pebbles probably came from granitic and pegmatitic bedrock that, as mapped by Cochran and Warlow (1980) and Atwater and Rinehart (1984), crops out abundantly between Manila Creek and Brush Creek (fig. 1*B*). The lowest of the three thick diamictons probably spans most of the 2-m interval of unrecovered core near altitude 445 m in borehole 3. I have seen only the top 6 cm of this diamicton, near altitude 447 m in borehole 2, and that has a structureless

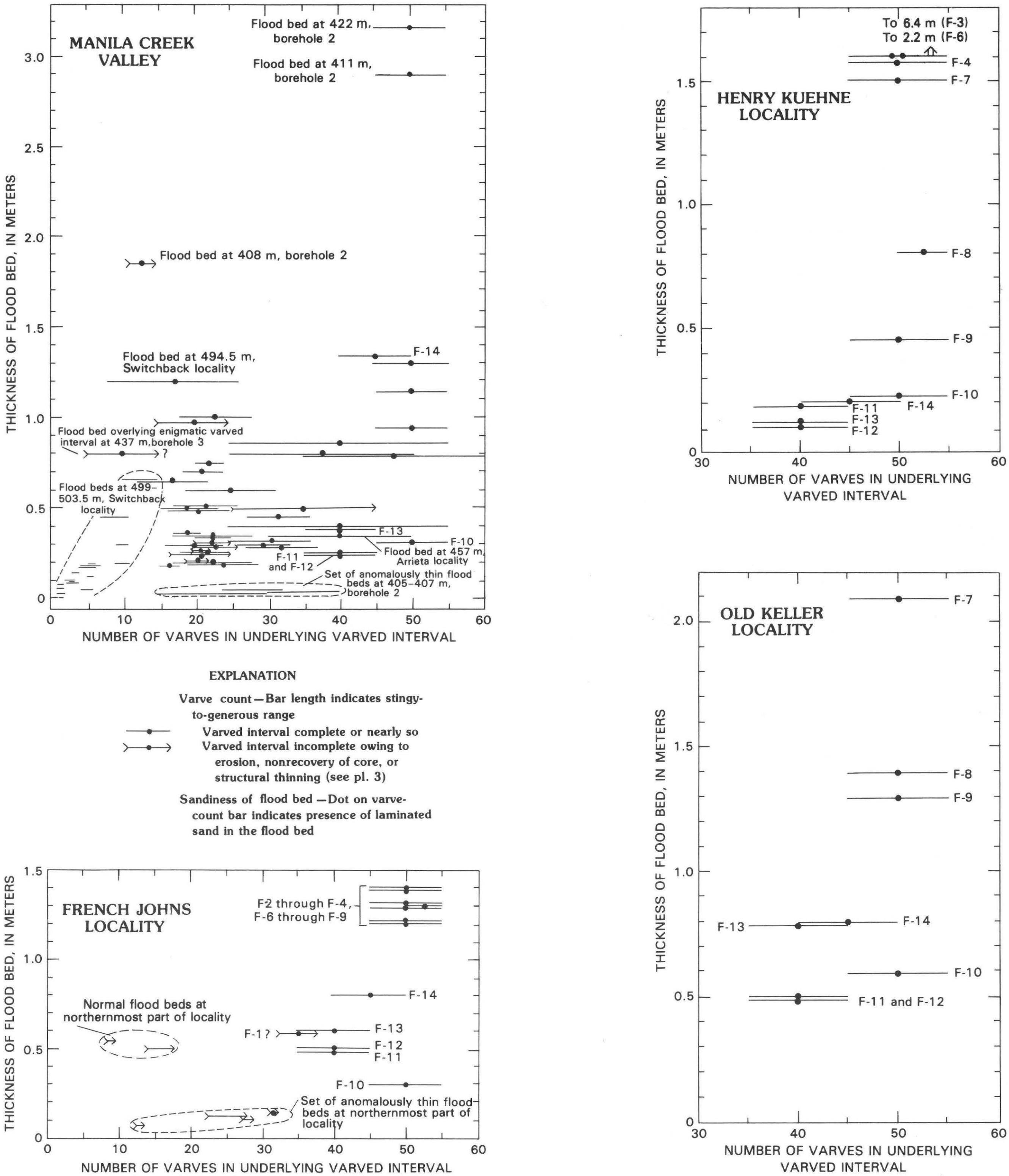



**Figure 23.** Flood-bed (F) thickness versus number of varves in the underlying varved interval. Varve counts for intervals underlying flood beds F–2 through F–14 (that is, varved intervals V–2 through V–14) are the composite estimates given in figure 6 and derived in table 1. In Manila Creek valley, floods recurring more frequently than once a decade produced thin, sand-free flood beds; most floods with greater recurrence intervals produced thicker sand-bearing beds. Note thinness, relative to other beds underlain by several tens of varves, of flood beds F–10 through F–13 (upper set of anomalously thin flood beds) at all localities, and of the flood beds at 405–407 m in borehole 2 and their correlatives at the northernmost part of the French Johns locality (lower set of anomalously thin flood beds).

matrix of silty clay. The middle of the three thick diamictons, demonstrably about 2 m thick, contains a 4-cm layer of very fine to fine sand in borehole 3. Below this sand layer the diamicton's matrix is clay; above it the matrix coarsens upward from clay to sand, then fines to silty clay. The uppermost thick diamicton is 20 cm thick in borehole 3 and 50 cm thick in borehole 2. In both boreholes the matrix is clayey, horizontally laminated, and gradational into succeeding varves. In borehole 2 the uppermost diamicton contains pockets of well-sorted very fine to fine sand.

All diamictons in the Manila Creek section probably were deposited in Lake Columbia, either from icebergs or by debris flows. Those tabular and horizontal diamictons in interval V–11 and below are too thin and nondisruptive to have been deposited at the sole of an overriding glacier; a rain of sediment from dirty floating ice is far more plausible. Lacustrine deposition is also implied by laminated sand and mud in the middle and uppermost diamictons at 443–451 m in the boreholes, and a lacustrine origin may be extrapolated to the lowest diamicton in that interval. It is possible that the middle and lowest diamictons at 443–451 m were deposited as debris flows having an upland source. One such debris flow forms the uppermost part of a flood bed at the Sage Trig locality (fig. 26). At 443–451 m in the boreholes, however, the clustering of thick diamictons and their interbedding with tens of varves imply persistence for decades of a coarse-sediment source unavailable during deposition of the rest of the Manila Creek section. This source was probably a maximally advanced Sanpoil sublobe, which could have plucked granitic bedrock north of Manila Creek valley and delivered angular clasts of that rock to Manila Creek valley by means of ice-front debris flows or dirty icebergs.

If the diamictons at 443–451 m in Manila Creek valley represent subaqueous ice-front debris flows (that is, if they are "subaquatic flow tills" in the sense of Evenson and others, 1977), then the Sanpoil sublobe must have extended into the Manila Creek area during the several decades when those diamictons were deposited. Independent evidence of such extension is equivocal. On the one hand, the northernmost part of the French Johns locality exposes tilted and faulted beds and a large southward-overturned flame structure that may record glacial override (figs. 10, 13, 20; pl. 3). This

