Weathering Rinds on Andesitic and Basaltic Stones as a Quaternary Age Indicator, Western United States

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GEOLOGICAL SURVEY PROFESSIONAL PAPER 1210

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Weathering rinds can effectively differentiate Quaternary deposits according to relative age and, with calibration, can be used to estimate numerical ages

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WEATHERING RINDS ON ANDESITIC AND BASALTIC STONES AS A QUATERNARY AGE INDICATOR, WESTERN UNITED STATES

By STEVEN M. COLMAN and KENNETH L. PIERCE

ABSTRACT

Approximately 7,335 weathering rinds were measured on basaltic and andesitic stones in Quaternary glacial deposits to assess the use of weathering rinds as a relative- and numerical-age indicator. These rinds were studied at 150 sites in 17 different areas of the Western United States. Sampling methods were designed to limit the variability of environmental factors other than time (climate, vegetation and other organisms, parent material, and topography) that affect rind development. Only andesitic or basaltic lithologies were sampled, and sampling sites were restricted to terraces or flat moraine crests in areas that differ only moderately in climate. Within the restrictions of these sampling procedures, variation in rock types among sampling areas appears to be the most important factor, other than time, that affects weathering-rind development. Differences in climate among sampling areas also have a major effect, whereas the influence of such factors as vegetation, topography, and soil-matrix texture appears to be comparatively minor.

Statistical analysis demonstrates that weathering rinds are an excellent quantitative indicator of age. Within a sampling area, deposit age is the most important source of variation in rind thickness, and all differences in mean rind thickness between deposits of different stratigraphic ages are important.

Rind-thickness data for independently dated deposits near West Yellowstone, Mont., and elsewhere demonstrate that the rate of increase in weathering-rind thickness decreases with time. Because the rate decreases with time, the ratio of the rind thicknesses of two deposits in the same area provides a minimum estimate of the numerical-age ratio of the two deposits. Based on the West Yellowstone sequence, a logarithmic function appears to best represent the relation between weathering-rind thickness and time. However, because of the effects of climate and rock type on rind development, a logarithmic time-function must be calibrated for each sampling area. Because of the absence of independent numerical-age estimates in areas other than West Yellowstone, the age of one deposit (with rinds >0.5 mm thick) in each area was inferred by correlations based on stratigraphy and relative-age criteria. The inferred age of this one deposit in each area was then used as the calibration point for the rind-thickness curve for that area. The ages of the other deposits in each area were estimated from their rind thickness and the calibrated weathering-rind curves.

Ages estimated from weathering-rind thicknesses and the resulting conclusions depend on several assumptions and inferences, but the data clearly suggest that, if the rate equations can be calibrated, weathering rinds can be used to approximate numerical ages, perhaps to within 10–20 percent. In addition, age estimates based on weathering rinds provide quantitative comparisons that constrain regional correlations. In the areas examined, ages of glacial deposits estimated by these methods appear to group into at least four time intervals: about 12,000–22,000, about 35,000–50,000, about 60,000–70,000, about 135,000–145,000 yr ago, and possibly several older time periods. These time intervals are approximately coeval with times of high worldwide ice volume indicated by marine oxygen-isotope records. The ages also indicate that several separate ice advances occurred during the Wisconsin Glaciation in the Western United States, including both a mid-Wisconsin advance and an early Wisconsin advance in several areas. None of the age estimates for end moraines in our sample areas fall between 75,000 and 130,000 yr ago. End moraines of a given age are not present in all areas and the number of end-moraine ages differs from area to area, probably because of differences in glacier response to local climatic variations.

INTRODUCTION

This study was prompted primarily by the need for better dating and correlation of Quaternary deposits in the Western United States. The paucity of material suitable for dating these deposits by available numerical[1] (mostly radiometric) methods has persistently hampered regional correlations. In most cases, inferences concerning ages have been drawn and correlations proposed for these deposits on the basis of the extent of weathering and of modification of morphology. However, weathering and erosion processes provide only a measure of relative age, because (1) their results as functions of time are imperfectly understood, (2) difficulties arise in the quantification of their results, and (3) their rates are controlled by several environmental factors. Correlations based on relative ages are tentative at best, because rates of weathering and erosion can vary significantly, both over short distances and with small variations in parent material. In addition, relative-age differences do not indicate the magnitude of absolute-age differences.

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[1] Throughout this report we will use the term "numerical" for dating techniques that produce age estimates on a ratio scale of years, and "relative-age" for those which produce ages on an ordinal scale. (See Griffiths, 1967, p. 245–249, for a discussion of different types of scales.) We resist using the term "absolute" for any dating technique.

These difficulties emphasize the need for, and the usefulness of, a numerical dating method based on a commonly applicable weathering parameter; previous studies have shown that weathering rinds on andesitic and basaltic stones have some potential for use in such a technique. The advantages of weathering rinds over the plethora of other time-dependent weathering and erosional features result from the potential for isolating a single weathering parameter, for objectively measuring that parameter, and for controlling the variables that affect it. For these reasons, weathering rinds may be a more consistent and representative measure of age than other weathering and erosional features for ages of 10^4 to 10^5 yr.

Weathering rinds were measured on andesitic and basaltic stones in this study because of certain advantages that result from the fine grain size and mafic composition of these lithologies, for example: (1) a tendency for matrix and grain-by-grain alteration rather than intergranular staining, resulting in a relatively consistent thickness of weathered material and a well-defined "weathering front" (inner boundary of weathering); (2) a disinclination for granular disintegration, which often destroys rinds on coarser grained rocks; and (3) a relatively fast rate of weathering compared to that of more felsic rocks of similar grain size.

PURPOSE

This study examines the development of weathering rinds on andesitic and basaltic stones with time, with the goal of using weathering rinds as a dating method for Quaternary deposits in the Western United States. In order to accomplish this goal, the influence of variables other than time (sampling and environmental variables) on rind development must be evaluated. The study of weathering rinds as a dating technique will begin with their use as a relative-age criterion for local sequences of deposits, followed by the use of weathering-rind thickness as an approximate numerical-age indicator and regional correlation tool.

PREVIOUS WORK

A number of workers have used weathering rinds on andesite and basalt as a relative-age indicator in local areas in the Western United States (Crandell, 1963, 1972; Crandell and Miller, 1974; Birkeland, 1964; Carrara and Andrews, 1975; Kane, 1975; Porter, 1975, 1976; and Scott, 1977). Each of these local studies proved weathering rinds to be a highly effective tool for separating deposits of different ages. In particular, Porter (1975) was able to demonstrate that weathering rinds in the Yakima Valley, Wash., were statistically consistent for deposits of one age, and significantly different for deposits of different ages. He did not define a numerical function for the change in weathering-rind thickness with time, because of a lack of independent dates for calibration. However, he did suggest that the rate of rind formation may decrease with time.

Weathering rinds on other types of rocks have also been examined for their use as potential age indicators. Obsidian hydration, which produces rinds by hydration rather than by the oxidation-hydrolysis processes predominating in the rinds examined in this study (Colman, 1977), has been used to study Quaternary deposits and found to be an effective numerical dating technique (Friedman and Smith, 1960; Pierce and others, 1976). A number of workers, including Birkeland (1973), Benedict (1973), Carroll (1974), Thorn (1975), and Burke and Birkeland (1979), among others, have studied weathering rinds on granitic rocks and demonstrated that they can be useful relative-age indicators. Weathering rinds on granitic rocks are, however, subject to problems associated with intergranular staining and granular disintegration.

Desert varnish is a rind-like feature, but detailed chemical studies (Engel and Sharp, 1958; Hooke and others, 1969) have demonstrated that desert varnish is largely a surface coating, due at least in some cases to accretion of Fe- and Mn-bound clay (Potter and Rossman, 1977). Although desert varnish generally is developed to a greater degree with deposit age in a given area, large variations in rate of development exist, and local measurements are commonly inconsistent. Consequently, desert varnish has been used only as a relative-age indicator (Hunt and Mabey, 1966).

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GENERAL DESCRIPTION OF WEATHERING RINDS ON ANDESITIC AND BASALTIC STONES

A weathering rind is defined for the purposes of this study as a zone of oxidation colors whose inner boundary approximately parallels the outer surface of a stone (figs. 1, 2). Other weathering reactions commonly accompany oxidation (Colman, 1977), but the rinds measured were defined primarily by visible discoloration. The original gray to black color of the rock is altered to colors ranging from buff through yellow to reddish (2.5*Y* to 7.5*YR* hues). The coloring of some weathering rinds is layered; but vague, diffuse inner parts of rinds were not measured. These "inner rinds" (fig. 2*D*) are usually dark reddish gray and are usually many millimeters thick, but they vary considerably in thickness around a single stone and are only displayed by some stones. Thin sections of the "inner rinds" show that they are usually products of alteration of olivine and (or) glass. The kind of alteration that produces the "inner rinds" and the reason for their large

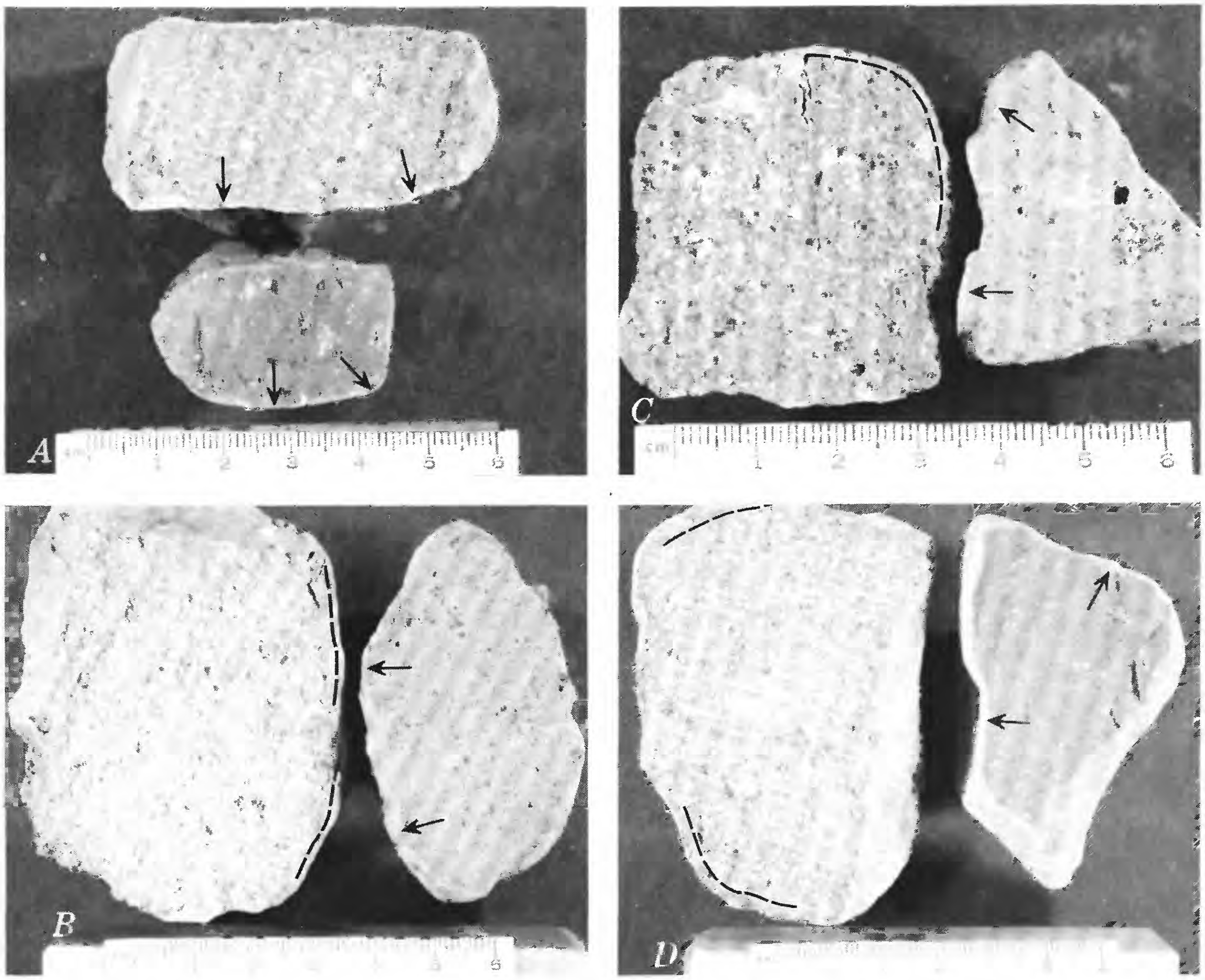

FIGURE 1.—Examples of weathering rinds on andesitic rocks near Lassen Peak, Calif. Sampling sites for each deposit are given in Appendixes A and B. Arrow or dashed line, areas where true rind thickness is shown. Apparent variation in rind thickness is mostly a function of camera angle and unevenness of the broken surface. A, from Tioga Till (about 0.1 mm); B, from "early Tioga" (Kane, 1975) till (about 0.4 mm); C, from Tahoe Till (about 0.8 mm); D, from pre-Tahoe till (about 2.0 mm).

