ADDENDUM 2 – Missoula Flood and Columbia Plateau Loess Figures

(From O'Connor et al., 1995 and Berger and Busacca, 1995)

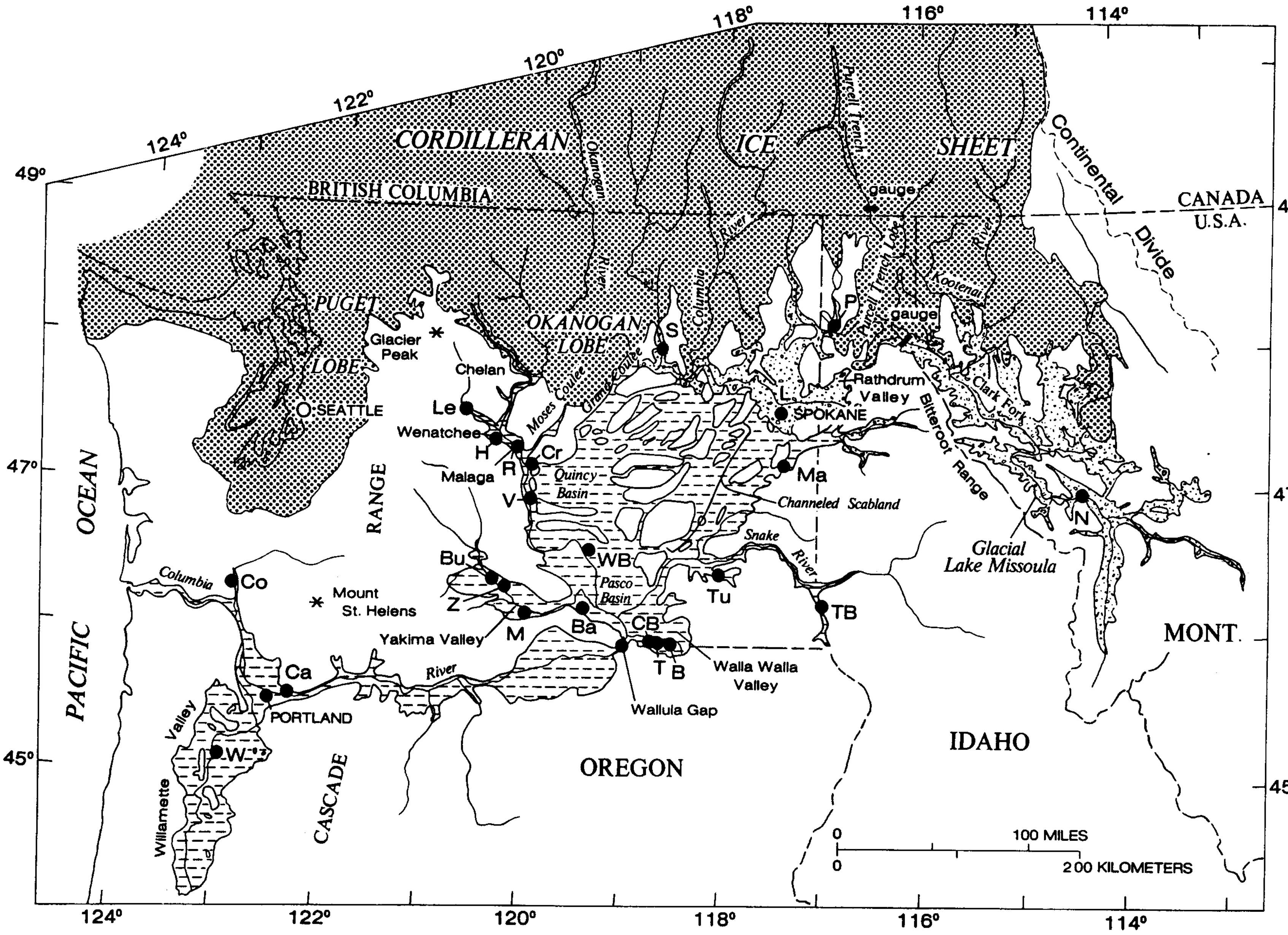

Figure 1. Map of Columbia River valley and tributaries. Small dots show maximum area of glacial Lake Missoula east of Purcell Trench ice lobe and maximum extent of glacial Lake Columbia east of Okanogan lobe. Lined pattern shows area that, besides these lakes, was swept by the Missoula floods. Closed circles indicate sites of bedded flood sediment discussed in text: B = Burlingame canyon; Ba = Badger Coulee; Bu = Buena; Ca = Camas; Co = Cowlitz valley; Cr = Crescent Bar; CB = Cumings Bridge; CR = Castle Rock; H = Horse Lake Canyon; L = Latah Creek; Le = Leavenworth; M = Mabton; Ma = Malden; N = Ninemile Creek; P = Priest valley; R = Rock Island bar; S = Sanpoil valley; T = Touchet; Tu = Tucannon valley; TB = Tammany bar; V = Vantage; W = Willamette valley section; WB = White Bluffs; Z = Zillah.

samples of individual samples, we infer that there was abundant old carbon existing on the landscape and that only the very youngest age determinations (those dates <20 ka [20,000 years]) are helpful in determining the ages of the floods. Some of the "charcoal" samples that gave >40-ka ages are probably pre-Quaternary coal. Other very old charcoal samples, including one friable charcoal sample that cleaved along growth rings, were probably from sites where they had been protected from decay for many thousands of years. The many samples between 20 and 30 ka were probably entrained from sites of sediment accumulation and soil formation prior to the floods, and their dates reflect carbon photosynthesized during several thousands of years prior to the floods. Consistent with this, humate extracts and plant fragments, isolated from larger bulk samples, gave substantially younger dates than the ages of the bulk samples; thus they more closely limit the age of the floods. We emphasize that many of the older dates came from horizons above or at the same stratigraphic level of those that contained materials yielding <15-ka ages, indicating that there was a lot of old organic material being transported by the floods. Consequently, we doubt that radiocarbon dating of these types of transported materials can be considered reliable evidence of