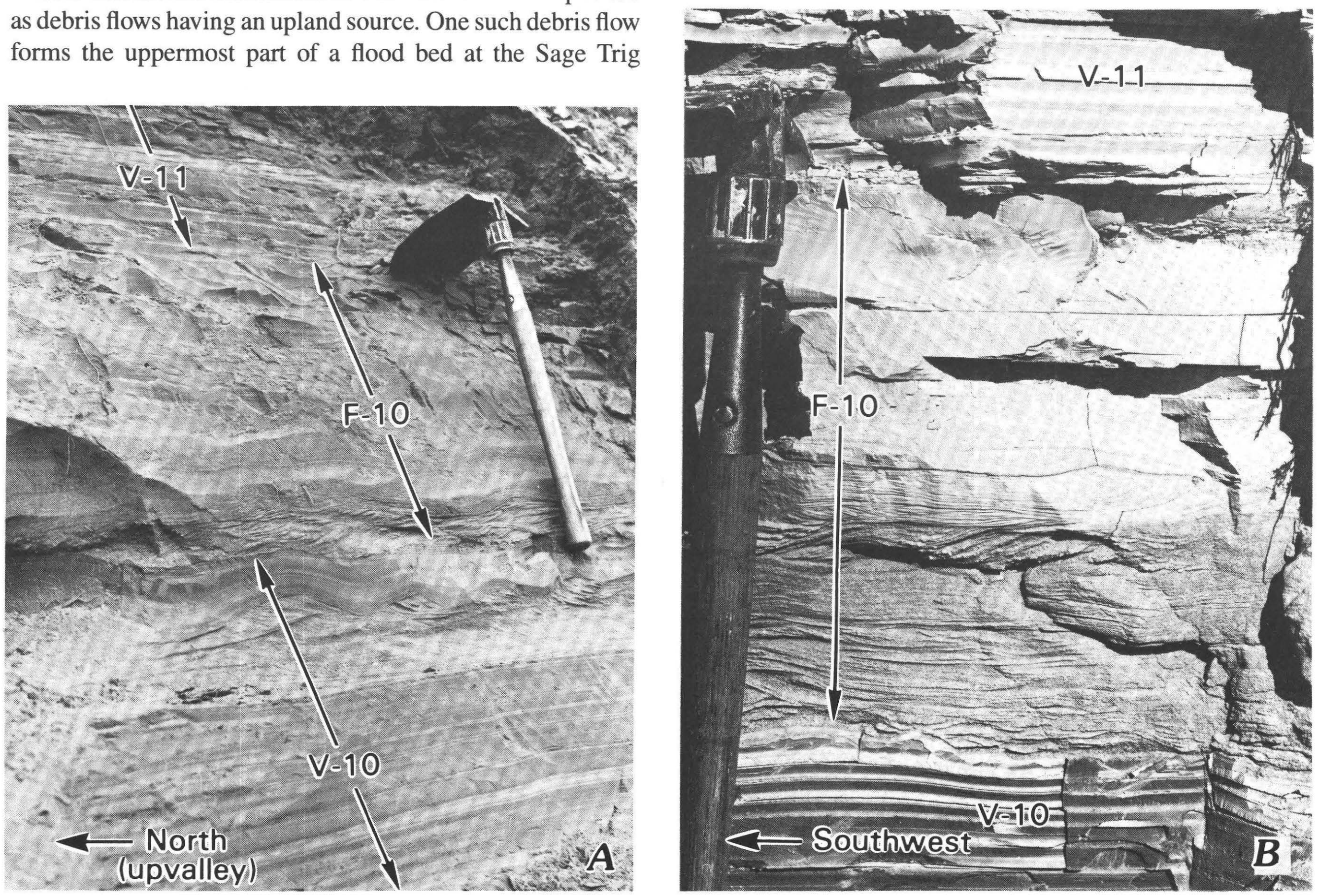



**Figure 24.** Thin flood bed F–10. *A*, At the Ranger Station locality. Ripple-drift crosslamination in lowermost part of bed F–10 indicates upvalley-running flood; in contrast, the cross laminae in the topmost varve of interval V–10 were deposited by downvalley-running meltwater. *B*, At the French Johns locality, 11 km downvalley. True dip of the prominent crosslamination in the middle of bed F–10 is to the south (downvalley), probably because of drainage of flood waters after passing of flood crest. Faint lines on shovel handle are 10 cm apart. See plate 2*A* for map location, figure 6 and plate 2*B* for stratigraphic position.

override could have occurred during deposition of the thick diamictons in Manila Creek valley, for these diamictons postdate the entire glaciolacustrine section at the French Johns locality (pl. 2*B*). On the other hand, there is no comparable evidence of glacial override in the correlatives of the French Johns section that are exposed 6 and 10 km north of Manila Creek at the Old Keller and Ranger Station localities (figs. 6, 24*A*). Therefore, if the Sanpoil sublobe indeed extended into Lake Columbia as far south as Manila Creek, it must have done so without widely deforming some of the soft sediments that it overrode. Perhaps it was an ice shelf that grounded only locally. Alternatively, the deformation at the French Johns locality may be due not to glacial override of any kind but to a landslide that predated completion of the 430-m terrace shown at upper left in figure 10.

## AGE OF THE SECTION

A radiocarbon age and the apparent absence of any major hiatus together indicate a last-glacial age for the entire Manila Creek section. The radiocarbon age, on a single piece of wood from a compound varve (fig. 27) at altitude 449 m in borehole 3, is 14,490 ± 290 yr B.P. (USGS–1860). The only likely sites for a major hiatus are the fault in the northernmost part of the section at the French Johns locality (fig. 10, pl. 3), and the 2.5-m unrecovered interval near altitude 445 m. However, trends in varve counts, varve thickness, and flood-bed thickness cross these potential breaks without interruption (fig. 17). Moreover, if that half of the Manila Creek section below the unrecovered interval at 445 m predated the last glaciation, then correlatives of the lacustrine section at the French Johns locality (fig. 6) should not be so widely exposed.

The radiocarbon age can be extrapolated upward and downward through the Manila Creek section by means of varve counts. For convenience I assume that the dated wood, albeit detrital, is not more than a few decades older than the lacustrine deposit containing it. If this assumption is wrong, then the ages reported below err on the old side. The following estimates use the midpoint of each stingy-to-generous range of varve counts, and also make allowances for varves inferred or known to have been uncounted. The reported uncertainties equal the rounded sum of the 290-yr standard deviation of the radiocarbon age and the errors allowed by the stingy-to-generous range for varve counts.

| | |
|---|---|
| Top of section | 13,050 ± 650 yr B.P. |
| Highest flood bed | 13,350 ± 550 yr B.P. |
| Thin gray-topped flood bed F–11 | 14,800 ± 375 yr B.P. |
| Thin brown-topped flood bed, altitude 406 m, borehole 2 | 15,350 ± 400 yr B.P. |
| Bottom of section and lowest flood bed | 15,550 ± 450 yr B.P. |

Thus, if the wood of sample USGS–1860 accurately dates its host deposit, the 2,000- to 3,000-year period represented by the Manila Creek section probably occurred between 16,000 and 12,400 yr B.P.

Regional ice-sheet chronology limits to 2,500 years the amount by which these age estimates may err on the old side. During the last glaciation, as reviewed above in the section entitled "Varved Intervals," the Okanogan lobe retreated from the Columbia River valley sometime before 11,200 yr B.P. The uppermost part of the Manila Creek section should be no younger than this because, as argued below under the heading "Okanogan Lobe," the Manila Creek section represents nearly all the time when the last-glacial Okanogan lobe dammed the Columbia River to altitude 500 m or more. Thus the estimate for the top of the section (12,400–13,700 yr B.P.) suggests that the detrital wood is no more than 1,200–2,500 years older than the host deposit.

## IMPLICATIONS

### Frequency and Number of Floods from Lake Missoula

The flood history implied by the Manila Creek section corroborates Waitt's (1980) hypothesis of a multiply, periodically self-dumping Lake Missoula. The 89 recorded floods clearly came from a self-dumping lake: regular recurrence prevailed in all but one suspected instance; the period between the last floods was just a few years, consistent with late-glacial thinning of an ice dam; and the period between floods was generally related to the magnitude of flood effects (compare Waitt, 1980, p. 674-675). Moreover, the age and frequency of flooding indicated by the Manila Creek section resemble what has been inferred elsewhere for floods from Lake Missoula.