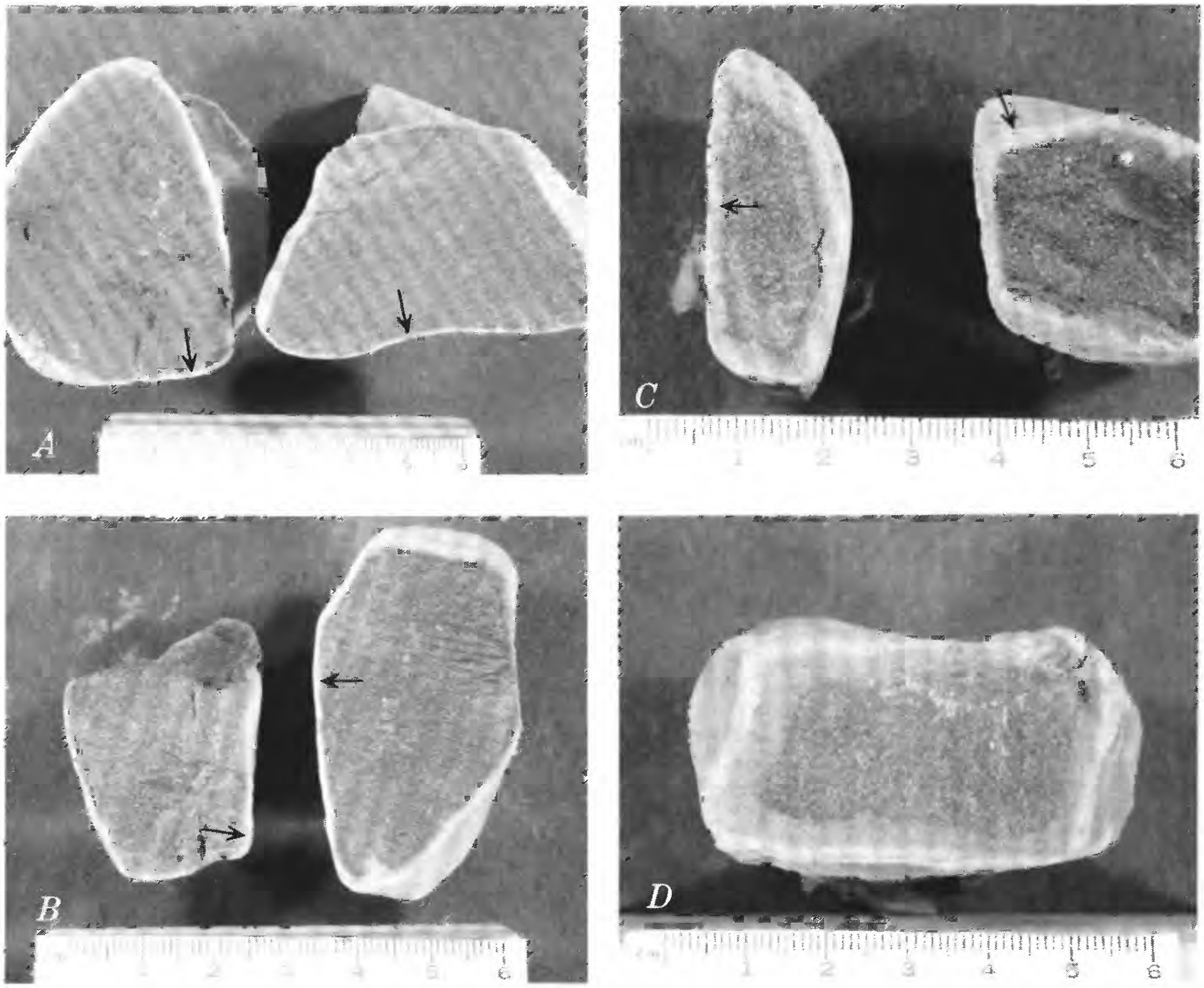

FIGURE 2.—Examples of weathering rinds on basaltic rocks near McCall, Idaho. Sampling sites for each deposit are given in Appendixes A and B. Arrow, area where true rind thickness is shown. Apparent variation in rind thickness is mostly a function of camera angle and unevenness of the broken surface. A, from Pinedale Till (about 0.3 mm); B, from Intermediate till (about 0.8 mm); C, from Bull Lake Till (about 1.8 mm); D, example of an inner rind, from Bull Lake Till.

variation are not known, but in many cases deuteric alteration along joints and subsequent differential erosion appear likely.

The hardness of weathering rinds varies from almost that of the unaltered rock to extremely soft and mushy. Weathering-rind hardness appears to decrease with time, and rinds from older deposits can often be sliced with a knife, smeared with the fingers, or crushed where hit with a hammer.

FACTORS AFFECTING WEATHERING-RIND THICKNESS

A large number of variables or factors potentially affect weathering-rind thickness. These factors can be classed into two general groups, which here will be called sampling factors and environmental factors. Elements of the sampling procedure that are capable of introducing variation into the measurement of weathering rinds include (1) selection of sampling sites, (2) collection of samples from sampling sites, (3) procedures for measuring the selected samples, and (4) the operator who performs the sampling and measuring. Possible variation in rind thickness introduced by these factors was largely eliminated from this study by using a standard set of sampling and measuring procedures, which will be described in the next section. The effect of different operators will be partially evaluated in the statistical analysis section.

Environmental factors that affect weathering-rind thickness are essentially identical to those postulated by Jenny (1941) as the factors in soil formation: climate, parent material, vegetation, topography, and time. Jackson and Sherman (1953, p. 241–248) have stated that the factors that control chemical weathering are essentially those that control soil development. Many of these factors are composed of several subvariables. Topography includes the effects of erosion and deposition; climate includes temperature, precipitation, and their seasonal distribution; parent material includes rock type, rock texture, and soil matrix texture.

Because the purpose of this study was to examine the relationship between weathering-rind thickness and time, we attempted to minimize the variation in other factors—by sampling them over a restricted range. For example, out of the wide range of possible lithologies, only basaltic and andesitic stones were sampled. However, variables other than time could not be completely eliminated, and as a result, we attempted to evaluate the effect of residual variation in environmental factors. To a large extent, the effect of time could be isolated from the effect of other variables. The evaluation of variables other than time will follow the discussion of sampling procedures.

SAMPLING DESIGN AND METHODS

STRUCTURE OF THE DATA

The basic organization of data in this study is a nested, multi-level sampling design. This design consists of the following levels:

1. seven different sampling areas,
2. several stratigraphic ages of deposits within each sampling area,
3. several landforms (moraines, terraces) of each age,
4. several sampling sites on each landform,
5. many measurements at each sampling site.

In some areas, the landform level was not used.

The sampling design used in this study was conceived primarily to evaluate the relation between weathering-rind thickness and time (age). Age is therefore isolated on the second level of the nested sampling design. Variation in two important factors in rind development, rock type and climate, occurs mostly between sampling areas, so that these factors can be held nearly constant by analyzing each sampling area separately.

The influence of factors other than time on weathering-rind thickness was investigated using several different subsets of the rind thickness data. Some of these subsets are part of the data collected for the basic nested sampling design; other subsets were collected specifically to evaluate the influence of factors other than time. For example, the influence of climate was evaluated by comparing rind thicknesses on similar rock types in deposits thought to be about the same age in different sampling areas. However, the rock types were not identical, and the ages of the deposits are not known with absolute certainty. Therefore, the influences of rock type and climate are to some extent "confounded," that is, their influences cannot be completely separated. Such evaluations of the influence of each factor are tempered by the amount of confounding in the data.

Another subset of data used to evaluate the influence of factors other than time was data collected with the specific purpose of isolating one of these factors. For example, in some cases, a single deposit, such as an outwash terrace, could be traced along a considerable climatic gradient. By sampling a single rock type at places on the deposit with different climates, rock type and age were held constant, and the influence of climate could be evaluated independently. Because we attempted to keep variables such as rock type and climate relatively uniform within each sampling area in order to evaluate the influence of age, much of the data collected to specifically isolate other variables was not used in the nested sampling structure. Only sites where variables such as rock type and climate are relatively uniform were used to evaluate the influence of age.

The basic data collected in this study are contained in Appendixes A and B. Appendix A provides the mean[1],

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[1] Mean = $\overline{X} = \Sigma X_i/n$, where X_i are individual observations, and n is the number of observations.

standard deviation[2], and number of measurements at each site, along with the deposit and rock type on which rinds were measured. Appendix B gives site locations and other site data.

AREAS AND TYPES OF DEPOSITS SAMPLED

Approximately 7,335 weathering rinds were measured at about 150 sites in 17 different areas in the Western United States. Most of the deposits sampled were either glacial or glaciofluvial because of the possibility of correlating deposits resulting from large-scale climatic fluctuations, and because of the possibility of correlating these deposits with dated paleoclimatic records. However, data collection was concentrated in seven areas because they contained well-developed sequences of deposits of different ages, because they contained abundant, relatively uniform rock types, and because they had climates conducive to rind formation. The stratigraphic ages of deposits sampled in each of the seven areas were defined by mapping of previous workers (fig. 3). These areas are (1) near West Yellowstone, Mont.; (2) near McCall, Idaho; (3) the Yakima Valley near Cle Elum, Wash.; (4) the Mount Rainier area, Washington; (5) the Satsop River drainage and adjacent parts of the Chehalis River Valley, Wash., here referred to as the Puget Lowland; (6) the Lassen Peak area, California; and (7) near Truckee, Calif. The locations and data for the other sampling areas are given in Appendixes A and B. These areas proved relatively less suitable either because of the scarcity of basalts or andesites, because of the large variability in these lithologies (especially andesites), or because of very dry climates.

SAMPLE SITE SELECTION

Land surface stability was the primary criterion for selecting sampling sites, and evidence of erosional or depositional disturbance of the weathering profile was minimal at most sites chosen. Sampling sites were commonly located on relatively flat moraine crests or on flat terrace surfaces. This type of site precludes burial by colluvium; sites with thick eolian mantles were also avoided. These sites were not chosen by formal random selection procedures from all possible sites of the above description because of access considerations. However, we are aware of no bias in the selection of sample sites, and the selected sites are thought to be representative.

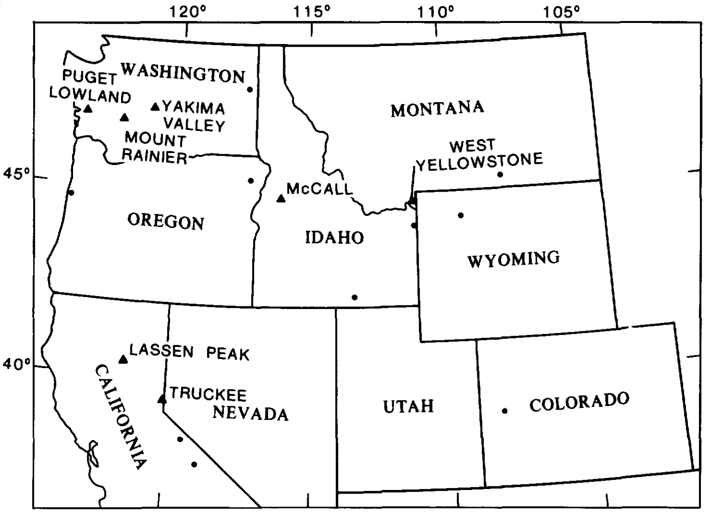

FIGURE 3.—Index of sampling localities, Western United States. Triangle, principal sampling area. Solid dot, secondary sampling locality. References to the surficial mapping on which the sampling was based are as follows: West Yellowstone, Mont. (Alden, 1953; Richmond, 1964, 1976; Pierce, 1973; Waldrop, 1975; Waldrop and Pierce, 1975; Pierce and others, 1976); McCall, Idaho (Schmidt and Mackin, 1970); Yakima Valley, Wash. (Porter, 1969, 1976); Mt. Rainier, Wash. (Crandell and Miller, 1974); Puget Lowland, Wash. (Carson, 1970); Lassen Peak, Calif. (Crandell, 1972; Kane, 1975); Truckee, Calif. (Birkeland, 1964).