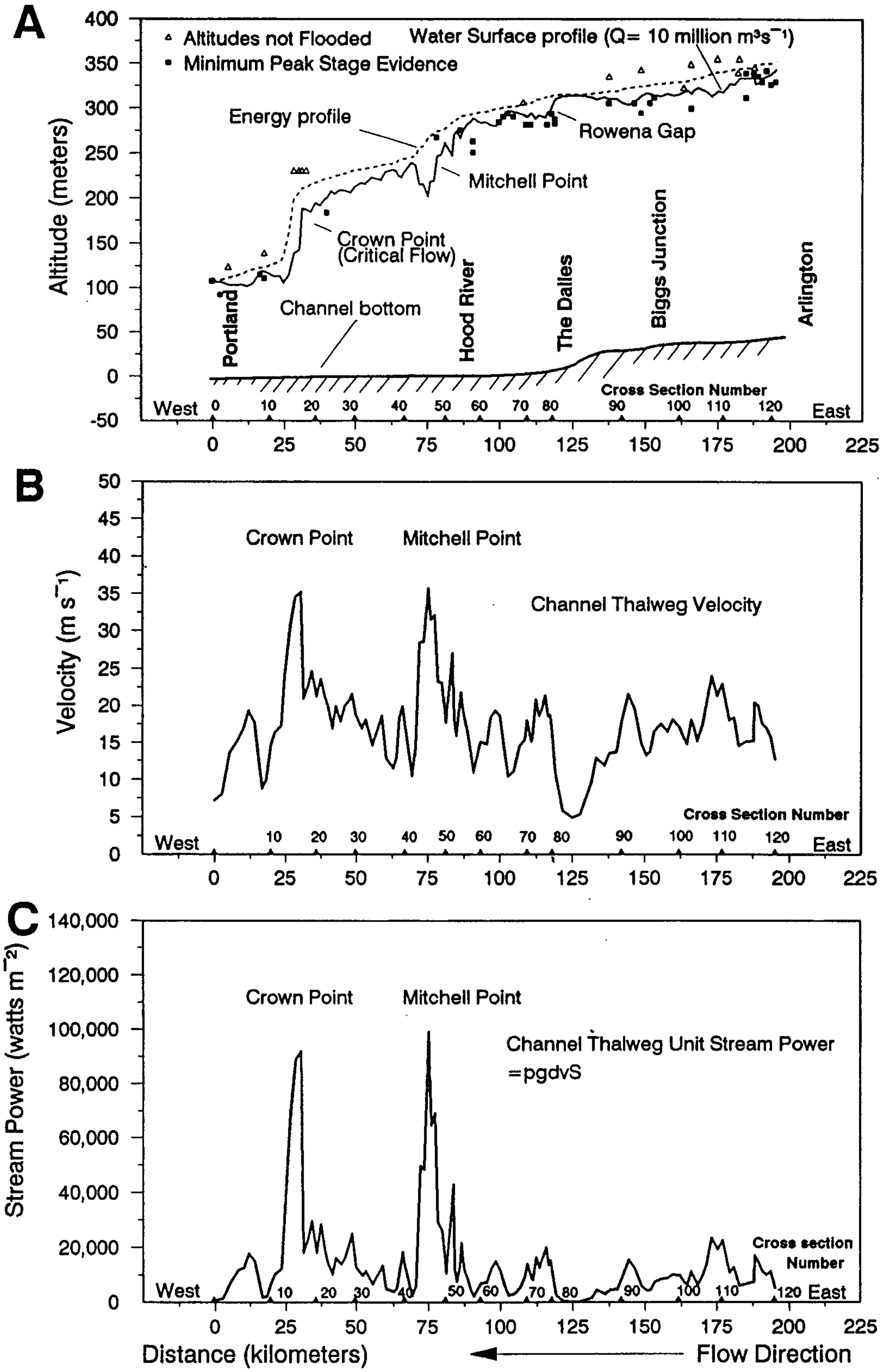

Figure 3. Profiles of calculated hydraulic conditions between Portland and Arlington. All profiles determined on the basis of step-backwater calculations for a 10 million m^3/s discharge for 120 cross sections. A: Water-surface and energy-surface profiles (and field evidence of maximum flood stages). B: Channel velocity. C: Unit area stream power.