Known flood beds in the Manila Creek section range in age from 13,350 ± 550 yr B.P. to 15,550 ± 450 yr B.P., with the possibility that this range is too old by as much as 2,500 years (see above). Taken at face value, the range fits neatly between 11,000 yr B.P. and 17,000 yr B.P., the broad limits on floods from Lake Missoula as deduced from regional ice-sheet chronology (Waitt, 1985, p. 1283). Most of the range also fits within these limits if it is 2,500 years too old. Furthermore, the age range of flood beds in the upper part of the Manila Creek section probably overlaps the age of certain ash layers of Mount St. Helens set S. The ash layers, securely dated at about 13,000 yr B.P. (Mullineaux and others, 1978), accumulated in southern Washington and northern Oregon during an interval between two successive, relatively late floods from Lake Missoula (Waitt, 1980, 1985; Baker and Bunker, 1985, p. 31). As many as 18 Missoula-flood rhythmites overlie the set S layers in southern Washington (Waitt, 1985, p. 1284). If these rhythmites correlate one-for-one with the uppermost 18 flood beds in the Manila Creek section, then the uppermost Manila Creek flood bed is 80–145 years younger than the set S layers (varved intervals paired with the uppermost 18 flood beds contain a total of 80–145 varves; fig.

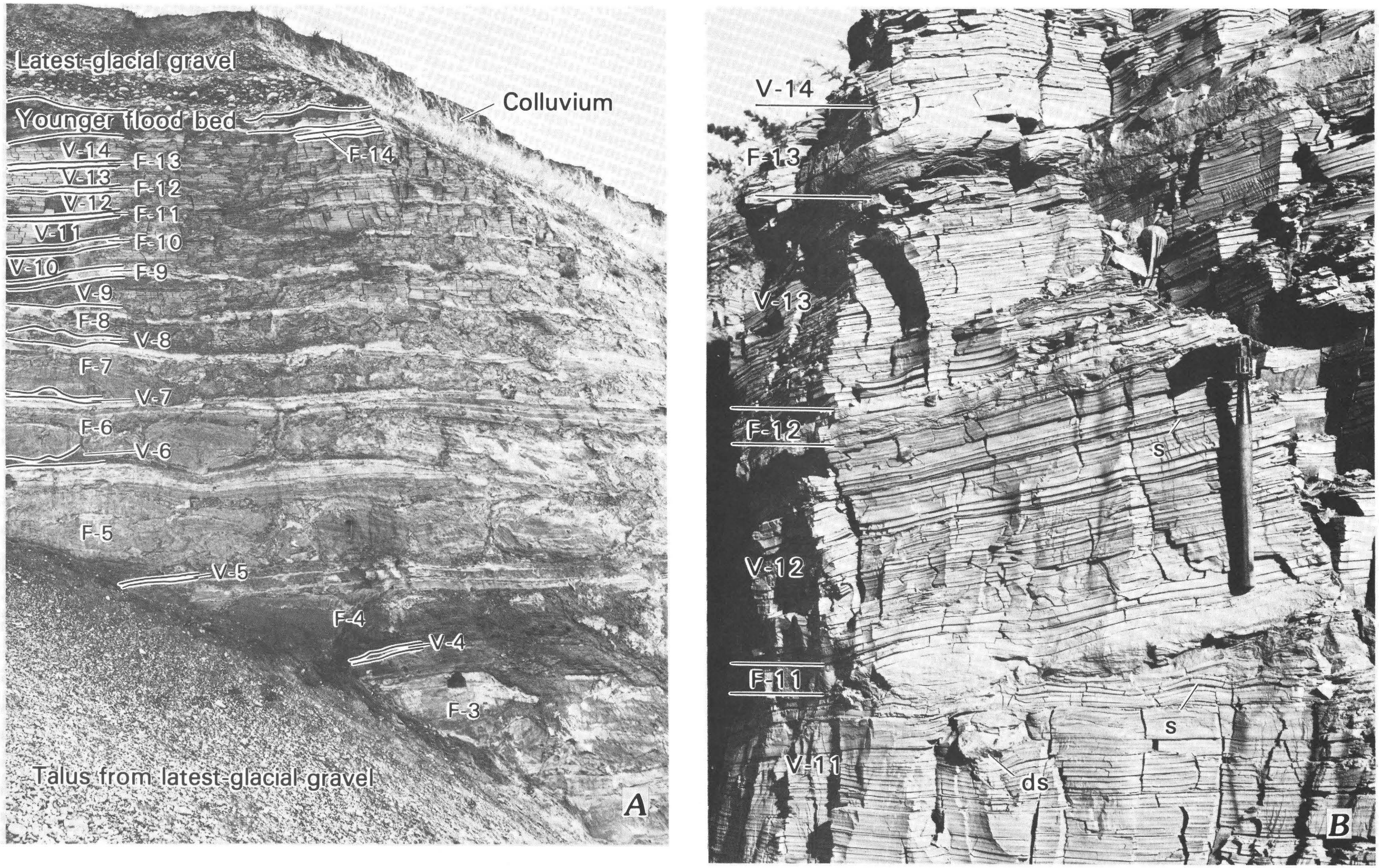

Latest-glacial gravel
Colluvium
Younger flood bed
F-14
V-14
F-13
V-13
F-12
V-12
F-11
V-11
F-10
V-10
F-9
V-9
F-8
V-8
F-7
V-7
F-6
V-6
F-5
V-5
F-4
V-4
F-3
Talus from latest-glacial gravel
A
V-14
F-13
V-13
F-12
S
V-12
F-11
S
V-11
ds
B


**Figure 25.** Comparison of thin flood beds F–11, F–12, and F–13 with other flood beds at the Henry Kuehne locality (pl. 2*A*, fig. 6). ***A***, Overall upsection thinning of flood beds and corresponding decrease in erosion and deformation of underlying varved intervals. Although the flood-bed thinning between beds F–3 and F–9 may be unique to the Henry Kuehne locality (compare French Johns locality, figs. 6 and 10), the anomalous thinness of F–10 through F–13 is widespread in the Sanpoil River valley (figs. 6, 23). Just left of the field of view, the "younger flood bed" thickens to 8 m and cuts out section as low as V–9. This flood bed, whose thick part resembles bed F–3 (shown in fig. 8*B*), implies a return to vigorous flooding sometime after the episode of attenuated floods implied by beds F–10 through F–13 (see also fig. 17 and pl. 2*B*). Handle of shovel (in bed F–5) is 0.5 m long. ***B***, Beds F–11, F–12, and F–13, and the almost-complete varved intervals that bound them. The thin (8-mm) bed of very fine sand (s) is, like a prominent sand bed at the French Johns, Old Keller, and Ranger Station localities, situated about 8 varves below the top of V–12 (fig. 6; table 2). A dropstone (ds) 10 cm in diameter appears near the top of V–11. The uppermost varves of V–11, including the thin, discontinuous sand layer (s) in the third varve below F–11, were warped and partly detached during deposition of F–11. ***C***, Thick flood beds having erosional bases and containing injected and extruded parts of varved intervals. Varved interval V–6 thickens left of shovel into a diapir that invades the bottom part of flood bed F–6. Parts of V–6 that must have been extruded onto the lake floor during deposition of F–6 form the rubbly layer within F–6 that thins away from the diapir and mostly caps the sausage-shaped bodies of plane-laminated sand. Deposition of F–6 concluded with accumulation of tabular beds of sand, silt, and clay above the rubbly layer. The overlying varved interval, V–7, invades flood bed F–7 at several points in the field of view.

17 and pl. 3). The resulting age for the uppermost flood bed in the Manila Creek section (about 12,900 yr B.P.) lies within the range of my tabulated estimate for that bed (12,800–13,900 yr B.P.). Alternatively, the set-S-capped rhythmite in southern Washington correlates with a flood bed lower in the Manila Creek section—say, with the bed at altitude 467 m (fig. 17), in which case the uppermost flood bed formed in the range of 12,000–12,400 yr B.P. and the wood of sample USGS–1860 predates its host by many centuries. These allowable correlations, considered together with the regionality of Missoula-flood effects (Waitt, 1985), should lessen doubt that varve-bounded flood deposits north of the Channeled Scabland correlate one-for-one with floodlaid rhythmites of southern Washington. This doubt led Baker and Bunker (1985, p. 25) to question whether the varve-bounded flood deposits necessarily corroborate Waitt's (1980) hypothesis.