SAMPLE COLLECTION

Several options existed in procedures for selecting the stones at each sampling site; these options included the type of stones selected and the position in the weathering profile from which the samples were taken.

In this study, stones were collected from the soil profile at depths of about 20-50 cm, usually from the upper part of the B horizon, or, if a B horizon was not present, from the uppermost C (Cox) horizon. All stones encountered in the soil profile at the proper depth were removed and broken with a rock hammer. A preliminary reconnaissance of the rock types present in the deposits of a given sampling area formed the basis for selection of the lithologies on which rinds were measured. These lithologies are those that were common throughout a given sampling area, and that were relatively consistent in appearance from site to site. All stones of these lithologies encountered at each sampling site were retained for measuring rind thickness. Appendix C contains generalized petrographic descriptions of the lithologies used in this study in each of the principal sampling areas.

The upper part of the B horizon (or the Cox horizon if a B horizon was not present) was used as the sampling

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[2] Standard deviation $= s = \left(\frac{\Sigma(X_i - \overline{X})^2}{n-1}\right)^{1/2}$

horizon, because the B horizon is generally more weathered than lower horizons (Birkeland, 1974, p. 9) and is less subject to the problems of disturbance associated with the A horizon.

The A horizon represents the zone of maximum leaching (Birkeland, 1974, p. 9), but several factors—including its relative thinness, disturbance by frost or animals, loss of material by erosion, and accretion of loess, colluvium, or other material—make it less reliable than the B horizon as a sampling horizon. The C horizon is generally less weathered than the B horizon (Birkeland, 1974, p. 9), and weathering rinds in C horizons are thinner than those in associated B horizons.

Weathering-rind thickness appears to progressively decrease with depth in the weathering profile, from the B horizon downward. In a number of locations, particularly near McCall, Idaho, rind thickness was observed to decrease progressively below the standard sampling depth. (See, for example, C76-54C versus C75-104B, Appendix A.) Porter (1975) has made the same observation for rinds in the Yakima Valley. Where completely unoxidized parent material was encountered (Cn horizon), virtually no weathering-rind development was observed, for example C76-54A (Appendix A).

In contrast to our sampling procedures, some workers have used weathering rinds on stones at the ground surface (Porter, 1975; Burke, 1979) to determine relative ages. Porter (1975) observed no noticeable difference between surface rinds and shallow-subsurface rinds in the Yakima Valley. Our observations support this conclusion for the Yakima Valley, where at least for the younger drifts, the rinds are almost as hard as the rock itself. However, a number of observations clearly indicate that the rinds on surface stones can yield unreliable data for studying weathering with time, especially for older deposits.

First, the hardness of the weathering rinds obviously affects their preservation on the surface. The soft, mushy rinds produced by advanced weathering are almost certain to be eroded from surface stones. The rinds on subsurface stones in older deposits in most of the sampling areas had to be handled with care in order to preserve the full thickness of the weathering rind. In the Lassen Peak area, stones which were brought to the surface of Tahoe deposits by logging-road construction showed abundant evidence of flaking and removal of weathering rinds, even though they had been at the surface a few tens of years at most (fig. 4). At McCall, Pierce determined that a thin stream of warm water removed most of the soft rinds on stones from older deposits.

Even where the loss of weathering rinds at the surface is not a problem, major differences commonly exist between rinds on surface stones and those on shallow subsurface stones. On fine-grained andesitic intrusive rocks at the surface of moraines of Pinedale age in the West Yellowstone area, weathering rinds under lichen-covered surfaces were two or more times thicker than those on the undersides of the same stones. This difference is consistent with the conclusions of Jackson and Keller (1970), who documented greater depths of weathering under lichen-covered surfaces than on lichen-free surfaces on basalt in Hawaii. At another Pinedale locality near West Yellowstone, rinds were measured on both shallow subsurface and surface basalts. The results were 0.44 ± 0.22 (1 standard deviation, $n=41$) for the subsurface sample, and 0.67 ± 0.21 ($n=25$) for the surface sample (collected by R. M. Burke, measured by Colman). A probability value of less than 0.01 for a Student's t-test provides strong evidence against the hypothesis that these two samples are from the same population.

Differences in thickness between rinds on surface stones and those on shallow subsurface stones may be related to differences in duration of exposure to weathering. A surface stone begins to weather as soon as it is exposed, but weathering of a subsurface stone is probably minor until the oxidation front migrates downward past the stone. Stones in unoxidized parent material have virtually no rinds (C76-54A, for example). An interval of at least several thousand years seems to be required before the oxidation zone extends to the typical 30-cm sampling depth used in this study.

The formation of rinds on basaltic stones at the surface also may be controlled by different processes than those that control the formation of rinds on stones within the soil. Rinds on subsurface basaltic stones near Wallowa Lake, Ore. (Appendix A), appeared considerably different than rinds on surface basaltic stones measured by Burke (1979). The surface rinds were thicker on the average, but much more variable; many stones have no rinds. The surface rinds were also harder and redder than the subsurface ones. One possible explanation for the difference is the effect of grass and forest fires on the surface rinds.

Because of the difficulty in controlling the variables that affect weathering-rind development on surface stones—including lichens, fire, rolling by animals, uneven wetting, and erosion of weathered material—weathering rinds were sampled from within the weathering profile in this study, as described in the

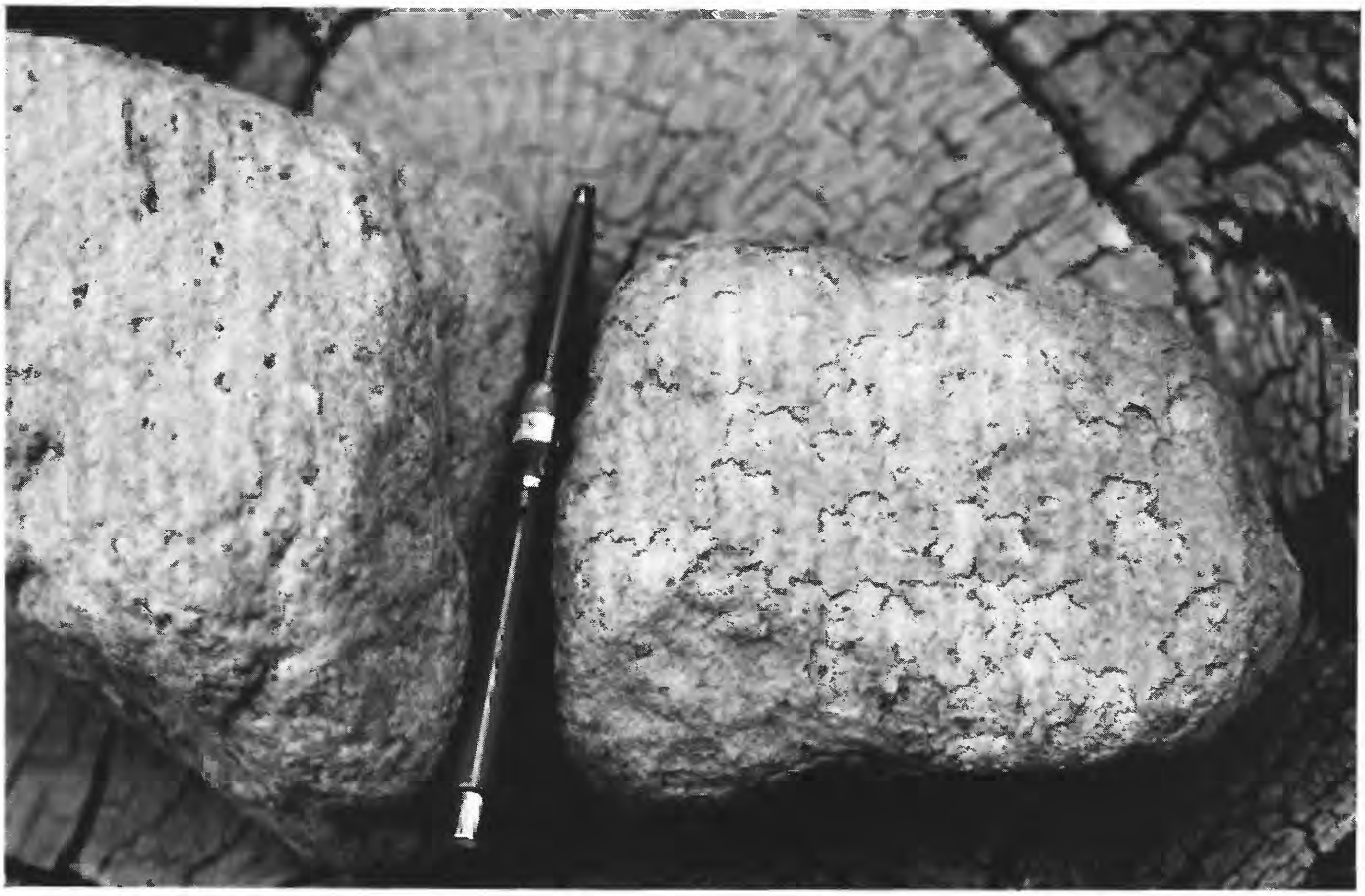

FIGURE 4.—Destruction of weathering rinds on stones brought to the surface of Tahoe Till by logging-road construction near Lassen Peak, Calif. Outer part of weathering rinds on these two stones of nearly identical lithology is quite soft. Rind on underside of stone on left is preserved, whereas rind on exposed upper side of stone on right is flaking off.

preceding section. This procedure minimizes the effect of the above variables and helps to isolate time as a factor.

In conclusion to this discussion, it should be noted that the sampling procedures used in this study are most appropriate for deposits in the range of 10^4 to 10^5 yr old. In younger deposits, weathering may not reach the depths sampled in this study, and rinds developed on surface stones may be more useful for deposits in the 10^3-yr-old range. Deposits older than about 0.5 m.y. have usually suffered considerable erosion, and their surface is probably now below the position of the original B horizon. Thus, the weathering of these deposits is not strictly comparable to that of younger deposits whose surfaces have been minimally lowered. Despite this limitation on our methods, rinds on early to middle Pleistocene deposits are usually much thicker and better developed than those in nearby late Pleistocene (about 10^5-yr-old) deposits, so that rinds are still a useful age indicator for the older deposits.

MEASUREMENT PROCEDURES

Rind thickness was measured to the nearest 0.1 mm, using a 6-power magnifying comparator containing a scale graduated in 0.2 mm increments, on stones that were split open and sampled as described in the previous section. In most cases, only half or less of the perimeter of each stone was appropriate for measuring rind thickness. Places not considered suitable for measurement include: (1) where the broken face was not approximately perpendicular to the outer surface of the stone, (2) where part of the rind was crushed or flaked in the process of breaking the stone, and (3) where the outer surface of the stone was concave outward, allowing soil matrix to cling tightly to the stone.

An important assumption that will be necessary in the analysis of the relation between rind thickness and time is that the stones on which rinds were measured were unweathered when entrained, or were abraded in transport, and were therefore deposited with fresh, unweathered surfaces. Accordingly, the measured weathering rinds developed progressively from the time of deposition. Several observations suggest that this assumption is valid, and that preexisting rinds on stones inherited from bedrock or from older, reworked deposits are rare. First, stones sampled from unweathered C (Cn) horizons exhibit virtually no rinds (C76-54A, for example). Second, stones that show evidence of weathering prior to deposition are rare. Such stones include those having rinds with asymmetric thicknesses around the stone, which suggests partial abrasion of a preexisting rind, and stones whose thicknesses are far removed from the distribution of rind thicknesses for the rest of the sample. Stones with markedly asymmetric rinds (varying by more than a few tenths of a millimeter) were not measured. Exceptionally thick rinds were measured but were considered outliers to the sample rind-thickness distribution; they were not included in the calculation of sample means.

On stones that exhibited no visible variation in rind thickness, the rind was measured in a single, convenient place. Although formal randomizing procedures were not used in the selection of the place where the rind was measured, care was taken to avoid obvious bias, and the measurements obtained in this manner are considered effectively random. In a few cases (usually 10 percent or less), rinds exhibited small but apparent variation in thickness around the stone. In these cases, a place that appeared representative was chosen in which to measure the rind. These measurement procedures preclude the use of formal significance levels and precise calculations for statistical analysis, but do not invalidate the usefulness of such analyses.