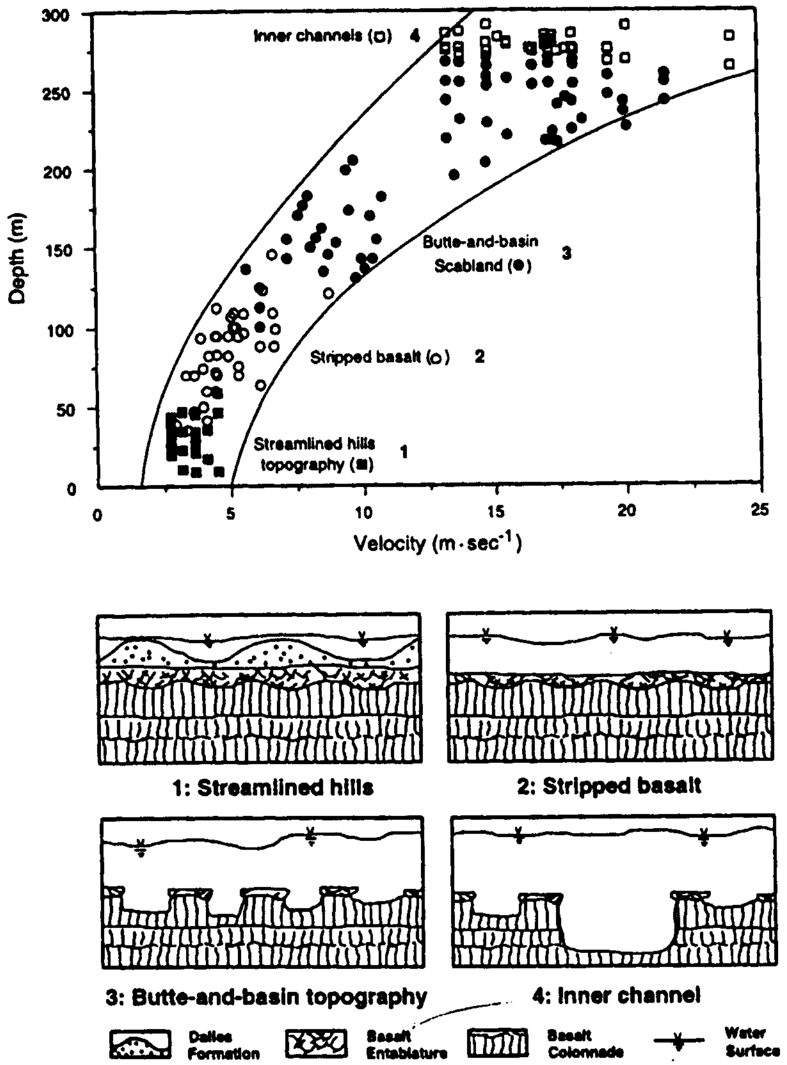

Figure 6. Relationships of local flow velocity and flow depth to erosional flood features. The numbers are assigned to steps of the hypothetical sequence of erosion for the development of scabland topography proposed by Baker and Komar (1987).

(Figures 3B and 6). Furthermore, the calculations indicate shear stresses below $100\,\mathrm{N\,m^{-2}}$ and stream powers lower than $500\,\mathrm{W\,m^{-2}}$. The length/width ratio of the streamlined landforms has an average value of 3·2, which falls within the range of 3–4 presented by Komar (1984) in the minimization of drag forces. Similar lemniscate-like forms were described in the channelled scabland by Bretz (1923) and Baker and Nummendal (1978) as a residual form of loess 'islands' standing on the Miocene basalt. In the Gorge, these forms cannot be considered residual since the surrounding anastomosed channels were also scoured into the Dalles Formation.

With deeper and higher flow velocities the unconsolidated materials of the Dalles Formation were stripped away, uncovering the underlying Columbia River Basalt Group. The erosional features on bare basalt surfaces or 'scabland' (Bretz, 1923) occurred in a suite of morphologies that represent different stages of energy expenditure by macroturbulent flood flows (Figures 4 and 5A). At the low end of energy expenditure the resulting landforms correspond to intact bare basalt surfaces with scarce longitudinal grooves (Figure 6). These stripped basalts are mostly limited to ledges over 180 m in altitude located east of Rock Creek and between the Deschutes River and Rufus at the north side of the Gorge (Figure 3A). The step-backwater modelling shows that stripped basalt areas are associated with flow velocities of $3\text{–}9\,\mathrm{m\,s^{-1}}$ and flow depths between 25 and 125 m (Figures 3B and 6). Shear stress values range between 50 and $380\,\mathrm{N\,m^{-2}}$, with an average value of $150\,\mathrm{N\,m^{-2}}$. The calculated rate of energy expenditure or stream power per unit area ranges between 350 and $2800\,\mathrm{W\,m^{-2}}$, with an average of $780\,\mathrm{W\,m^{-2}}$.