Regarding frequency, varve counts by Chambers (1971, app. III) at the Ninemile Creek section indicate a broad maximum near 40 years for the period between last-glacial emptyings of Lake Missoula. Given the likelihood of haitus or disconformity between varved rhythmites of the Ninemile Creek section (Chambers, 1971, p. 30, 59), the varve-count maximum at Ninemile Creek probably matches the broad 45- to 55-year maximum that I infer from the lower part of the Manila Creek section, and thus permits approximate one-for-one correlation between varved intervals of Lake Columbia and varved rhythmites of Lake Missoula (fig. 17). The more-

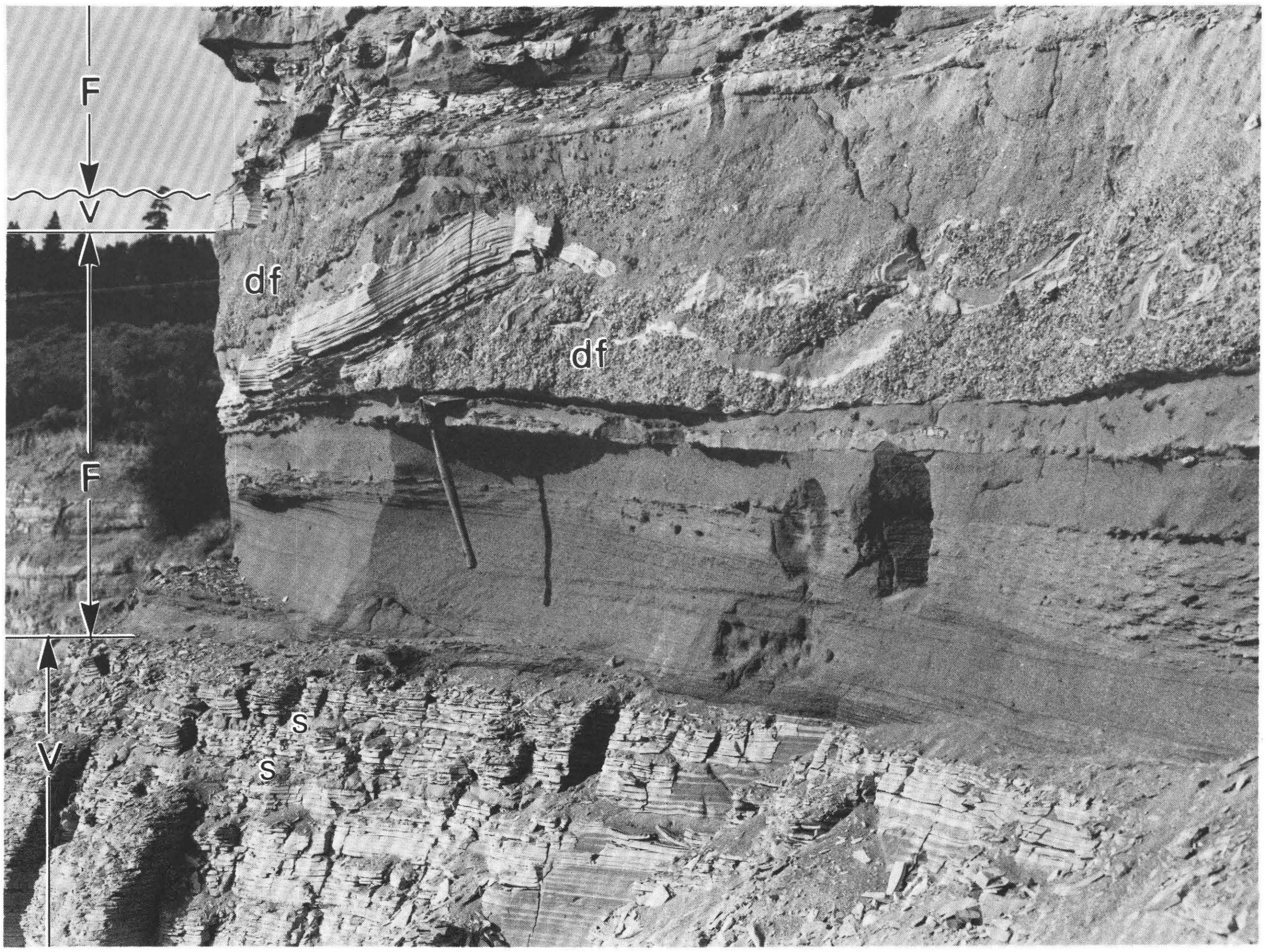
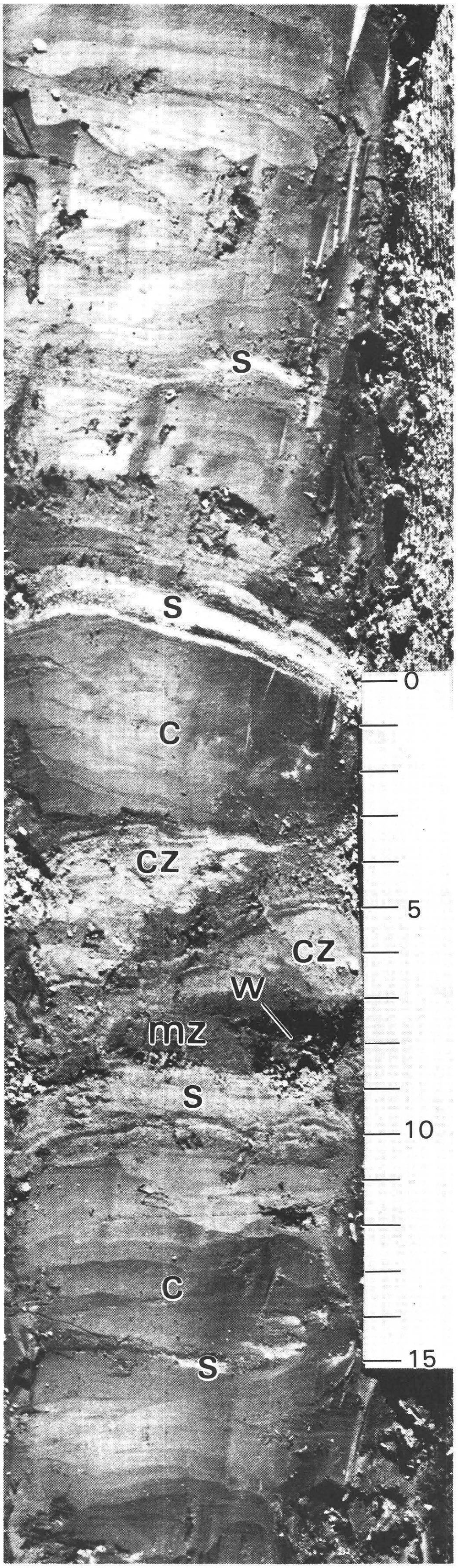



**Figure 26.** Debris flow in upper part of a flood bed, Sage Trig locality (pl. 2*A*; fig. 6). The debris flow (df), dominated by angular fragments of granitic rock, grades upward from gravel to sand. At left edge of exposure the debris flow conformably overlies a tabular turbidite of structureless sand, which in turn overlies laminated silt. But above and right of the shovel, the debris flow has lifted and partly digested this turbidite and the laminated silt. The overlying varved interval has been greatly thinned by erosion, diapirism, or both during deposition of the succeeding flood bed; the wavy line at upper left signifies disconformity. The underlying varved interval contains beds of medium to coarse sand (s), probably turbidites formed from remobilized flood-bed sand (compare fig. 8*C*, which shows another probable turbidite lower in the same varved interval). Shovel handle is 0.5 m long.




frequent floods recorded higher in the Manila Creek section conceivably could have come from some lake other than Lake Missoula, perhaps glacial Lake Clark or glacial Lake Kootenay (pl. 1). But neither the trends in varve counts (fig. 17) nor the characteristics of flood beds connote any abrupt shift in source lake. I therefore credit all 89 flood beds to a single lake—glacial Lake Missoula.