In most cases, between 30 and 60 measurements were made at each sampling site. With repeated measurements of rinds on the same stones, individual measurements could usually be reproduced to within ±0.1 to 0.2 mm, depending primarily on the sharpness of the weathering front (the inner boundary of the weathering zone). Very thin rinds, in the range of 0.0-0.1 mm thickness, are at the limit of measurement. Such rinds were recorded as 0.1 mm if surface oxidation of the stone obscured the texture of the rock and penetrated the stone surface. The rind was recorded as 0.0 mm thick if the texture of the rock could be seen through the slight oxidation of the surface.

ENVIRONMENTAL FACTORS OTHER THAN TIME

Because the main focus of this report is on the relation between weathering rinds and time, we wish to first evaluate the influence of other environmental factors. Besides the effect of sampling procedures, factors that affect chemical weathering features are essentially the same as those that control soil development (Jackson and Sherman, 1953, p. 241-248). As discussed previously, these variables are climate, vegetation and other organisms, relief (topographic position), parent material, and time (Jenny, 1941, p. 15).

As discussed earlier, the variability of rind thickness due to sampling techniques essentially has been eliminated by using a standard set of procedures. In addition, the sampling procedures have greatly reduced the influence of environmental factors by including only a limited range of such factors. Their remaining effect on rind thickness is the subject of the following sections. The influence of these factors is complex, because the factors themselves are interrelated (fig. 5), and their effects are commonly confounded; that is, their effects cannot be completely separated.

TOPOGRAPHIC POSITION

Just as erosion and burial affect the development of soil profiles, our observations indicate they also affect the development of weathering rinds. The effects are essentially those described by Jenny (1941) as the relief (topography) factor. The effects of erosion and burial on weathering-rind development are illustrated by the data for sampling sites on till of Hayden Creek age near Mount Rainier. The data for these sites (Appendix A) exhibit considerable scatter, which we attribute to the fact that all of the sampling sites except two, C76-40 and C78-116, are either being eroded or are buried by eolian deposits. The stones at C76-40 and C78-116, the two undisturbed sites, have much thicker rinds than stones at the other sites, even though C76-40 and C78-116 are on recessional moraines that are at least slightly younger than the other moraines sampled.

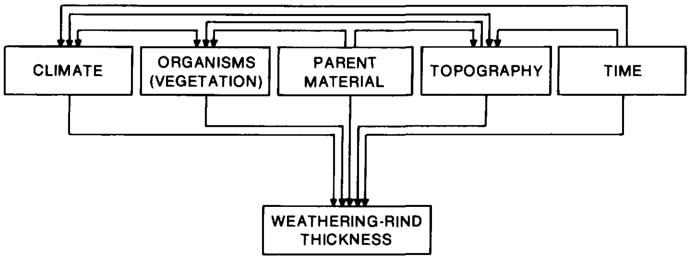

FIGURE 5.—Interrelations among factors affecting weathering-rind development.

Obviously, where erosion has removed the zone of maximum weathering in the upper part of the soil, the weathering rinds on remaining stones will be anomalously thin. Sample sites were chosen to avoid actively eroding areas, but especially for relatively old till deposits, completely uneroded sites probably do not exist. Despite efforts to choose sites with minimal erosion, the data suggest that minor differences in topography may have an appreciable affect on weathering rinds. For example, three sampling sites were located on the crest of the outermost Bull Lake moraine near McCall. In order of decreasing average rind thickness they are: C75-109 (1.96 mm), just off the crest (erosion=deposition?); C76-56 (1.69 mm), on a broad, flat part of the crest; and C76-55 (1.44 mm), on a relatively sharp part of the crest. Although other variables are probably involved, one explanation for the differences in rinds among these sites is variation in the erosion to which the sites have been subjected.

However, erosion at most sampling sites does not seem to have significantly affected rind thicknesses. For sites on flat outwash terraces, an assumption of negligible erosion can be easily justified. As will be discussed in a later section, rind thicknesses from sites on outwash terraces were compared with those from sites on till of the same age. Rinds sampled from the till sites tended to be slightly thicker than those from outwash-terrace sites. Although variation in vegetation and soil drainage conditions may affect these rind thicknesses, the fact that rinds from the till sites were actually thicker than those from the non-eroded outwash-terrace sites suggests that erosion of carefully chosen moraine crest sites about 10^5 yr old or younger is relatively minor. Even on older deposits where some degree of erosion is unavoidable, carefully chosen sites probably yield consistent data with a minimum influence of erosion.

Burial of deposits also affects the rate at which weathering rinds form in the deposit, principally by placing the upper part of the buried deposit below the zone of maximum weathering. Many of the study areas were locally covered by a mantle of eolian deposits, commonly loess. Loess-covered sites were avoided in collecting data for the analysis of the relation between weathering-rind thickness and time. However, separate comparisons of loess-free sites with sites having a variety of loess thicknesses demonstrated that relatively thin eolian deposits (less than 50-100 cm) did not appreciably slow weathering-rind development in the upper part of the buried material. In contrast, where eolian deposits are greater than 50-100 cm thick, weathering rinds in the underlying deposits are commonly quite thin. This was the case with Hayden Creek deposits near Mount Rainier, cited earlier; the Salmon Springs terrace deposits in the Puget Lowland are another example. Salmon Springs gravels buried beneath thick loess (C76-33, 37A) have rinds only a few tenths of a millimeter thick, whereas those beneath thin loess (C76-37B) have rinds greater than 1 mm thick. Because of these data, only sites with less than 50-100 cm of loess were used in the analysis of the relation between weathering-rind thickness and time.

PARENT MATERIAL

We deliberately restricted the lithologies on which weathering rinds were measured to basalts and andesites. This restricted range of chemical composition, mineralogy, and texture automatically reduces variation in weathering-rind thickness. However, basalts and andesites still have a range of lithologic variation, and the effect of this variation on weathering-rind development, along with the effect of the soil matrix, is the subject of this section. Many of the comparisons of parent material in this section also involve differences in climate, so that although the effect of climate will be discussed in detail in the next section, climate must also be considered in this section.

Apparently, rates of rind development differ for basalts and fine-grained andesites of similar textures. Although basalts and andesites were seldom found together in the principal sampling areas, rind data from different areas allow some comparison of rind development for the two lithologies. When rind thickness is plotted against time separately for basalts and andesites for each of the study areas (see fig. 19), the curves plot in order of mean annual precipitation of the study areas. However, when basalts and andesites are considered together, the relation of the curves to precipitation is not clear. This suggests that basalts and andesites have different rates of rind development, which can obscure the relation between rate of rind development and precipitation.

Comparison of rind thicknesses for deposits thought to be about the same age in different areas suggests that rinds form somewhat faster on basalt than on andesite. This observation is consistent with the generally accepted conclusion that mafic rocks tend to weather more rapidly than felsic rocks (Goldich, 1938; Loughnan, 1969, p. 93; Birkeland, 1974, p. 138). Differences in precipitation between areas complicate comparisons, but assuming increased moisture favors rind development (a point demonstrated in the section on climate) the comparisons can still be validly made. For example, the basalt-rich Indian John Member of the Kittitas Drift in the Yakima Valley and the andesite-rich pre-Tahoe till near Lassen Peak are probably about the same age, and have almost identical rind thicknesses. However, the Lassen Peak area is considerably wetter than the Yakima Valley. Had the climate of the two areas been similar, the rinds on the basalt in the Yakima Valley would have been thicker than those on the andesite near Lassen Peak in deposits of the same age.

The relative influence of rock type on rind development can be compared to that of other factors, whose specific effects are discussed in subsequent sections. Between sampling areas, difference in rock type appears to be more important than factors such as climate, vegetation, and topography.

Although the influence of climate on the weathering of basalts and andesites overrides that of rock type in some places in the Western United States (R. W. White, oral commun., 1975), in the present study, rock type appears to be a greater influence than climate. The relative effects of rock type and climate on the weathering of basalts and andesites can be assessed by comparing: (1) rind thickness for deposits of a single age *in a single sampling area*, and (2) rind thickness for deposits thought to be the same age (based on soils, morphology, and other relative-age criteria, and on the calibrated rind curves developed in this study) *in different areas*. For the first type of data, rock type is not a factor, and climate is the only variable that affects rind thickness; for the second type of data, both climate *and* rock type affect rind thickness. Basalts and andesites were treated separately, so only the influence of differences among basalts, or among andesites, was considered in the effect of rock type. The two types of data are compared in figure 6, where rind thickness is plotted against mean annual precipitation.

The first type of data, that affected by climate alone, is plotted in figure 6, as well as the second type, that affected by climate plus rock type (assuming the correlations are correct). Only one aspect of climate, namely precipitation, is considered in figure 6. Other climatic parameters, such as temperature, may affect the lines in figure 6 significantly, but such effect remains largely unevaluated. The fact that the lines representing the influence of precipitation plus rock type slope much more steeply than the lines representing the influence of precipitation alone in figure 6 indicates that precipitation plus rock type has a much greater effect on rind thickness than does precipitation alone. Therefore, variation in rock type (combined with unevaluated variation in climatic factors such as temperature) has a greater effect than variation in precipitation.

The closeness of fit of points T, U, and V to line 8 in figure 6 might be interpreted, by itself, to indicate a strong influence of precipitation on rind thickness. However, other lines representing the influence of rock type plus precipitation (for example, line 9) suggest that the fit of points to line 8 is fortuitous; the lines representing the influence of precipitation alone

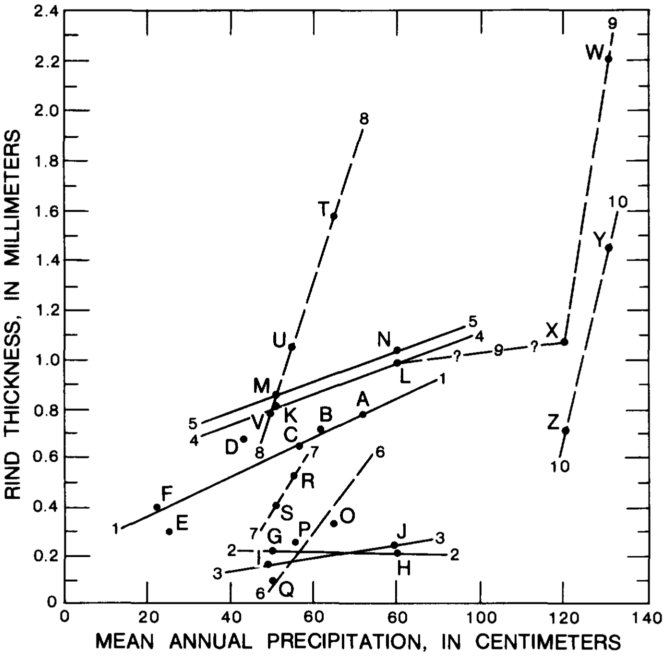

FIGURE 6.—Plot of rind thickness versus mean annual precipitation at sample localities in Western United States. Mean annual precipitation values are from U.S. Weather Bureau (1959). Points A-N are means of individual sites (Appendix A); points O-Z are means for all sites for the given age and sampling area. Solid lines connect points of the same age, lithology, and sampling area; dashed lines connect points of the same general lithology (basalt or andesite), of the same inferred age, but from different sampling areas; fg, fine-grained andesite; cg, coarse-grained andesite; areas not marked, basalt. The two points for Hayden Creek Till (W and Y) correspond to two interpretations of the age of the Hayden Creek advance.

Point	Area	Age	Line
A-F	Yakima Valley, Wash.	Bullfrog	1
G-H	Truckee, Calif. (fg)	Tahoe	2
I-J	Truckee, Calif. (cg)	Tahoe	3
K-L	Truckee, Calif. (fg)	Donner Lake	4
M-N	Truckee, Calif. (cg)	Donner Lake	5
O	McCall, Idaho	Pinedale	6
P	Yakima Valley, Wash.	Domerie	6
Q	W. Yellowstone, Mont.	Deckard Flats (recessional Pinedale)	6
R	Yakima Valley, Wash.	Ronald	7
S	W. Yellowstone, Mont.	Pinedale	7
T	McCall, Idaho	Bull Lake	8
U	Yakima Valley, Wash.	Indian John	8
V	W. Yellowstone, Mont.	Bull Lake	8
W	Mt. Raimier, Wash. (fg)	Hayden Creek	9
X	Lassen Peak, Calif. (fg)	pre-Tahoe	9
Y	Mt. Raimier, Wash. (fg)	Hayden Creek	10
Z	Lassen Peak, Calif. (fg)	Tahoe	10

in figure 6 indicate a much smaller influence of precipitation.