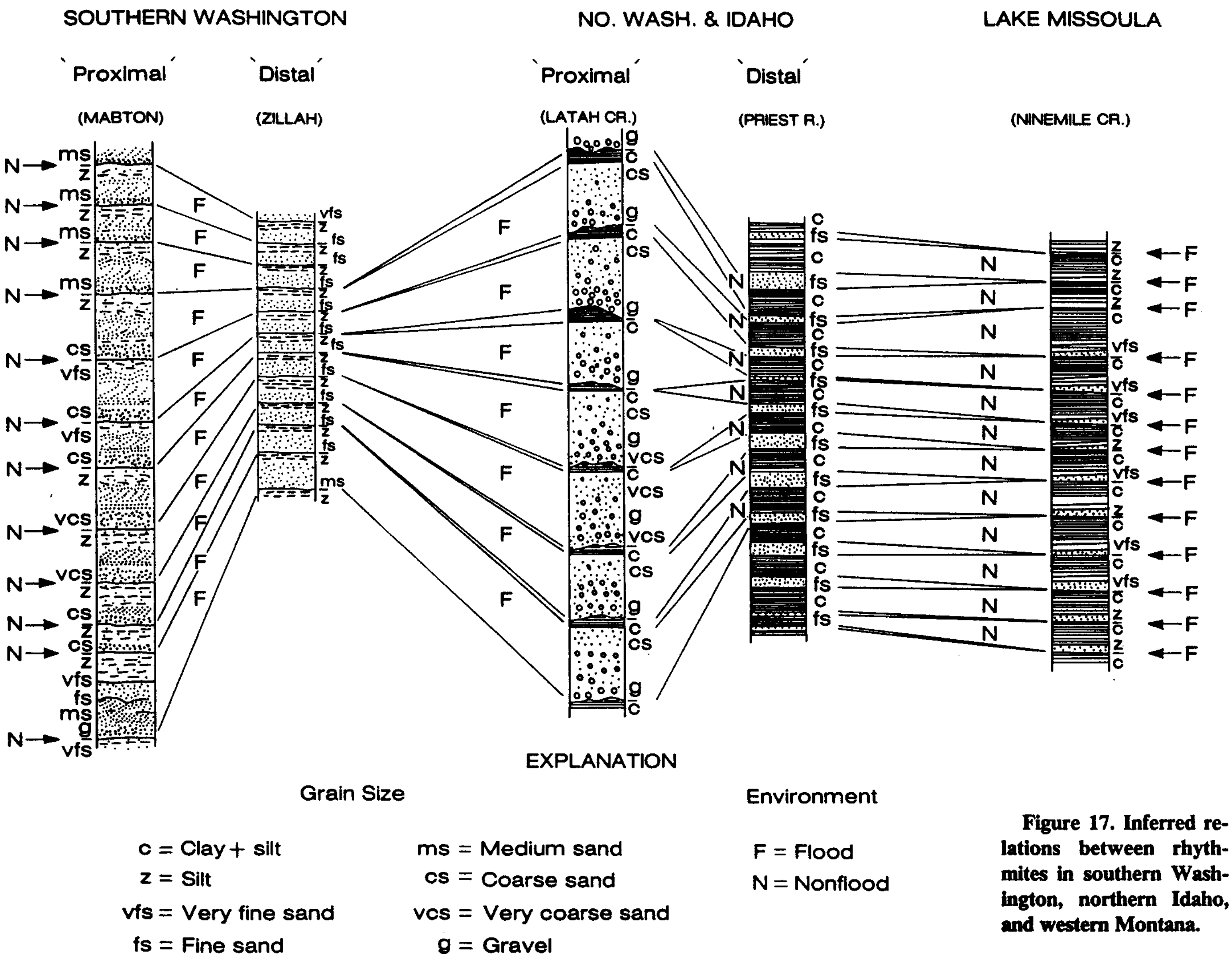

Figure 17. Inferred relations between rhythmites in southern Washington, northern Idaho, and western Montana.

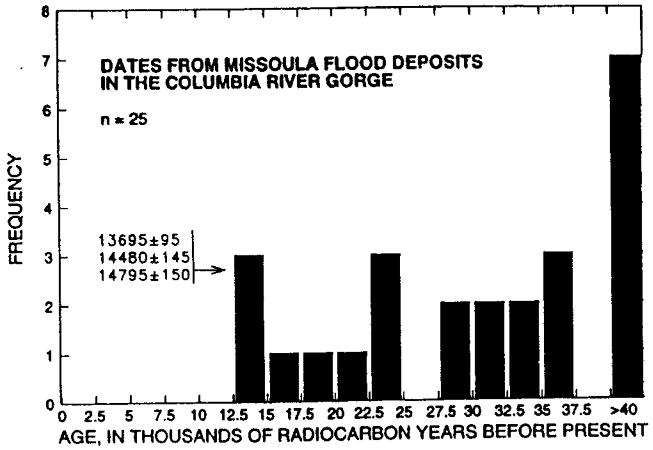

Figure 4. Histogram of radiocarbon ages from samples collected (by Benito and O'Connor) from within or below Missoula flood deposits. All samples were collected between Hood River and Arlington, and most were from high-altitude gravel bars. We emphasize that all of these ages are maximum limiting ages for the deposits that contain or overlie the samples.

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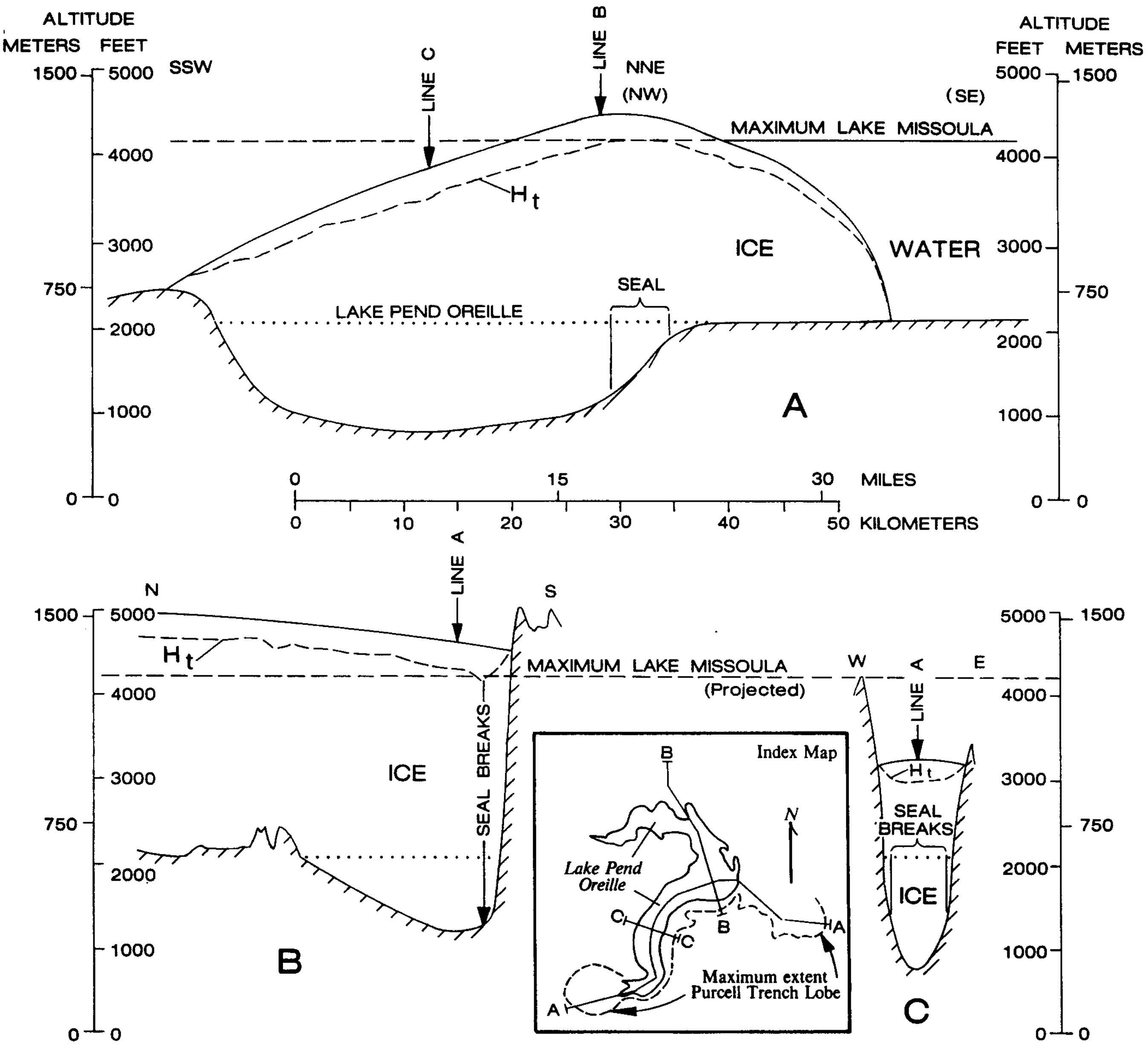