Why does the Manila Creek section thereby imply more than twice the approximately 40 last-glacial drainings of Lake Missoula inferred in southern Washington by Waitt (1980) and in Montana by Chambers (1971)? One reason is that none of the Manila Creek section is far above local glacial-age base level. At altitude 503 m, the highest flood bed in Manila Creek valley could have formed with a flood stage only a few meters above Bretz's (1932, p. 76) inferred late-glacial lake level at the northern end of the upper Grand Coulee (pl. *2B*). By contrast, the highest floodlaid rhythmite in the Burlingame Canyon section of Waitt (1980) required an approximate flood stage there of at least 180 m, 90 m above the Columbia River at nearby Wallula Gap (pl. 1). Therefore, many of the frequent small floods recorded in the upper part of the Manila Creek section may have failed to leave a deposit at the Burlingame Canyon section. Such non-deposition has been inferred in southern Washington by Baker and Bunker (1985, p. 31) and by Waitt (1985, p. 1234), who found that floodlaid rhythmites above the set-S ash layers are fewer at high altitude than at low altitude. Late-glacial non-deposition is also likely for the Ninemile Creek section of Chambers (1971): thinning of the Purcell Trench lobe could have kept late-glacial Lake Missoula from surmounting this section, which at altitude 940 m stands 200 m above the minimum lake level allowed by the 740-m thalweg of Rathdrum valley (Clarke and others, 1984, p. 290). Another reason for the large number of recorded floods in the Sanpoil River valley is that the Manila Creek section has been extended by boreholes, whereas the Burlingame Canyon and Ninemile Creek sections have not. Even this borehole extension is no guarantee of completeness; the contact with probable bedrock in borehole 2 may be a buttress unconformity, for the bedrock surface is nearly 30 meters lower just 300 m east of borehole 2 (pl. *2A*). Allowing for a buttress unconformity in

**Figure 27.** Piece of wood in core from middle of composite Manila Creek section, Manila Creek valley, borehole 3 (pls. 2, 3). The wood (w), which gave a $^{14}C$ age of 14,490 ± 290 yr B.P. (USGS–1860), lies in a layer of medium silt (mz) between a layer of very fine sand (s) and two lenses of coarse silt (cz). This composite silt-and-sand sequence is bounded by gray clay (c) containing pockets of very fine sand below and a 1-cm layer of very fine sand above. Despite lack of rhythmicity, the deposits shown in the photograph have much more in common with varves than with flood beds; probably they represent one or more compound varves. Deformation of the sand layer above the wood may have occurred either shortly after deposition or during coring. Scale in centimeters.

borehole 2, and further allowing for a few composite or missing flood beds in the lowest 9 m of section in borehole 2, I infer that the last-glacial Lake Missoula floods into Manila Creek valley numbered about 100.

It does not follow that 100 last-glacial Lake Missoula floods coursed most of the Channeled Scabland. Like the top of Waitt's (1980) Burlingame Canyon section, scabland intakes at the Cheney and Hawk Creek divides (pl. 1) probably were too high for overtopping by many of the frequent, apparently small floods recorded in the upper part of the Manila Creek section. Perhaps these floods bypassed all parts of the Channeled Scabland except those served by the Grand Coulee. Eastern scabland tracts may have been similarly bypassed by frequent, small early-glacial floods unrecorded at the base of the known Manila Creek section.

## History of the Cordilleran Ice Sheet

Glaciolacustrine deposits of the Sanpoil River valley permit proxy dating of ice-sheet advance and retreat because certain of these deposits probably mark milestones for particular ice lobes (fig. 17). The milestones can be dated with respect to one another by means of varve counts. Also they can be assigned absolute ages by means of varve-count extrapolation from the $^{14}C$ age (USGS–1860) on wood from borehole 3. As shown above, the extrapolated ages may be too old by as much as 2,500 years. This caveat, though not repeated below, applies to all the absolute ages that I propose for the Purcell Trench, Columbia River, and Okanogan lobes (fig. 28).

### Purcell Trench Lobe

The inferred Missoula-flood history at Manila Creek may help answer four questions about the last-glacial history of the terminal 50 km of the Purcell Trench lobe: (1) During what time was the Purcell Trench lobe sufficiently extended to block the Clark Fork and thereby dam Lake Missoula? According to my interpretation and dating of flood beds in the Manila Creek section, the Purcell Trench lobe advanced across the Clark Fork no later than 15,550 ± 450 yr B.P. (lowest known flood bed) and retreated from that position about 13,350 ± 550 yr B.P. (highest flood bed). (2) When was the lobe at its terminus? If ice-lobe extent varies directly with ice-dam thickness, and if ice-dam thickness controls flood frequency (figs. 3*A*, 3*B*; Thorarinsson, 1939), then the Purcell Trench lobe probably reached its terminus sometime during deposition of intervals V–2 through V–10, that is, sometime between 15,200 ± 400 and 14,750 ± 375 yr B.P. (3) Did the Purcell Trench lobe readvance while in overall retreat from the terminus? The one or two reversals in varve-count decline (labeled R in fig. 17) may register thickening of Lake Missoula's ice dam during such readvance (fig. 28). Alternatively, they may indicate periods of relatively low inflow to Lake Missoula. (4) Did the Purcell Trench lobe advance more rapidly than it retreated, while in the southernmost 50 km of its last-glacial excursion? If the lobe blocked the Clark Fork for similar lengths of time before and after a maximum near 15,000 yr B.P., then the deposits of many tens of advance-glacial Lake Missoula floods may be missing at the base of borehole 2. Alternatively, as represented in figure 28, the advance-glacial floods were few and the Purcell Trench lobe resembled the Okanogan lobe in advancing faster than it retreated.

### Okanogan Lobe

During what time interval did the Okanogan lobe dam the Columbia River during the last glaciation? The lowermost part of the Manila Creek section probably formed in a recently born Lake Columbia, because the varves in that part of the section are chiefly thin and sand-poor (figs. 17, 18). Therefore it is likely that the last-glacial Okanogan lobe first dammed the Columbia River shortly before 15,550 ± 450 yr B.P. Retreat of the Okanogan Lake from the Columbia River valley should have occasioned prompt downcutting by the Columbia and by a tributary as large as the Sanpoil River. Such downcutting would have denied Manila Creek valley the Sanpoil River outwash that extends nearly to the top of the Manila Creek section, at least through the thick varves shown in figure 19. Virtually until completion of the Manila Creek section at about 13,050 ± 650 yr B.P., therefore, the Okanogan lobe continued to block the Columbia River valley. Thus the Okanogan lobe dammed the Columbia River for nearly all the 2,000- to 3,000-year period represented by the known Manila Creek section.

The time of maximum extent of the main part of the Okanogan lobe is probably represented by one of the two sets of anomalously thin flood beds low in the Manila Creek section. I have inferred above that these flood beds indicate attenuation of Lake Missoula floods while on the way to the Sanpoil River valley. The regional paleogeography (pl. 1) suggests two means of attenuation: damping of the floods by a high-level Lake Columbia; and deflection by a fully extended Columbia River lobe at the mouth of the Spokane River. In regards to damping, some of the largest floods from Lake Missoula probably raised the level of Lake Columbia from its 500-m norm to the 750-m altitude of the highest widespread ice-rafted erratics (pl. 2*A*; fig. 2). In the Sanpoil River valley, such a change in water level would have at least doubled the lake's depth and doubtless generated strong currents. By contrast, with Lake Columbia already at the high (715-m) level indicated by beach gravel on Mount Tolman (fig. 5), a large flood could move relatively little additional water into the Sanpoil River valley before Lake Columbia reached the 750-m maximum. Moreover, tailwater ponding and consequent lessening of peak Missoula-flood discharge (Clarke and others, 1984, p. 294) are more likely for a high-level Lake Columbia than for a low-level Lake Columbia (pl. 1). Thus, it is logical to suppose that at least one of the sets of anomalously thin flood beds represents attenuation of floods in the high-level Lake Columbia that formed when the fully extended Okanogan lobe blocked the Grand Coulee.