The amount of glass and olivine in the rock is another variable that appears to influence the development of weathering rinds. Examination of thin sections of rinds reveals that glass and olivine are particularly unstable in the weathering environment, and their alteration is the most important source of oxidation colors in the early stages of rind development. The basalts in the deposits in the Puget Lowland illustrate this relation. These rocks contain no olivine, and the small amount of original glass has devitrified, probably by slight burial metamorphism. Compared to basalts that do contain glass and (or) olivine in deposits of comparable ages, the basalts in the Puget Lowland deposits have anomalously thin weathering rinds.

Rock texture is another aspect of parent material that can affect the rate of weathering-rind development. A conscious effort was made in sampling to minimize variations in texture, but some variation was unavoidable. In areas of andesitic rocks, two arbitrarily defined textures were sampled, based on field appearance, and were designated fine grained and coarse grained (Appendix C). Fine-grained andesites contain few or no phenocrysts and usually have a dense, aphanitic matrix, whereas in coarse-grained andesites, phenocrysts comprise more than one-third of the rock volume, and the matrix is somewhat more granular. For comparison, average rind thicknesses for fine-grained andesites were plotted against those for coarse-grained andesites from the same sampling sites (fig. 7). On the average, rinds on fine-grained andesites are 84 percent as thick as those on coarse-grained andesites.

The texture of the soil matrix can also affect the rate of weathering-rind development by affecting soil moisture or the rate at which water moves through the soil. To evaluate the effect of soil-matrix texture, average rind thicknesses for sample sites on outwash were plotted against average rind thicknesses for sites on till, for each age of deposit in each sampling area (fig. 8). Rinds developed in outwash are, on the average, 89 percent as thick as those developed in till of the same age. The effect of soil-matrix texture is complicated by the fact that different soil-matrix textures often support different vegetation communities, and the influences of soil matrix and vegetation on weathering-rind development are difficult to evaluate separately. However, the sample data suggest that rinds develop slightly faster in till than in outwash. This may be due to the finer texture and higher water retention capacity of the till matrix, which allows the soil water more time to approach equilibration during weathering reactions. The effect also may be partly the result of the influence of different types and amounts of vegetation, which is commonly sagebrush or grass on outwash, and coniferous forest on till.

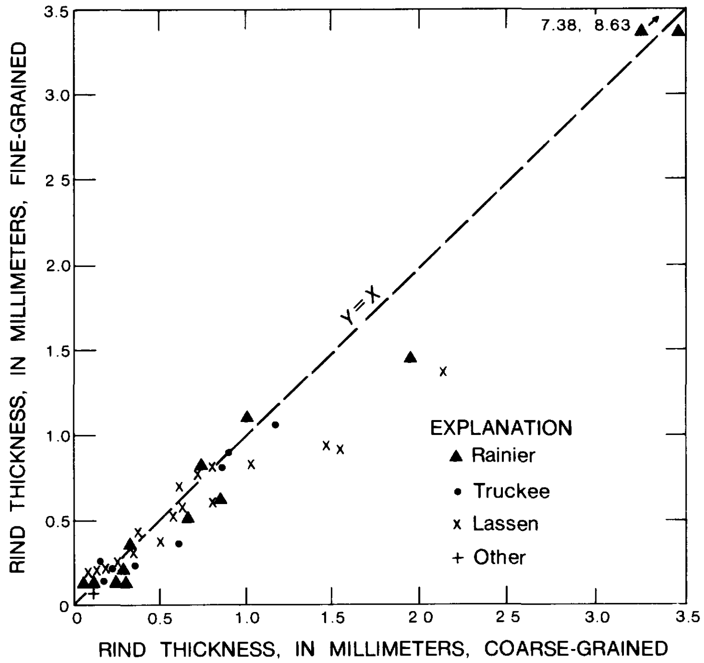

FIGURE 7.—Average weathering-rind thicknesses on stones of fine-grained andesite plotted against those of coarse-grained andesite from same sampling sites. See text and Appendix C for description of rock types. The average ratio of rind thickness on fine-grained andesites to that on coarse-grained andesites is 0.84.

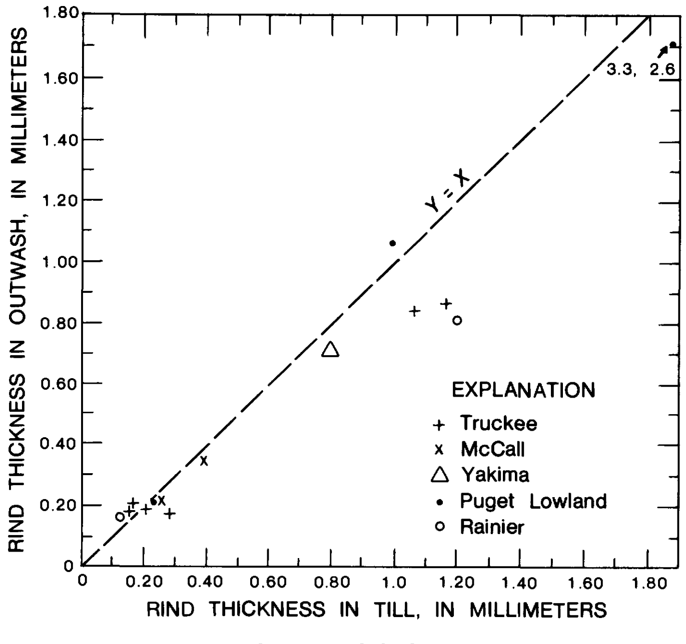

FIGURE 8.—Average weathering-rind thicknesses on stones from outwash plotted against those from till, with age, rock type, and sampling area held constant. The average ratio of rind thicknesses for sites on outwash to that of sites on till is 0.89.

VEGETATION

The effect of different types of vegetation on rind development is difficult to evaluate because the amount and type of vegetation are difficult to measure and because amount and kind of vegetation are so dependent on climate and parent material. An attempt was made to compare rind development at sites bearing forest vegetation with that at sites bearing grass and (or) sage vegetation on deposits of the same age. However, because most contrasts in vegetation on deposits of the same age corresponded with a contrast in soil-matrix textures (between till and outwash), only five data pairs were obtained for deposits of the same age and similar texture, but with different vegetation (fig. 9). For these data, rinds developed under grass and (or) sage average 87 percent as thick as those under forest vegetation. Because of the small number of data points, however, the conclusion is tenuous. This possibly slower rate of rind formation under grass and (or) sage may explain some of the difference between rinds developed in till and in outwash (fig. 8).

Vegetation and soil pH are related, as are pH and the degree of weathering (Jenny, 1941, p. 216). Soil matrix pH's (1:1, soil:water) were measured for soil samples collected at rind sampling horizons in 1975 (Appendix B). The variation in pH is small and inconsistent; no relation to age or rind development is apparent.

CLIMATE

Climate is a variable that is generally accepted as a major influence on weathering processes (Jenny, 1941, p. 104; Loughnan, 1969, p. 67; Birkeland, 1974, p. 211). Climate includes a large number of interrelated variables; however, all of the principal sampling areas in this study have similar seasonal distributions of temperature and precipitation, so that mean annual temperature (MAT) and mean annual precipitation (MAP) values are considered reliable variables for purposes of climatic comparisons.

Climatic variables at individual sites may be slightly different from those at nearby weather stations due to microclimatic, orographic, or altitudinal effects. Because most sampling sites were located on flat moraine crests or terrace surfaces, climatic differences between these sites and nearby weather stations are thought to be minimal. No field evidence that would suggest major microclimatic effects due to insolation, aspect, wind, snow drift, or evapotranspiration was observed at any of the sites used in the analysis of the relation between rinds and time.

Nevertheless, other data (for sites not used in the analysis of the relation between rind thickness and time) indicate that climate can change substantially over short distances, and that such changes have an important effect on rind thickness. Two sites near West Yellowstone, Mont. (C75-102A and 102B, Appendixes A, B), are only about 30 m higher in altitude than the weather station at West Yellowstone but are in a more favorable topographic position to intercept storms. The effect of soil moisture on rind thickness at these sites is indicated by snow course data (Farnes and Shafer, 1975), which suggest that they have average snow packs about 1.7 times that at West Yellowstone. The average rind thickness at these sites is 0.99 mm, compared to 0.78 for sites of the same age in a setting closer to that of West Yellowstone. Similarly near McCall, Idaho, two sites (C78-124 and 125) on recessional Pinedale deposits in a side valley are located about 400-450 m above McCall. Snow course data (Wilson and Carstens, 1975) suggest that the snowpack at these sites may be more than 2 times that at McCall, although the relationship to moisture is complicated by the difference in temperature between the sites and McCall. Rind thickness at these sites averages 0.67 mm, compared to 0.25 mm for the youngest Pinedale deposits near McCall.

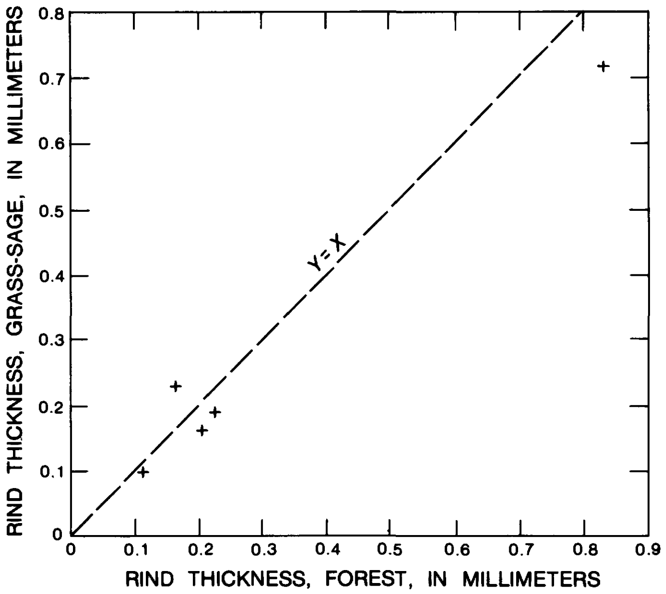

FIGURE 9.—Average weathering-rind thicknesses on stones from sites with grass and (or) sage vegetation plotted against those from sites with forest vegetation. Age, type of deposit, and sampling area have been held constant. The average ratio between rinds developed under grass and (or) sage, and rinds developed under forest vegetation is 0.87.

A dramatic example of the effect of precipitation on the rate of weathering-rind development is found along the Bullfrog terrace (Porter, 1976) in the Yakima Valley, Wash. (fig. 10). Weathering rinds were measured at six localities along the terrace, over a distance of 45 km, in which MAP decreases by a factor of about 3, whereas MAT increases by less than 1°C

(7.9°C at Cle Elum, Wash., 8.3°C at Ellensburg, Wash.). Within the area of this climatic gradient, rind thickness decreases by a factor of about 2 (fig. 10), even though the slight increase in MAT should increase the rates of the chemical reactions that form rinds. Thus, the climatic gradient's effect on weathering-rind thickness is largely due to moisture differences. The influence of moisture differences may be partly indirect, through differences in type and amount of vegetation, which varies from coniferous forest to sparse grass and sage.

Near Truckee, Calif., data from terraces that transect different climatic zones also demonstrate a positive correlation between MAP and rind thickness. Near Verdi, Nev., MAP is about 50 cm, compared to 80 cm near Truckee (U.S. Weather Bureau, 1959). Rind thicknesses measured in Tahoe and Donner Lake deposits near Verdi are generally thinner than those for deposits of the same age at Truckee (fig. 6, lines 2–5). The slope of the rind thickness versus MAP line for the Truckee-Verdi area is similar to that for the Bullfrog terrace in the Yakima Valley (fig. 6, line 1).