Figure 19. Sections through ice dam. The all-important ice-surface profile is only crudely known by sparse reconnaissance. (A) Longitudinal section; (B) cross section through seal area; (C) cross section through deepest part of Lake Pend Oreille.

flood down the Columbia River valley and probably also across the Channeled Scabland.

The swift and repeated dumping of glacial Lake Missoula is thus explained by an ordinary hydraulic mechanism. The explanation is devoid of various improbable causes that have been suggested over the years: subglacial volcanic eruptions, extreme rates of surface melting, collapse of the ice dam by the weight of water behind it, weakening of the ice dam by ice stagnation, shuffling advances and retreats of the ice margin.

AGE, CORRELATION, AND NUMBER OF FLOODS

Relation to Ice Sheet, Ash Layers, and Radiocarbon Dates

Proof that only one graded backflood rhythmite is produced per Missoula flood permits revisions in the inferred age of the floods. Earlier speculations such as the notion of an "early Pinedale" flood 18,000 to 20,000 yr ago (Richmond and others, 1965; Bretz, 1969; Baker, 1973), are now suspect because of limiting ages on the Cordilleran ice sheet, Lake Missoula, and the Missoula floods. Glacial Lake Missoula could have existed only within the broad limits between preglacial ^{14}C dates as young as ~17,200 yr B.P. and postglacial dates as old as 11,000 yr B.P. in southernmost British Columbia (Clague, 1981, p. 13 and 17). If the Purcell Trench lobe took a millennium to advance 100 km from there to the Bitterroot Range and a millennium to retreat back into British Columbia, then Lake Missoula existed only between

between sections. Manning roughness coefficients were assigned for appropriate portions of each cross section according to the estimated degree of flow efficiency across the surface. Although there is no rational method available to determine roughness coefficients for flows of this scale, the chosen values were selected on the basis of systematic criteria and experience with modeling similar flows (O'Connor, 1990). Sensitivity tests were performed to estimate the effect of uncertainties in roughness coefficients on the resultant water-surface profiles. Flow energy losses resulting from flow expansions and contractions (form roughness) are calculated as being proportional to the change in kinetic energy from one cross section to another (Hydrologic Engineering Center, 1985). Different values of these coefficients were also used to test their effect on the calculated water-surface profiles, as described below.

STUDY REACHES

Wallula Gap

Wallula Gap is a narrow, 1.5-km-wide, 250-m-deep gorge through the Horse Heaven Hills anticline in south-central Washington (Fig. 2). The constriction is the southern boundary of the Pasco Basin, a basin that has accumulated as much as 300 m of late Tertiary and Quaternary