Two additional lines of evidence specify beds F–10 through F–13 as the set of thin flood beds more likely to correlate with maximum extension of the main part of the Okanogan lobe. (1) These flood beds are among the thick varves and range from 150 to 500 varves below the thick diamictons that, as argued above in the sections entitled "Varved Intervals" and "Diamictons," probably correlate with maximum extension of the Okanogan lobe's Sanpoil appendage. The lower set of anomalously thin flood beds, by contrast, is interbedded with thinner varves and is nearly

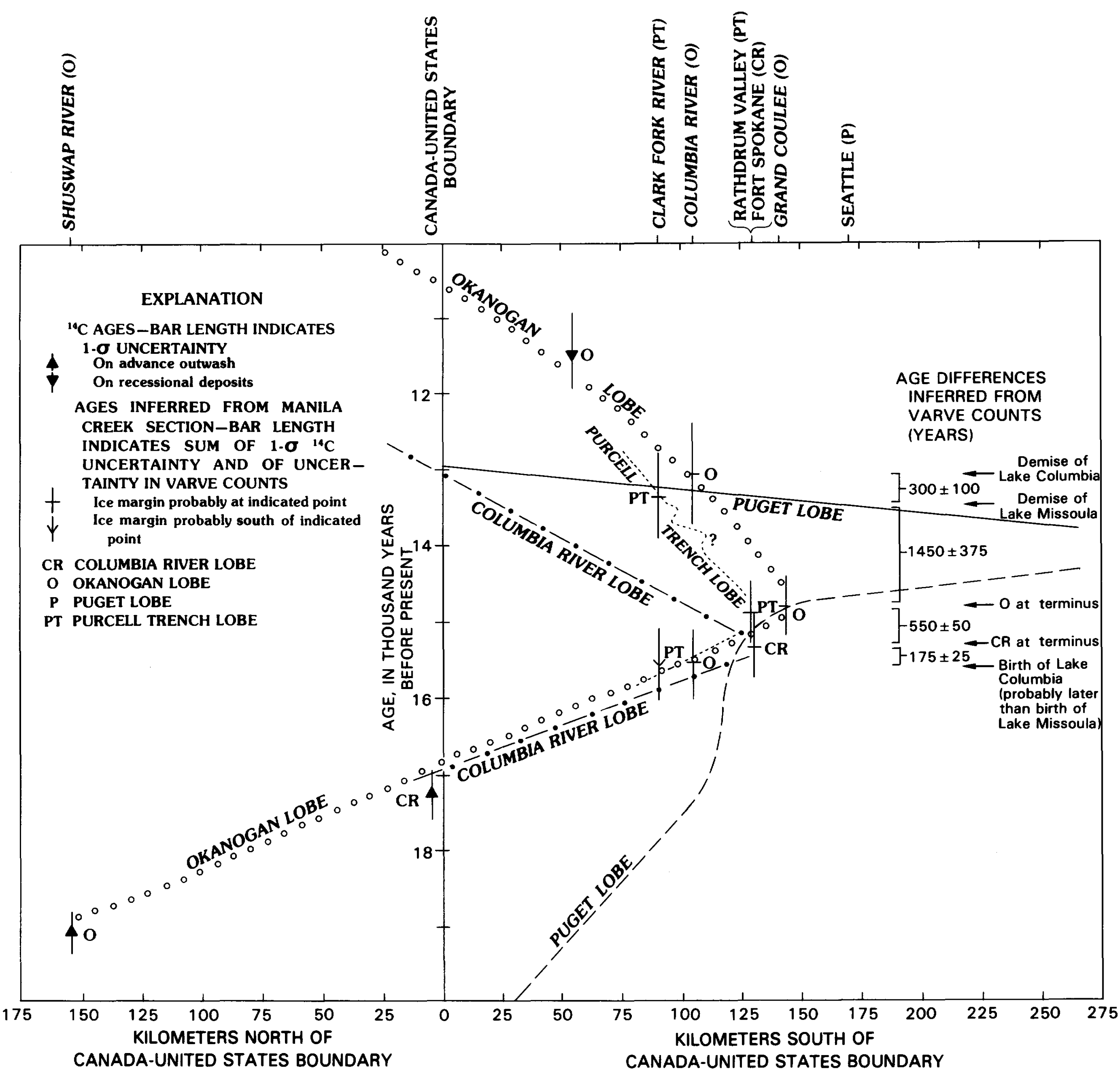



**Figure 28.** Advance and retreat of four lobes of the Cordilleran ice sheet during the last glaciation. Diagram for Puget lobe from Waitt and Thorson (1983, p. 56); line dashed where poorly constrained. Other diagrams based on interpretations in this report (fig. 17), plus three radiocarbon ages from southeastern British Columbia (Clague and others, 1980; I–10,021 and I–10,022 [pl. 1], and GSC–913) and two radiocarbon ages from north-central Washington (Mack and others, 1979, p. 214; TX–2689 and TX–2690). Age differences shown beside brackets are based solely on varve counts. Error bars attached to ages from Manila Creek section incorporate the one-sigma (±290-year) counting error in $^{14}C$ sample USGS–1860 as well as cumulative uncertainty in counts of varves above or below sample USGS–1860. All ages from Manila Creek section may err on the old side because sample USGS–1860 is detrital wood (fig. 27) that may predate its host deposit by as much as 2,500 years.

1,000 varves below the thick diamictons (fig. 17, pls. *2B*, 3). If the Sanpoil sublobe was approximately in phase with the main part of the Okanogan lobe, the main part of the Okanogan lobe was farther advanced during deposition of the upper set of thin flood beds than during deposition of the lower set. (2) The gray uppermost parts of flood beds F–11, F–12, and F–13 connote a high-level Lake Columbia because, whereas a large flood into a low-level lake might have suspended much oxidized clay by sweeping exposed land up to altitude 750 m, a similar flood into a high-level lake would have suspended mainly lake-bottom sediment, most of it the reduced mud of varves. The flood beds of the lower set, by contrast, are olive brown in their uppermost parts and therefore more likely to have formed in a low-level Lake Columbia.

Thus the Okanogan lobe probably was at its last-glacial terminus, at the Grand Coulee, for about two centuries (sum of varve counts, intervals V–10 through V–13) around 14,800 ± 375 yr B.P. (the estimated age of flood bed F–11). And if it blocked the Columbia River valley from 15,550 ± 450 to 13,050 ± 650 yr B.P., the Okanogan lobe must have advanced more rapidly than it retreated (fig. 28).

The gap of 150–500 varves between the upper set of anomalously thin flood beds and the thick diamictons suggests that the main part of the Okanogan lobe was maximally advanced several centuries before that lobe's Sanpoil appendage. Such diachronism within the Okanogan lobe might be explained by calving and consequent retreat of the Sanpoil sublobe while Lake Columbia was at a high level, followed by readvance of the sublobe after Lake Columbia returned to a low level. This explanation is consistent with the exceptional thickness and sandiness of varved interval V–9, which I place from 50–100 years before initial Okanogan-lobe blockage of the Grand Coulee; intervals V–10 through V–13, which I correlate with the time of that blockage (figs. 6, 9, 14), are noticeably thinner and finer grained. Perhaps the Sanpoil sublobe retreated from an advanced position, correlative with interval V–9, while the main part of the Okanogan lobe reached and maintained its maximum terminal position, correlative with intervals V–10 through V–13.

### Columbia River Lobe

Because they do not seem to indicate a high-level Lake Columbia, and because they contain and are interbedded with berg-dropped diamictons (pls. *2B*, 3), the lower set of anomalously thin flood beds near Manila Creek (fig. 22) may mark attenuation of Lake Missoula floods by a fully extended Columbia River lobe. If so, the Columbia River lobe was at its last-glacial terminus, in the Spokane River valley (pl. 1), for one or two centuries around 15,350 ± 400 yr B.P. That would be about 2,000 years after the lobe approached the Canada-United States boundary, provided that 17,400-year-old wood accumulated just before the lobe first crossed that boundary during the last glaciation (see plate 1 and Clague and others, 1980). The timing of the lobe's retreat may be constrained by lacustrine deposits in the Columbia River valley 25–50 km downvalley from the international boundary. These deposits, mentioned by Jones and others (1961, p. 13, 77-78), probably accumulated in late-glacial Lake Columbia in front of a retreating Columbia River lobe. If so, a retreating Columbia River lobe neared the international boundary around 13,050 ± 650 yr B.P. (age of the demise of Lake Columbia), having thus retreated about as rapidly as it advanced (fig. 28). Perhaps retreat of the Columbia River lobe was hastened by calving into Lake Columbia. In this respect the Columbia River lobe may have resembled the Puget lobe, whose rapid late-glacial retreat north of Seattle (fig. 28) is usually attributed to calving (see review by Waitt and Thorson, 1983, p. 61).