Comparison of rates of weathering-rind development between principal sampling areas also illustrates the effect of precipitation. Rind thickness versus time curves for each area (developed in a later section) demonstrates that rates of weathering-rind development generally increase with increasing MAP. For example, basalts in deposits thought to be about 140,000 yr old at West Yellowstone (50 cm MAP), in the Yakima Valley (55 cm MAP), and at McCall (65 cm MAP) have weathering rinds averaging 0.78, 1.05, and 1.57 mm thick, respectively. The West Yellowstone deposits have been dated by combined obsidian hydration and K-Ar methods (Pierce and others, 1976), and the other deposits are thought to be about the same age based on soils, morphology, and stratigraphic relations. These data are plotted in figure 6, line 8; however, as noted in the previous section, much of this variation in rind thickness is due to differences in rock type in addition to differences in climate. The influence of precipitation alone is much less than that of climate and rock type combined (fig. 6).

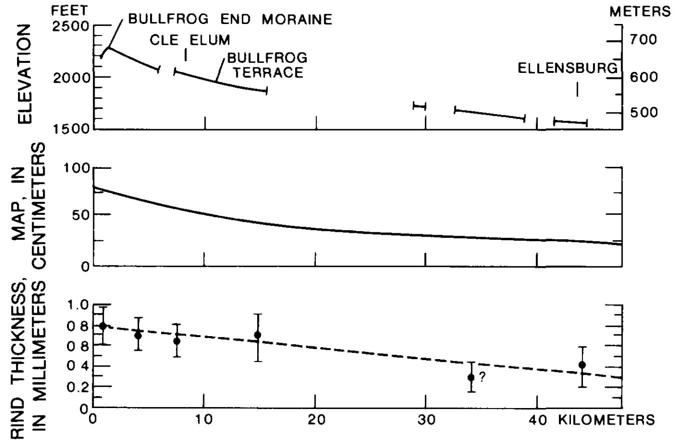

FIGURE 10.—Elevation, MAP, and weathering-rind measurements along the Bullfrog terrace (Porter, 1976), Yakima Valley. The precipitation profile is based on records at Ellensburg and Cle Elum, Wash., and at several stations upstream from Cle Elum (U.S. Weather Bureau, 1959). The rind-thickness values represent the mean ±1 standard deviation for the measurements at each site, whose location has been projected into the line of profile. Trend line of rind thickness against distance down-valley was calculated by least-squares regression ($r = 0.90$). See figure 6, line 1, for plot of rind thickness versus MAP.

The effect of temperature on weathering-rind development remains largely unevaluated because of several problems. First, the range of MAT for the principal study areas is rather small (between 1.7° and 10.5°C, Appendix B), and the effects of variation in MAT are usually masked by the effects of much larger variations in MAP, for example, along the Bullfrog terrace in the Yakima Valley, Wash. What variations do exist in MAT are usually inversely related to those in MAP, and higher temperature and lower precipitation (or vice versa) have offsetting effects on rind development. In addition, the effect of temperature on rind development is difficult to separate from the effect of precipitation; for example, even with MAP held constant, an increase in temperature would result in a decrease in soil moisture, thus reducing or perhaps even eliminating the effect of the increase in temperature. Climatic indices combining precipitation and temperature, such as Arkley's (1963) leaching index, have been devised; but in view of the apparent dominance of precipitation over temperature as a control on weathering-rind development, the use of such an index does not seem warranted.

Observations in a number of secondary sampling areas (for example, along the Bighorn River near Hardin, Mont.: 30 cm MAP, 7.8°C MAT) suggest that the development of rinds is inhibited in dry, continental climates, especially where calcium carbonate accumulates within the soil. The presence of carbonate implies that relatively little leaching has occurred, and carbonate tends to retard the weathering of primary silicates (Grim, 1968, p. 518). The later conclusion was supported by observations in several locations of thicker weathering rinds on the upper, carbonate-free sides of stones than on the carbonate-coated undersides.

SUMMARY

Climate, organisms (vegetation), parent material, topography, and time—the five soil-forming factors (Jenny, 1941)—are the most important factors affecting weathering processes (Jackson and Sherman, 1953, p. 241-248), including weathering-rind formation. These factors are also complexly interrelated, and most—especially climate, organisms, and parent material—contain subfactors.

The sampling procedures for this study were designed to reduce or isolate the variation in factors other than time. Sampling sites were located within a relatively narrow range of climate, partly because the calcic soils of dry climates are not conducive to weathering-rind formation. We restricted variation in rock type, the primary parent-material factor in weathering-rind formation, by sampling only basaltic and andesitic lithologies. Most sampling sites were topographically restricted to erosionally stable sites, commonly terrace surfaces or flat moraine crests. Vegetation at the sampling sites appears to be controlled by climate and soil parent material, which made independent evaluation of its direct effect difficult.

We attempted to isolate and evaluate the variation in factors affecting weathering-rind development that was not eliminated by the sampling procedures. Of the factors other than time, variation in the rock type on which rinds were measured appears to have the most important effect. Variation in climate, especially precipitation and possibly also temperature, among sampling areas also appears to have a major influence on rind thickness. The direct effect of variation in other factors, such as vegetation, topography, and soil-matrix texture, seems comparatively minor for our sampling sites. Within a sampling area, only data for sites with relatively uniform rock type and climate were used in the analysis of the relation between weathering-rind thickness and time. For these data the effect of time is much more important than the effect of any of the other factors, and the time factor is the subject of the rest of this report.

THE RELATION BETWEEN WEATHERING-RIND DEVELOPMENT AND TIME

The ultimate goal of this section is to establish a functional relation between weathering-rind thickness and time, which can be used as an approximate numerical-dating method. The analysis begins with weathering rinds as a relative-age dating method and progresses to a numerical model of weathering-rind development with time.

WEATHERING RINDS AS AN INDICATOR OF RELATIVE AGE

Several workers have used weathering rinds on andesitic and basaltic rocks to discriminate between deposits of different ages (Crandell, 1963, 1972; Crandell and Miller, 1974; Birkeland, 1964; Kane, 1975; Porter, 1975, 1976; and Scott, 1977). Following the procedure of the latter three workers, the data in this study will be presented in terms of means and standard deviations. This procedure appears to be the most objective and representative way of characterizing rind development for a given sampling site. Other measures of rind development, such as maximum thickness, are less easy to justify as being representative, even though there appears to be a reasonably consistent relation between mean and maximum rind thickness (Porter, 1975).

In addition to becoming thicker with time, weathering rinds tend to become softer ("mushier"), with increasing stratigraphic age. Although this effect appears to be systematic, we did not develop a quantitative method of measuring this variable.

When the weathering-rind-thickness data are plotted according to the stratigraphic ages assigned by previous workers (figs. 11, 12; references in fig. 3), the data group quite well. This grouping of weathering-rind data by geologic sequence clearly demonstrates that weathering rinds are an excellent indicator of relative age, and can be used effectively to differentiate deposits of different ages within local sequences. The consistency of results for the same age of deposit and the consistent differences between different deposits, within a sequence, strongly imply that rind thickness is controlled by some time function. In addition, the data invite comparisons between areas; for instance, deposits of the last major glacial advance in each area all have average weathering-rind thicknesses of between 0.1 and 0.3 mm.

Average rind thicknesses for each age of deposit within each area (fig. 13; table 1) were calculated by averaging the individual measurements for all sites on each age of deposit shown in figures 11 and 12. The data in figure 13 and table 1 are the primary input for the numerical model of weathering-rind development with time.

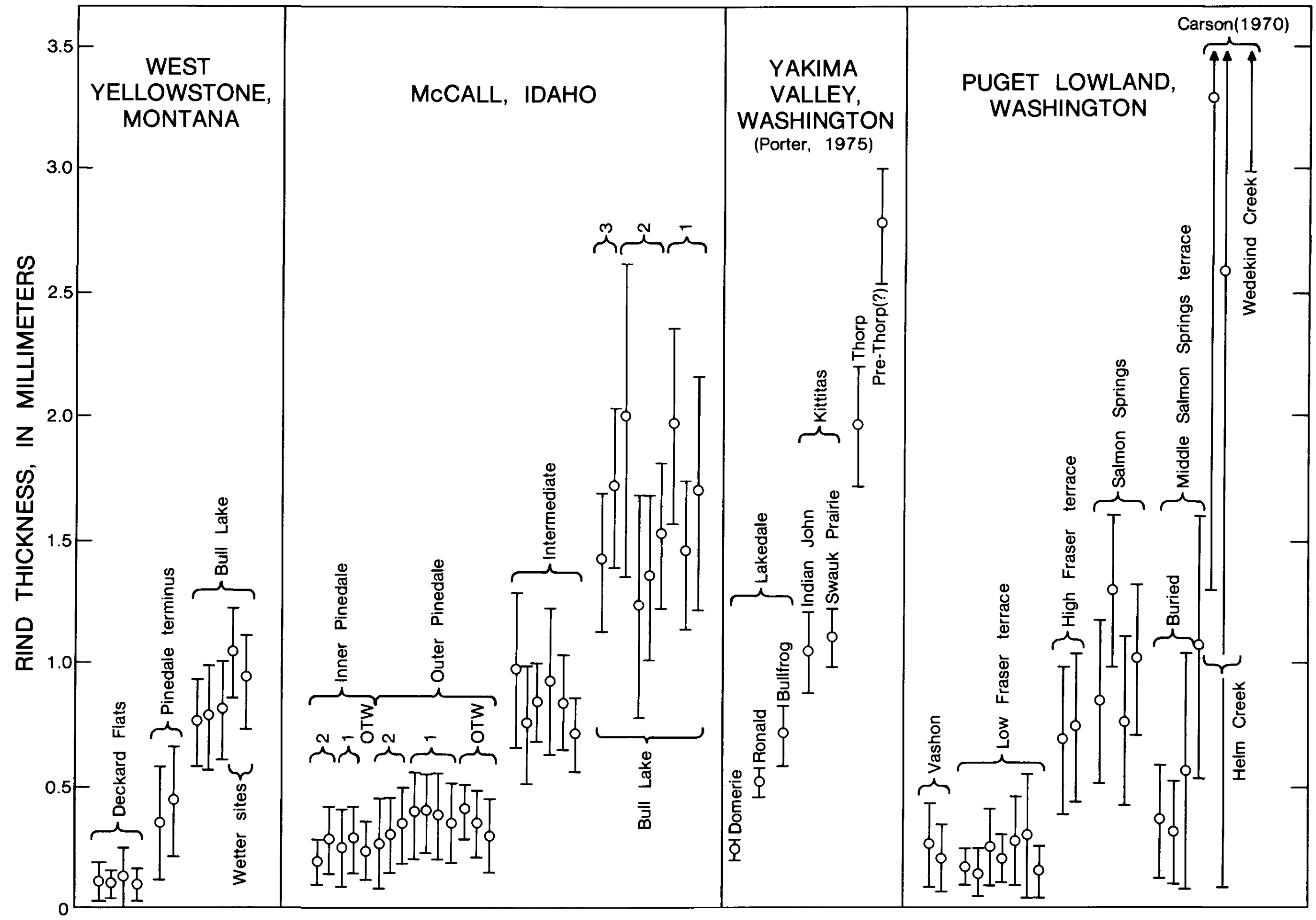

FIGURE 11.—Weathering-rind measurements on basalt. Each point and bar represents the mean ±1 standard deviation, respectively, of from about 30 to 60 stones measured at one site. Stratigraphic names are those of previous workers (references, fig. 3). See text and Appendix C for lithologic descriptions. Areas are arranged east to west. Numbers for McCall area denote sequence of moraines; 1, outermost.

STATISTICAL ANALYSIS

The data presented in the previous section suggest that weathering rinds are an effective relative-age criterion, and the associated figures provide a qualitative visual comparison of the effectiveness of weathering rinds in separating deposits of different ages. The purpose of this section is, first, to quantitatively evaluate the conclusion that rind thicknesses can separate different ages of deposits, and second, to examine the amounts and sources of variation in the weathering-rind thickness data. These goals will help define the effectiveness of weathering rinds as a dating technique and will suggest the amount of confidence that can be placed in the method.

The data analysis[1] in this study consists of "exploration" and "approximate confirmation." Tukey (1977, preface) has described the relative merits of exploration, approximate confirmation, and confirmation modes in data analysis. Exact confirmation requires specific circumstances and is relatively rigid, whereas the flexibility of exploration and approximate confirmation commonly makes them more useful in data analysis.