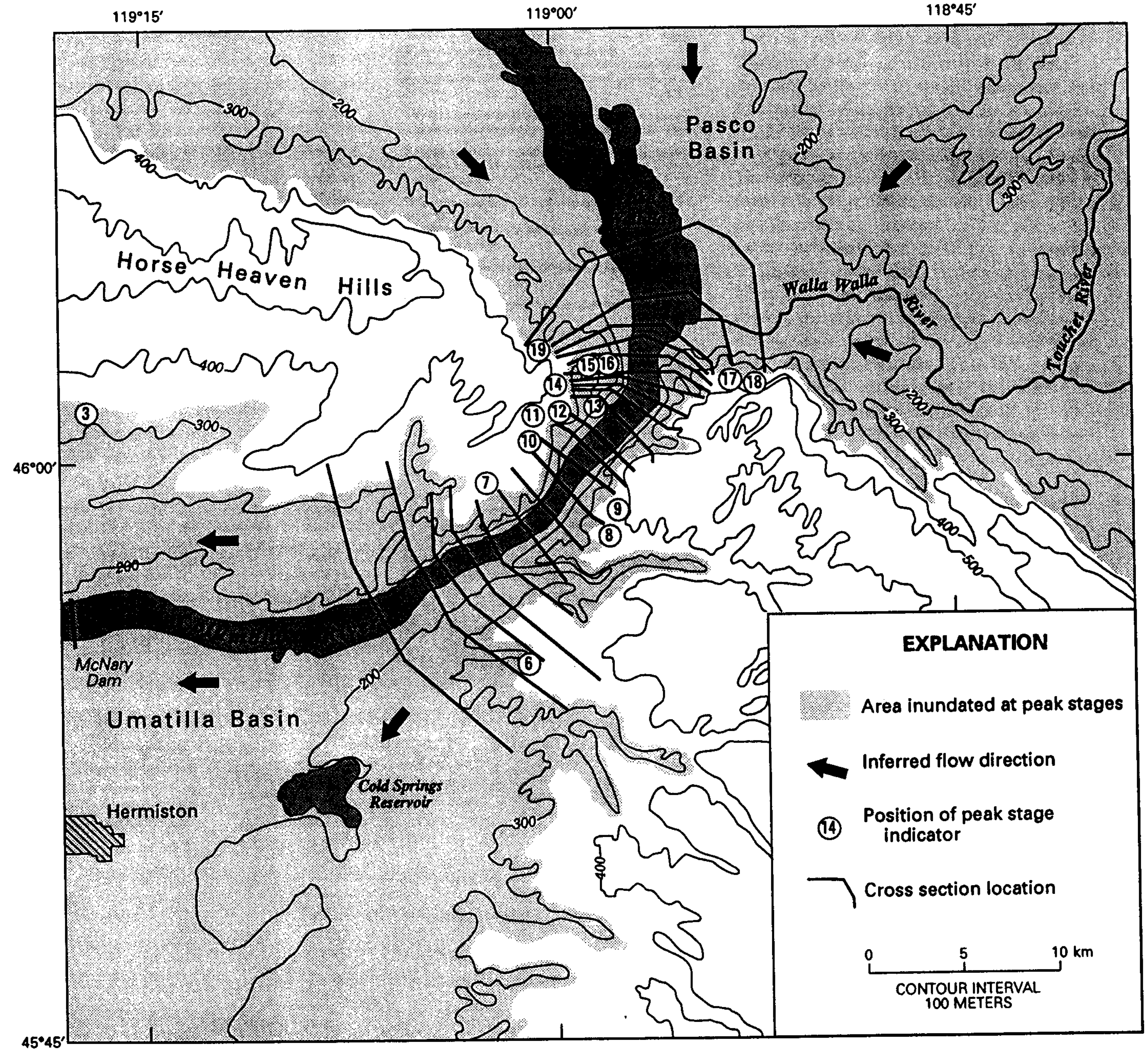

Figure 2. Topography, locations of evidence for maximum stages (Table 2), cross-section locations, and approximate area of inundation for the Wallula Gap reach at maximum flood stages. Note that some of the evidence for maximum stages is outside the map area.

sidering these ranges of model parameters and uncertainties in the maximum upstream stage, a minimum of 14 to 20 million $m^3 \cdot sec^{-1}$ flowed through the Spokane Valley. We emphasize that, because of our approach to reconstructing flow conditions for this reach, this is a ***minimum*** estimate for ***maximum*** flow through this reach, as well as being a minimum estimate for maximum glacial Lake Missoula outburst discharges.

This point is substantiated by evaluating the importance of uncertainty in the valley floor altitude at maximum stage. We performed a model trial assuming that the entire valley bottom was excavated to a depth of 60 m relative to its present altitude (consistent with the depths of the marginal lakes). For these conditions, the discharge that produces the required stages is about 27 million $m^3 \cdot sec^{-1}$. Clearly, the valley topography at the time of peak discharge is a major factor in establishing accurate discharge estimates in this reach. It is unlikely, however, that the valley floor was higher than its present altitude during maximum flood stages; hence our 17 million $m^3 \cdot sec^{-1}$ estimate is probably a valid minimum estimate.

The 17 million $m^3 \cdot sec^{-1}$ discharge determined here is less than the 21 million $m^3 \cdot sec^{-1}$ estimate calculated by Baker (1973) with the slope-area method. This discrepancy is probably generated by higher energy-loss coefficients used in this study and the more complete characterization of flow conditions afforded by the step-backwater calculation procedure.

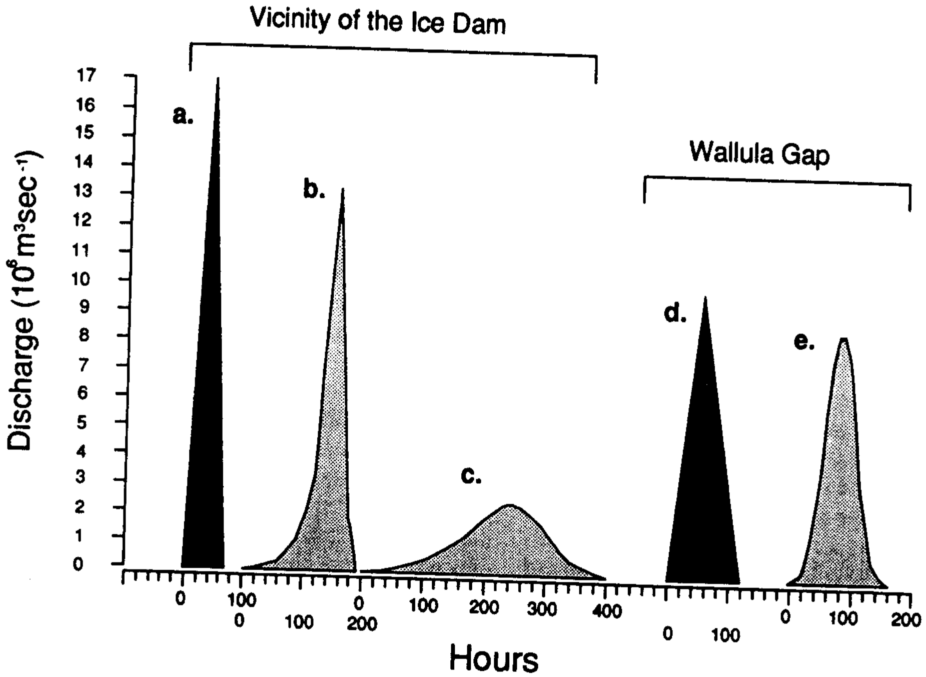

Figure 9. Postulated hydrographs for the largest Missoula Flood(s) (assuming complete emptying of Glacial Lake Missoula from its maximum level). All of the hydrographs represent the same total volume (2,184 km³). a and d are those postulated in this study on the basis of maximum discharges near the outlet and at Wallula Gap. b and c are those proposed by Clarke and others (1984) as resulting from a jökulhlaup release. b represents the extreme case of no "tailwater ponding" (flow impeded by downstream ponding in the Spokane Valley) and immediate conveyance of all of the lake water to the breakout location. c is the more realistic situation of downstream hydraulic conditions affecting the rate of release as well as the delayed response at the breakout point because of the complex lake geometry. e is the hydrograph proposed for Wallula Gap by Craig (1987).