### Asynchrony within the Ice Sheet

If glaciolacustrine deposits in the lower Sanpoil River valley correlate with ice-lobe events as inferred above, then the order of advance and retreat by major ice lobes was: Columbia River lobe (early); Purcell Trench lobe; and Okanogan lobe (late). Specifically I hypothesize that (1) the Columbia River lobe reached its maximum terminus before the Okanogan and Purcell Trench lobes reached theirs; (2) the Columbia River lobe was also earliest in retreat, withdrawing to near the international boundary while the Okanogan lobe still blocked the Columbia River; and (3) the Okanogan lobe was slightly later in both advance and retreat than the Purcell Trench lobe (fig. 28). A corollary of hypothesis (3) is that Lakes Missoula and Columbia were slightly staggered in time; I postulate that Lake Missoula was initiated before and outlasted by Lake Columbia.

### Tests of the Inferred Ice-Sheet History

Flood deposits and landforms in the Chelan-Rock Island segment of the Columbia River valley, located west and south of the Okanogan lobe's terminal area (pl. 1), afford tests of the inferred asynchrony between the Purcell Trench and Okanogan lobes. No Lake Missoula flood could have run down the Chelan-Rock Island segment while a near-maximum Okanogan lobe blocked the adjacent upstream reach of the Columbia River valley (Waitt, 1977). According to hypothesis (3) above, only the earliest of the last-glacial Lake Missoula floods should have found the Columbia River valley unobstructed by the Okanogan lobe, and therefore no unobstructed Missoula flood should have gone down the Chelan-Rock Island segment in late-glacial times. Flood-deposited gravel bars traceable from Wenatchee northward to the Okanogan lobe's maximum terminus, but not farther north, indeed suggest that at least one large last-glacial Lake Missoula flood descended the Chelan-Rock Island segment before the Okanogan lobe had become a formidable barrier in the Columbia River valley (Waitt, 1982, p. 9-10) and that the lobe later obliterated those deposits upstream from Chelan. But other deposits and landforms near Chelan indicate in addition that one or more late-glacial floods, perhaps as deep as 215 m, descended the Chelan-Rock Island segment *after* the Okanogan lobe had retreated at least 15 km up the Columbia River valley from the lobe's maximum terminus (Waitt, 1982, p. 9-12; Waitt and Thorson, 1983, p. 64; see also Bretz and others, 1956, p. 993-994). If from Lake Missoula, such late-glacial floods suggest that the Okanogan lobe ceased blocking the Columbia River valley before the final demise of Lake Missoula. Nevertheless, it is possible that some late-glacial Missoula floods floated a thin but persistent Okanogan-lobe dam. It is also possible that the late-glacial floods down the Chelan-Rock Island segment came from a lake other than Missoula (Bretz and others, 1956, p. 994). Thus my inferred asynchrony between the Okanogan and Purcell Trench lobes (hypothesis 3, above) may still be fully consistent with evidence from the Columbia River valley downstream of Chelan.

My correlation of only four Missoula floods with maximum extension of the Okanogan lobe and another four with maximum extension of the Columbia River lobe conflicts with a recent interpretation of alternating Missoula-flood beds and varved sediments at Latah Creek, near Spokane (pl. 1). According to Waitt (1984, p. 52-55), the Latah Creek section registers at least l6 Lake Missoula floods into a last-glacial lake that was dammed by a fully extended Okanogan lobe or a fully extended Columbia River lobe or both. Alternatively, many of these floods found merely a local lake in Latah Creek valley, dammed by Missoula-flood gravel. Several such gravel-dammed lakes persist today 25–60 km northeast of Latah Creek, in recesses beside Rathdrum valley; the largest is Coeur d'Alene Lake (Waitt, 1984, his fig. 2). Thus there may be no actual conflict between Waitt's (1984) evidence from Latah Creek and my estimates of the duration of glacial maxima.

## Age of the Grand Coulee

It has been supposed or implied that headward erosion of flood-cataract alcoves in the upper Grand Coulee (the upper of the two tandem canyons making up the Grand Coulee) intersected the Columbia River valley, thus completing opening of the coulee, during the last glaciation (Richmond and others, 1965, p. 237, 239; Baker, 1978, p. 33; Waitt, 1977; Waitt and Thorson, 1983, p. 57, 64). This supposition originated with Bretz (1932), who ascribed all the cataract recession to a great last-glacial "Spokane flood" that predated the last glacial maximum: a moraine caps flood-carved scabland on a butte in the upper Grand Coulee (Bretz, 1932, p. 35). However, because Bretz's Spokane flood probably represents many tens of floods (Waitt, 1980), the cataract recession could have occurred piecemeal, perhaps predating the last glaciation altogether (Waitt and Thorson, 1983, p. 57).

The characteristics of flood beds in the Manila Creek section favor pre-last-glacial age for completion of cataract recession in the upper Grand Coulee. As argued above, a Missoula-flood bed in the Sanpoil River valley should be thinner and finer grained, and should have a more nearly conformable basal contact, if deposited in a high-level Lake Columbia (Grand Coulee blocked by ice or rock) than if deposited in a low-level Lake Columbia (Grand Coulee open). Therefore, if flood-cataract alcoves in the upper coulee intersected the Columbia River valley during deposition of the Manila Creek section, the lowermost part of that section should contain thin, fine-grained flood beds that scarcely cut into subjacent varves. In reality, however, the lowermost flood beds are thick and coarse grained, and they may cut deeply into subjacent varves (pl. *2B* and 3, altitude 395–405 m in borehole 2). The few flood beds that suggest a high-level Lake Columbia are higher in the section and allow only temporary, probably full-glacial blockage of the Grand Coulee. Hence it is likely that cataract recession had been completed in the upper coulee before deposition of any of the known Manila Creek section. In addition, because the lowermost part of the Manila Creek loction may correlate with the earliest last-glacial blockage of the Columbia River valley by the Okanogan lobe, completion of cataract recession may also predate any vigorous last-glacial erosion that was occasioned by the Okanogan lobe's diversion of floodwater from the Columbia River valley into the Grand Coulee area.

Thus the last glaciation may have begun with the upper Grand Coulee at something close to its present depth. Some the earliest last-glacial floods from Lake Missoula probably ran through the coulee, but hardly with the vigor of those later large floods that found the Columbia River valley blocked by the Okanogan lobe. This blockage transformed the Grand Coulee into the Columbia's interflood course, except perhaps during a two-century period when the coulee was itself blocked by a maximally extended Okanogan lobe. Following the last Lake Missoula flood, a still-impounded Columbia River blanketed the floor of the upper Grand Coulee with silt (Bretz, 1932, p. 76). This postflood deposition probably lasted several centuries; thereafter, the Columbia River abandoned the Grand Coulee in favor of today's Columbia River valley, reopened by late-glacial withdrawal of the Okanogan lobe.

## REFERENCES CITED


Ashley, G.M., 1975, Rhythmic sedimentation in Glacial Lake Hitchcock, Massachusetts-Connecticut, *in* Jopling, A.V., and McDonald, B.C., eds., Glaciofluvial and glaciolacustrine sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication 23, p. 304-320.

Atwater, B.F., 1984, Periodic floods from glacial Lake Missoula into the Sanpoil arm of glacial Lake Columbia, northeastern Washington: Geology, v. 12, p. 464-467.

Atwater, B.F., and Rinehart, C.D., compilers, 1984, Preliminary geologic map of the Colville Indian Reservation, Ferry and Okanogan Counties, Washington, with a table of potassium-argon ages compiled by Robert J. Fleck: U.S. Geological Survey Open-File Report 84–389, scale 1:100,000.

Baker, V.R., 1973, Paleohydrology and sedimentology of Lake Missoula flooding in eastern Washington: Geological Society of America Special Paper 144, 79 p.