The sampling procedures and data collection for this study were designed to explore the amounts and sources of variation in rind thickness, as these data were largely unknown before the study began. The sampling and measurement procedures allow relatively rapid and efficient data collection, permitting evaluation of a variety of factors affecting rind thickness. However, these procedures are not sufficiently rigorous for precise, formal statistical tests. Such confirmatory analysis would require experiments in which involved, formal sampling procedures were used, and in which some prior knowledge of the amounts and sources of variation could be used to

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[1] The Fisher K-Statistics, Transformation, and Analysis of Variance programs of the U.S. Geological Survey "Statpac" (unpub. data, 1979) were used in the analysis.

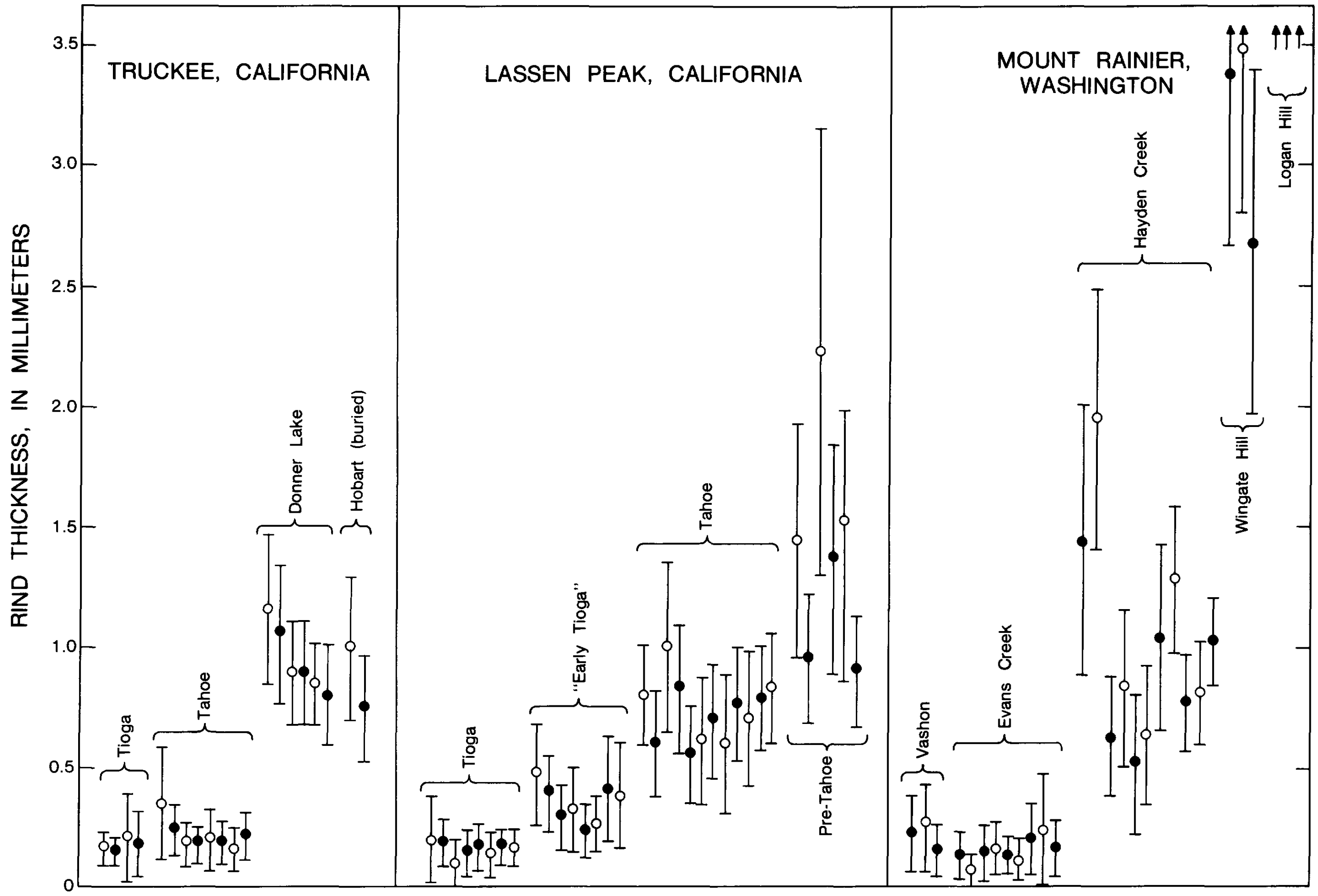

FIGURE 12.—Weathering-rind measurements on andesite. Each point and bar represents the mean ±1 standard deviation, respectively, of from about 30 to 60 stones measured at one site. Stratigraphic names are those of previous workers (references, fig. 3). Closed circles, fine-grained andesite; open circles, coarse-grained andesite. See text and Appendix C for lithologic descriptions. Areas are arranged south to north. Data for Logan Hill deposits near Mount Rainier are off the diagram.

design the necessary sampling pattern. In this study, lack of prior data on the amounts, nature, and sources of variation in rind thickness precluded a confirmatory analysis. However, the exploratory analysis accomplished here should allow precise confirmatory statistical studies to be designed in the future.

Two aspects of the sampling procedures, in particular, invalidate precise statistical calculations: (1) sampling sites were not chosen by formal randomization processes from all possible sites meeting the definition of a suitable sampling site, and (2) the selection of the location where the rind was measured on an individual stone was not formally random. Although we would argue that little or no bias has been introduced by our procedures, they do preclude exact probability calculations for statistical tests. Nevertheless, comparisons of the magnitudes of differences and amounts of variation are valid, especially because we believe that our sampling procedures have introduced little bias into the data. This approximate-confirmation procedure permits many useful inferences to be drawn about weathering rinds. The following statistical analyses will be interpreted from this viewpoint of approximate confirmation.

The definition of weathering rinds and the sampling procedures described earlier were conceived partly to facilitate the reproducibility of weathering-rind measurements. Reproducibility is an important property of any technique of measurement, and in most cases, the usefulness of a technique depends on the reproducibility of the measurements. Thus, close replication of weathering-rind measurements by different workers is critical to the usefulness of rinds as a dating technique.

R. M. Burke assisted us by independently sampling and (or) measuring rinds at a number of sites. We also compared our measurements in the Yakima Valley with those of Porter (1975), who used somewhat different sampling and measuring procedures. In addition, rinds were resampled and measured at a few sites at two separate times. The results demonstrate that

TABLE 1.—*Average weathering-rind thicknesses*

[Deposit names are those of previous workers (references, fig. 3); where not specified as terrace or outwash, deposits are till, or till and outwash undifferentiated; in andesite areas, fg, fine grained, cg, coarse grained. Thickness entries are the mean ±1 S.D. (standard deviation) of all measurements on a given deposit. In the Yakima Valley, data are from Porter (1975), for which standard deviations are apparently for means of site means, and for which the number of sites (-) is not given. Last three entries for Puget Lowland from Carson (1970), in which number of sites and number of measurements (-) are not given]

Deposit	Rind thickness ±1 S.D. (mm)	Total measurements	No. of sites
West Yellowstone, Mont., basalts			
Deckard Flats (recessional Pinedale).	0.10±0.07	86	2
Pinedale terminus	0.40±0.22	80	2
Bull Lake	0.78±0.19	162	3
McCall, Idaho, basalts			
Inner Pinedale	0.25±0.14	164	4
Inner Pinedale outwash	0.24±0.12	39	1
Average	0.25±0.14		
Intermediate Pinedale	0.31±0.17	97	3
Outer Pinedale	0.38±0.17	155	4
Pinedale outwash	0.35±0.13	102	3
Average	0.35±0.16		
Intermediate	0.85±0.24	238	6
Inner Bull Lake	1.53±0.30	74	2
Intermediate Bull Lake	1.58±0.46	181	4
Outer Bull Lake	1.71±0.39	99	3
Average	1.61±0.41		
Yakima Valley, Wash., basalts			
Domerie	0.25±0.04	225	-
Ronald	0.52±0.06	193	-
Bullfrog	0.71±0.12	279	-
Indian John	1.05±0.17	287	-
Swauk Prairie	1.10±0.11	413	-
Thorp	1.96±0.24	346	-
Pre-Thorp(?)	2.78±0.23	70	-
Mt. Rainier, Wash., andesites			
Vashon (fg)	0.19±0.13	94	3
Vashon (cg)	0.27±0.17	28	1
Evans Creek (fg)	0.16±0.10	80	4
Evans Creek (cg)	0.15±0.12	123	4
Hayden Creek[1] (fg)	1.37±0.43	84	2
Hayden Creek (cg)	1.95±0.54	38	1
Mt. Rainier, Wash., andesites—Continued			
Wingate Hill (fg)	3.01±0.69	80	2
Wingate Hill (cg)	3.50±0.69	39	1
Logan Hill (fg)	5.68±1.23	56	2
Logan Hill (cg)	8.63±1.88	15	1
Puget Lowland, Wash., basalts			
Vashon	0.23±0.15	68	2
Low Fraser terrace	0.21±0.14	120	3
High Fraser terrace	0.71±0.30	40	1
Salmon Springs	0.99±0.36	124	2
Middle Salmon Springs terrace	1.07±0.53	38	1
Average	1.01±0.40		
Helm Creek	3.3 ±2.0	-	-
Helm Creek terrace	2.6 ±2.5	-	-
Wedekind Creek	6 ±3	-	-
Lassen Peak, Calif., andesites			
Tioga (fg)	0.17±0.09	78	4
Tioga (cg)	0.16±0.12	156	4
"Early Tioga" (fg)	0.33±0.15	150	4
"Early Tioga" (cg)	0.36±0.19	192	4
Tahoe (fg)	0.72±0.23	237	6
Tahoe (cg)	0.82±0.25	262	6
Pre-Tahoe (fg)	1.06±0.31	89	3
Pre-Tahoe (cg)	1.75±0.63	89	3
Truckee, Calif., andesites			
Tioga (fg)	0.16±0.10	38	2
Tioga (cg)	0.18±0.13	40	2
Tahoe (fg)	0.21±0.09	155	4
Tahoe (cg)	0.22±0.14	138	4
Donner Lake (fg)	0.93±0.24	106	3
Donner Lake (cg)	0.97±0.23	103	3
Hobart (buried) (fg)	0.75±0.22	31	1
Hobart (buried) (cg)	1.00±0.30	39	1

[1] Although several Hayden Creek sites were sampled, the data for only two (C76-40, C78-116) are given, because they were the only loess-free, non-eroding sites sampled. Rinds from the other sites were somewhat thinner.

the reproducibility of weathering-rind measurements by workers using consistent procedures is quite good (fig. 14).

Specific topics investigated with statistical procedures include (1) the nature of distributions of sampled weathering-rind thicknesses (fig. 15), using moment statistics and the χ^2 distribution, and (2) the importance of the variation in rind thickness with time compared to that with other variables, using analysis of variance and multiple comparison tests. The detailed statistical analyses were performed on the data from the McCall and Lassen Peak areas, because of the particularly detailed sampling done in those areas.