GENERAL IMPLICATIONS

Flood Hydrographs

Peak discharge estimates at Wallula Gap and in the Spokane Valley, in conjunction with known storage volumes in Lake Missoula and the Pasco Basin, permit some simple conclusions regarding the flood hydrographs at both localities. For this analysis, we make the following simplifying assumptions. (1) The flood hydrographs were triangular. This is consistent with the general shapes of flood hydrographs produced by dam failures and by some types of jökulhlaups (Costa, 1988). (2) Maximum discharges at both Wallula Gap and in the Spokane Valley were associated with complete emptying of Lake Missoula from its maximum highstand (1,265 m). (3) An insignificant quantity of water bypassed the Spokane Valley flow route. Important physical parameters include the volume of Lake Missoula available for flooding: 2,184 km³, according to Clarke and others (1984); and the volume of hydraulically ponded water behind Wallula Gap: 1,210 km³ at the 375-m ponding level as determined from the stage-storage curve of Craig (1987).

Constructing a hydrograph for the Spokane Valley reach that satisfies our peak discharge estimate and the volume of Lake Missoula requires a flow duration of about 70 hr (Fig. 9). Because the 17 million $m^3 \cdot sec^{-1}$ estimate is a minimum discharge value, it is possible that the actual flow duration was even less. A similar hydrograph can be drawn for Wallula Gap with the added limitation that at peak stage (375 m in the Pasco Basin) there is 1,210 km³ of ponded storage upstream of Wallula Gap. This imposes a degree of asymmetry to the hydrograph: the waxing part of the hydrograph must have been less than 54 hr, and the waning period was at least 67 hr, with a total flow duration of at least 121 hr (Fig. 9).

Although these hydrographs must be viewed as first-order approximations, some conclusions can still be drawn. Flow duration associated with such a large discharge was probably remarkably short, on the order of three days within the Spokane Valley. Moreover, the peak discharge seems to have attenuated significantly between the outburst area and Wallula Gap. A large part of peak discharge diminution was probably the result of storage in the Pasco Basin. Stages in the Pasco Basin apparently rose at least 20% faster than they declined. Craig (1987) addressed some of the dynamic aspects of Missoula Flood hydrographs for portions of the flood route, including Wallula gap, and presented hydrographs with shapes that accord with his dynamic model (Fig. 9). Obtaining a complete dynamic picture of the maximum flood(s), however, remains difficult because of the plexus of flow paths across the Channeled Scabland and uncertainty regarding the degree of blockage of the Columbia River valley in north-central