———1978, Quaternary geology of the Channeled Scabland and adjacent areas, *in* Baker, V.R., and Nummedal, Dag, eds., Channeled Scabland: Planetary Geology Program, National Aeronautics and Space Administration, p. 17-35.

Baker, V.R., and Bunker, R.C., 1985, Cataclysmic late Pleistocene flooding from glacial Lake Missoula: a review: Quaternary Science Reviews, v. 4, p. 1-41.

Boulton, G.S., and Jones, A.S., 1979, Stability of temperate ice caps and ice sheets resting on beds of deformable sediment: Journal of Glaciology, v. 24, p. 29-43.

Bouma, A.H., 1962, Sedimentology of some flysch deposits: New York, Elsevier, 168 p.

Bretz, J H., 1932, The Grand Coulee: American Geographical Society Special Publication 15, 89 p.

———1969, The Lake Missoula floods and the Channeled Scabland: Journal of Geology, v. 77, p. 505-543.

Bretz, J H., Smith, H.T.U., and Neff, G.E., 1956, Channeled Scabland of Washington: new data and interpretations: Geological Society of America Bulletin, v. 67, p. 957-1049.

Chambers, R.L., 1971, Sedimentation in glacial Lake Missoula: Missoula, University of Montana, unpublished M.S. thesis, 100 p.

Clague, J.J., Armstrong, J.E., and Mathews, W.H., 1980, Advance of the Late Wisconsin Cordilleran ice sheet in southern British Columbia since 22,000 yr B.P.: Quaternary Research, v. 13, p. 322-326.

Clarke, G.K.C., 1982, Glacier outburst floods from "Hazard Lake", Yukon Territory, and the problem of flood magnitude prediction: Journal of Glaciology, v. 28, p. 3-21.

Clarke, G.K.C., Mathews, W.H., and Pack, R.T., 1984, Outburst floods from glacial Lake Missoula: Quaternary Research, v. 22, p. 289-299.

Cochran, D.S., and Warlow, J.C., 1980, Engineering and environmental geology, Mt. Tolman project, Ferry County, Washington: Unpublished report to Amax Exploration, Inc., and the Colville Confederated Tribes, Nespelem, Washington, 89 p., map scale 1:4,800.

DeGeer, G., 1912, A geochronology of the last 12,000 years: International Geologic Congress, 11th, Stockholm, 1910, Compte Rendu, v. 1, p. 241-258.

Evenson, E.B., Dreimanis, Aleksis, and Newsome, J.W., 1977, Subaquatic flow tills: a new interpretation for the genesis of some laminated till deposits: Boreas, v. 6, p. 115-133.

Flint, R.F., 1935, Glacial features of the southern Okanogan region: Geological Society of America Bulletin, v. 46, p. 169-194.

———1936, Stratified drift and deglaciation in eastern Washington: Geological Society of America Bulletin, v. 47, p. 1849-1884.

Flint, R.F., and Irwin, W.H., 1939, Glacial geology of Grand Coulee Dam, Washington: Geological Society of America Bulletin, v. 50, p. 661-680.

Griffiths, J.C., 1967, Scientific method in analysis of sediments: New York, McGraw-Hill, 508 p.

Gustavson, T.C., 1975, Sedimentation and physical limnology in proglacial Malaspina Lake, southeastern Alaska, *in* Jopling, A.V., and McDonald, B.C., eds., Glaciofluvial and glaciolacustrine sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication 23, p. 249-263.

Jones, F.O., Embody, D.R., and Peterson, W.L., 1961, Landslides along the Columbia River valley, northeastern Washington. U.S. Geological Survey Professional Paper 367, 98 p.

Lowe, D.R., 1982, Sediment gravity flows: II. Depositional models with specific reference to the deposits of high-density turbidity currents: Journal of Sedimentary Petrology, v. 52, p. 279-297.

Mack, R.N., Rutter, N.W., and Valastro, S., 1979, Holocene vegetation history of the Okanogan valley, Washington: Quaternary Research, v. 12, p. 212- 225.

Mathews, W.H., 1965, Two self-dumping ice-dammed lakes in British Columbia: Geographical Review, v. 55, p. 46-52.

McKenzie, G.D., 1980, Surficial deposits, *in* Cochran, D.S., and Warlow, J.C., Engineering and environmental geology, Mt. Tolman project, Ferry County, Washington: Unpublished report to Amax Exploration, Inc., and the Colville Confederated Tribes, Nespelem, Washington, p. 28-61.

McKenzie, G.D., and Stemen, K.S., 1983, Late Quaternary history of southern Sanpoil Valley and sediments of glacial Lake Columbia, eastern Washington [abs.]: Geological Society of America Abstracts with Programs, v. 15, p. 640.

Mehringer, P.J., Jr., Sheppard, J.C., and Foit, F.F., Jr., 1984, The age of Glacier Peak tephra in west-central Montana: Quaternary Research, v. 21, p. 36-41.

Mullineaux, D.R., Wilcox, R.E., Ebaugh, W.F., Fryxell, Roald, and Rubin, Meyer, 1978, Age of the last major scabland flood of the Columbia Plateau in eastern Washington: Quaternary Research, v. 10, p. 171-180.

Nye, J.F., 1976, Water flow in glaciers: Jökulhlaups, tunnels, and veins: Journal of Glaciology, v. 17, p. 181-207.

Pardee, J.T., 1918, Geology and mineral deposits of the Colville Indian Reservation, Washington: U.S. Geological Survey Bulletin 677, 186 p.

Porter, S.C., 1978, Glacier Peak tephra in the North Cascade Range, Washington: Stratigraphy, distribution, and relationship to late-glacial events: Quaternary Research, v. 10, p. 30-41.

Post, Austin, and Mayo, L.R., 1971, Glacier-dammed lakes and outburst floods in Alaska: U.S. Geological Survey Hydrologic Investigations Atlas HA–455, map scale 1:1,000,000.

Richmond, G.M., Fryxell, Roald, Neff, G.E., and Weis, P.L., 1965, The Cordilleran ice sheet of the northern Rocky Mountains, and related Quaternary history of the Columbia Plateau, *in* Wright, H.E., Jr., and Frey, D.G., eds., The Quaternary of the United States: Princeton, New Jersey, Princeton University Press, p. 231-242.

Schilling, D.H., and Hollin, J.T., 1981, Numerical reconstructions of valley glaciers and small ice caps, *in* Denton, G.H., and Hughes, T.J., eds., The last great ice sheet: New York, Wiley, p. 207-220.

Thorarinsson, Sigurdur 1939, The ice-dammed lakes of Iceland with particular reference to their values as indicators of glacier oscillations: Geografiska Annaler, v. 21, p. 216-242.

Waitt, R.B., Jr., 1977, Missoula flood *sans* Okanogan lobe [abs.]: Geological Society of America Abstracts with Programs, v. 9, p. 770.

———1980, About forty last-glacial Lake Missoula jökulhlaups through southern Washington: Journal of Geology, v. 88, p. 653-679.

———1982, Quaternary and late-Tertiary history of Columbia River valley and adjacent Cascade Range and Columbia Plateau, central Washington: Partial guide for Field Trip D, American Quaternary Association (AMQUA), Seattle, University of Washington, Quaternary Research Center, 23 pp.

———1984, Periodic jökulhlaups from Pleistocene glacial Lake Missoula—new evidence from varved sediment in northern Idaho and Washington: Quaternary Research, v. 22, p. 46-58.

———1985, Case for periodic, colossal jökulhlaups from Pleistocene glacial Lake Missoula: Geological Society of America Bulletin, v. 96, p. 1271-1286.

Waitt, R.B., Jr., and Thorson, R.M., 1983, The Cordilleran Ice Sheet in Washington, Idaho, and Montana, chap. 3 *of* Porter, S.C., ed., Late Pleistocene Environments of the United States, v. 1 *of* Wright, H.E., Jr., ed., Late Quaternary Environments of the United States: Minneapolis, University of Minnesota Press, p. 53-70.

Walker, E.H., 1967, Varved lake beds in northern Idaho and northeastern Washington: U.S. Geological Survey Professional Paper 575–B, p. B83–B87.

687-049/45019