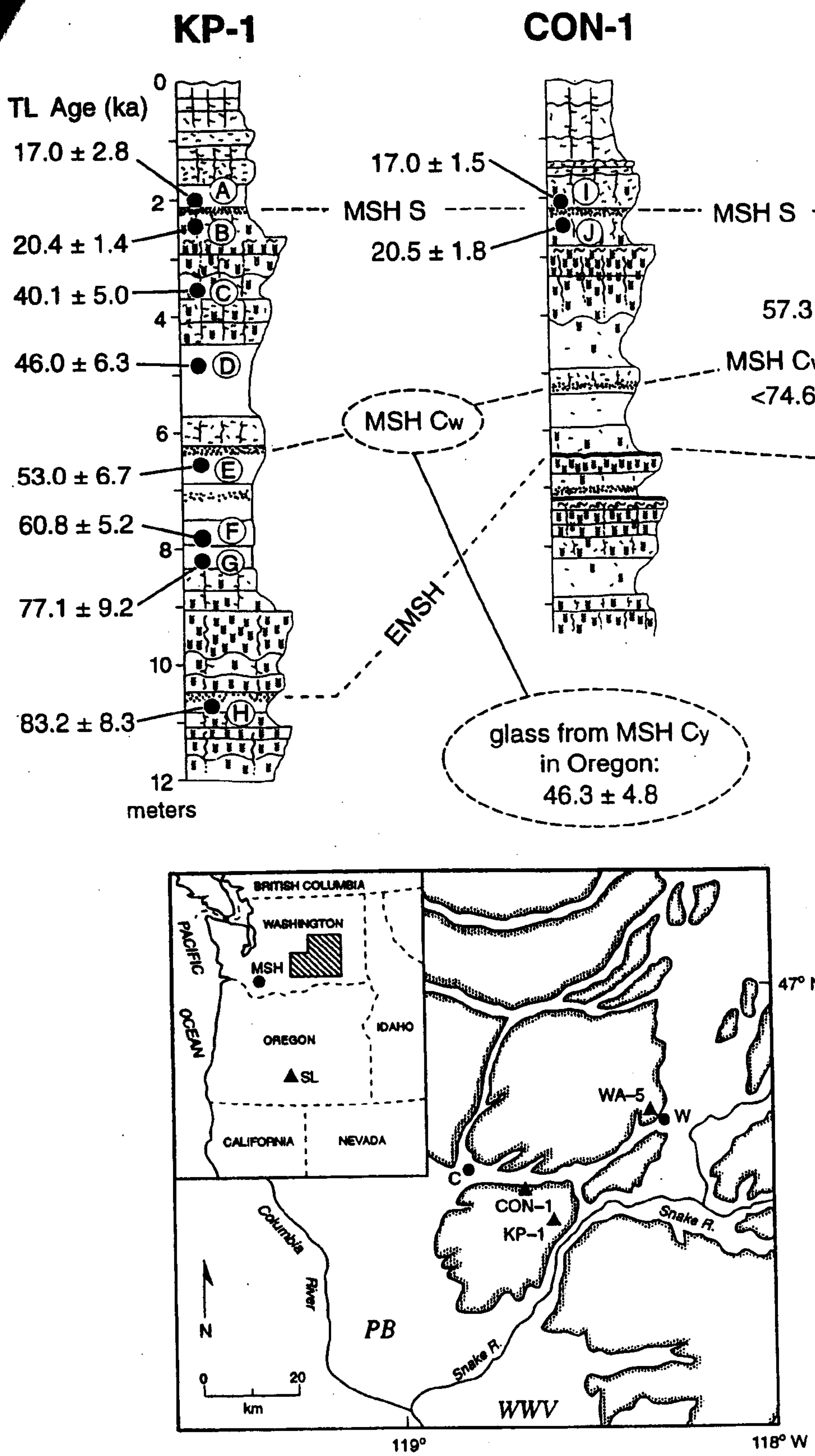

Figure 1. Locations of three sample sites: WA–5 (Washtucna roadcut 5, near Washtucna, W), CON–1 (Connell roadcut 1), and KP–1 (Kahlotus–Pasco roadcut 1), near Connell (C). Sections are displayed (left to right) in order of increasing distance from average source of loess [*McDonald and Busacca*, 1990, 1992]. The stippled areas denote loess islands. General source areas for loess: PB (Pasco Basin) and WWV (Walla Walla Valley). Location of Mount St. Helens (MSH) and Summer Lake (SL) are shown in the inset.

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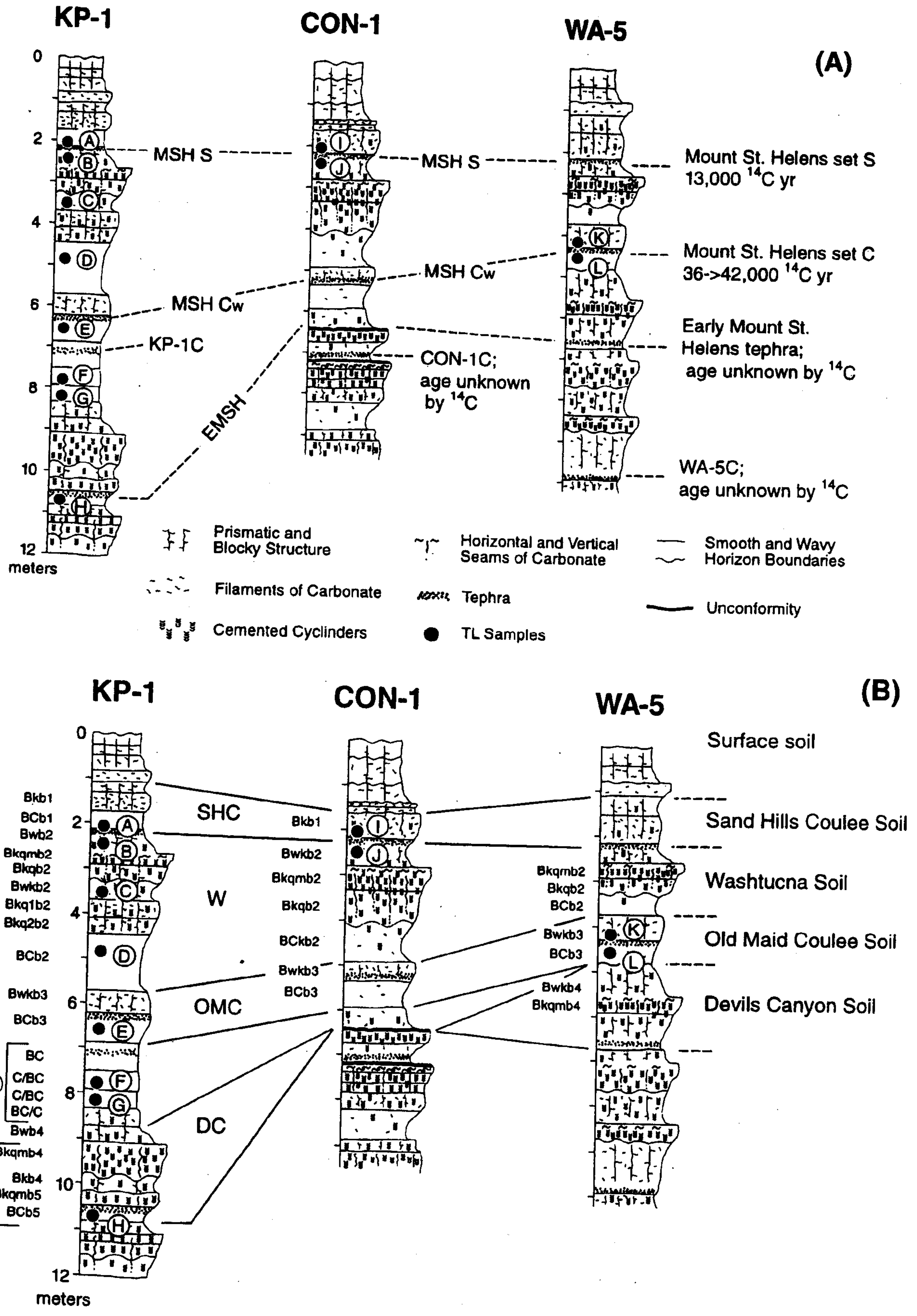
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CON-1C; age unknown by ¹⁴C
Mount St. Helens set S 13,000 ¹⁴C yr
Mount St. Helens set C 36->42,000 ¹⁴C yr
Early Mount St. Helens tephra; age unknown by ¹⁴C
WA-5C; age unknown by ¹⁴C
Prismatic and Blocky Structure
Filaments of Carbonate
Cemented Cyclinders
Horizontal and Vertical Seams of Carbonate
Tephra
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Surface soil
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