NATURE OF THE WEATHERING-RIND MEASUREMENT DISTRIBUTIONS

Complete moment statistics were calculated for each sampling site; the statistics used were Fisher K-statis-

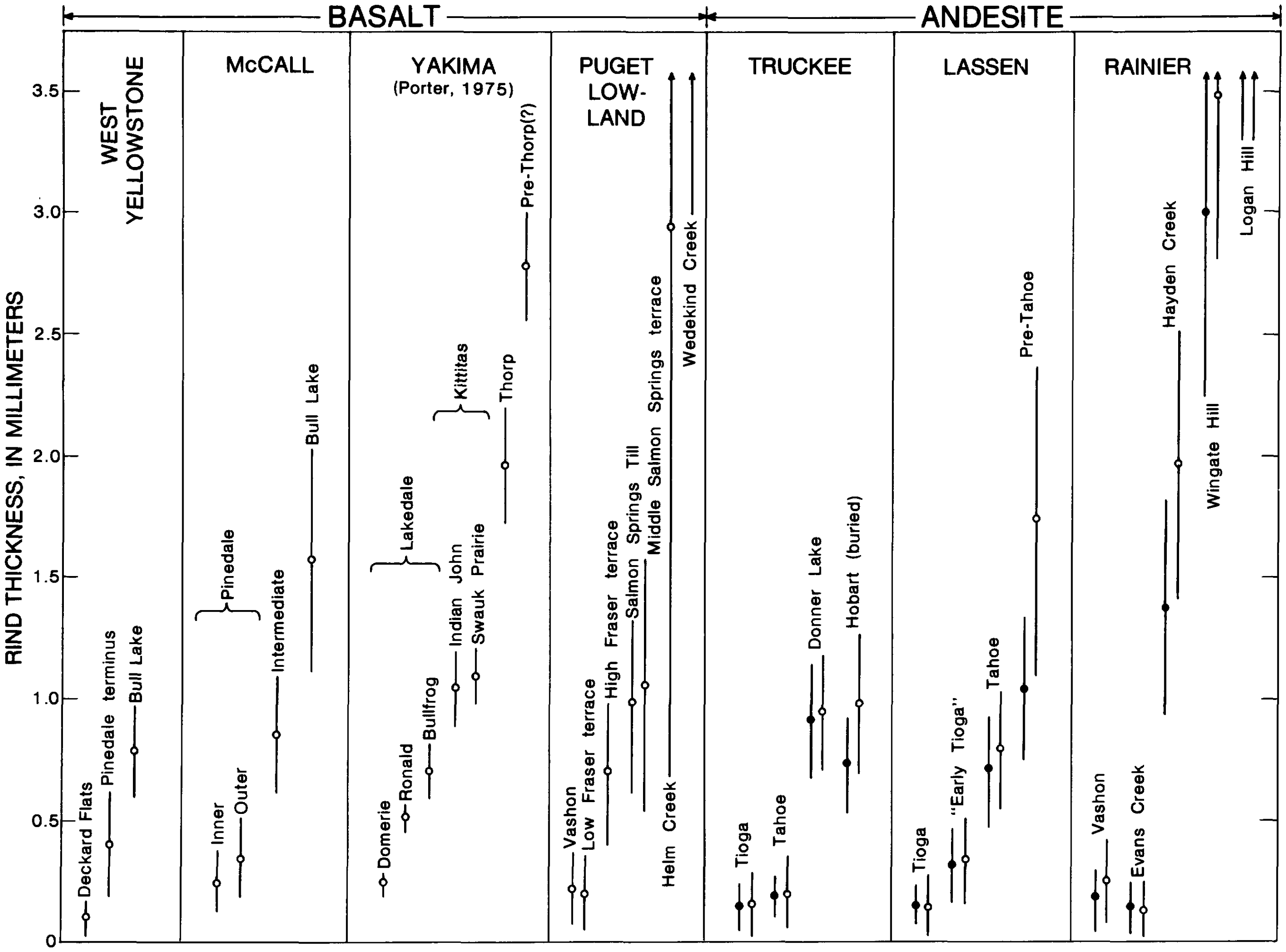

FIGURE 13.—Average weathering-rind thicknesses for the sequence of tills and terraces recognized in each of the principal sampling areas. Each point and bar represents the mean ±1 standard deviation, respectively, of all rind measurements for each age of deposit in each sampling area. Stratigraphic names are those of previous workers (references, fig. 3). In areas of andesitic rocks, closed circles, fine-grained andesite; open circles, coarse-grained andesite. See text and Appendix C for lithologic descriptions. Areas arranged as in figures 11 and 12. Arrows indicate data off the diagram.

tics, including g_1 (skewness) and g_2 (kurtosis) (Fisher, 1954). The g_1 and g_2 statistics, which have expected values of zero for normal distributions, were used to examine the types of distributions represented by weathering-rind measurements. The results (table 2) indicate that the distributions of weathering-rind measurements have a slight tendency to be skewed to the left (g_1 positive); measurement distributions of basalt at McCall and of fine-grained andesite at Lassen Peak tend to be platykurtic (flat, g_2 negative), whereas measurement distributions of the coarse-grained andesite at Lassen Peak tend to be leptokurtic (peaked, g_2 positive).

Confidence limits for g_1 and g_2 values calculated for rind-measurement distributions can only be estimated, because of the lack of rigor in the measurement methods (p. 17), and because the variances of g_1 and g_2 are precise only for sample sizes greater than about 100 (Griffiths, 1967, p. 262). However, these confidence levels are useful for comparison. Ten of the 85 calculated g_1 values for the McCall and Lassen Peak areas exceed the confidence limits (Griffiths, 1962, $\alpha = 0.05$) for the expected value of zero for normal distributions. Chi-square statistics were also calculated for the 10 distributions with high g_1 absolute values. Only four of the χ^2 values exceeded the confidence limits ($\alpha = 0.05$) for normal distributions. These comparisons, while not rigorously precise, suggest that weathering-rind distributions can reasonably be considered normal distributions.

The skewness (positive) of the distribution is especially apparent for sampling sites with very thin

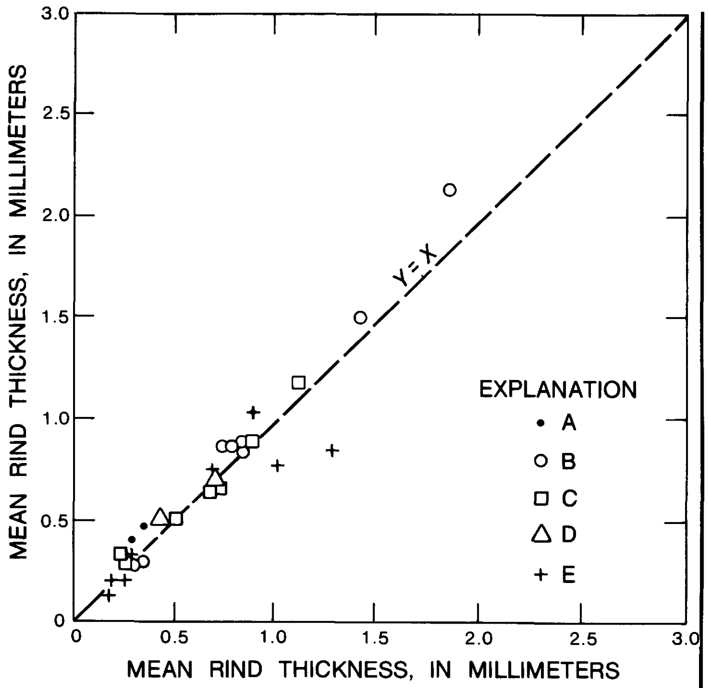

FIGURE 14.—Reproducibility of weathering-rind measurements. Data collected by S. M. Colman are plotted on the abscissa. In *A*, 1975 measurements are plotted on the abscissa. *A*, samples taken and measured by S. M. Colman in 1976 versus samples taken and measured by S. M. Colman in 1975 at the same site; *B*, measurements by K. L. Pierce versus those of S. M. Colman; *C*, measurements by R. M. Burke (written commun., 1976) versus those of S. M. Colman; *D*, measurements by Porter (1975) versus those of S. M. Colman; *E*, samples collected by K. L. Pierce versus those collected by S. M. Colman at adjacent sites; all measurements by Colman.

TABLE 2.—*Skewness (g_1) and kurtosis (g_2) for weathering-rind-thickness distributions*

Data set	Statistic	Number positive	Number negative
McCall, Idaho------	g_1	26	7
Lassen Peak, Calif. (fine-grained).	g_1	16	1
Lassen Peak, Calif., (coarse-grained).	g_1	15	2
McCall, Idaho------	g_2	9	24
Lassen Peak, Calif. (fine-grained).	g_2	6	11
Lassen Peak, Calif. (coarse-grained).	g_2	13	4

weathering rinds (fig. 15). In an attempt to reduce the skewness in the distributions, the data were subjected to a log transformation and the moment statistics were recalculated. Compared to the untransformed data, the positive and negative values of g_1 and g_2 are more evenly distributed for the log transformation data, and tend to have lower absolute values.

Thus, based on g_1 and g_2 statistics and on the χ^2 distribution, both the linear and log data fit the normal distribution model quite closely. Analysis of variance, discussed in the next section, was calculated for both the linear and log data; the conclusions that can be drawn from the analysis of the two sets of data are identical. However, the fact that the data are slightly

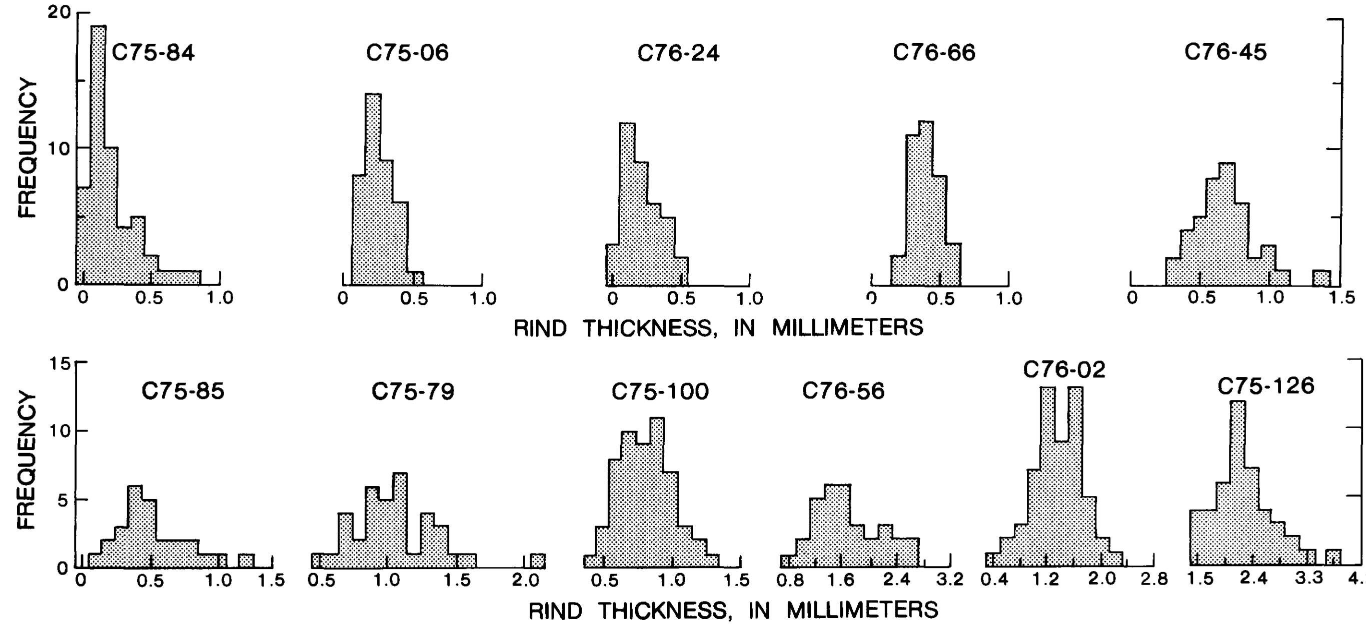

FIGURE 15.—Selected histograms of weathering-rind measurements. Sampling site number is given above each histogram; mean and standard deviation for each site are given in Appendix A, and site locations are given in Appendix B. Note different rind-thickness scales.

closer to a log-normal distribution than to a linear-normal distribution is significant and will be a useful piece of evidence in the construction of rind thickness versus time curves.

ANALYSIS OF VARIANCE

The nested sampling design for the McCall (fig. 16) and Lassen Peak areas was chosen so that variation in rind thickness from several sources could be compared using analysis of variance. The McCall sampling design has four nested subdivisions: (1) ages, (2) moraines within each age, (3) sites within each moraine, and (4) measurements within each site; the Lassen Peak sampling design has three subdivisions: (1) ages, (2) sites within each age, and (3) measurements within each site. The importance of variance contributed from each of these levels can be evaluated by analysis of variance procedures. The calculations (table 3) were made using the general methods of Anderson and Bancroft (1952) and Snedecor (1956) on the linear data.

The general model used in the analysis of variance is a nested oneway model in which any individual measurement $X(i, j, k, \ldots r)$ has the value $X(i, j, k, \ldots r) = M + A(i) + B(i, j) + C(i, j, k) + \ldots + E(i, j, k, \ldots r)$ where

M is the grand mean;

$A, B, C, \ldots E$ are random and normally distributed with zero means and variances $V(A)$, $V(B)$, $V(C), \ldots V(E)$;

$i, j, k, \ldots r$ are the nested levels in the subdivision.

Each F-ratio test in the analysis tests the null hypothesis: "These subsamples are random samples from the same normal population."

The nested levels in the sampling design isolate sources of variation and allow them to be compared. Measurement errors are confined to the measurement level, whereas local differences in rock type, climate, and vegetation are contained in the site and moraine levels. Differences in age, of course, are contained in the age level.

For the McCall data, the variation in rind thickness among ages is very large (F=182) compared to that among moraines, and the variation among sites is large (F=15) compared to that within a site (among

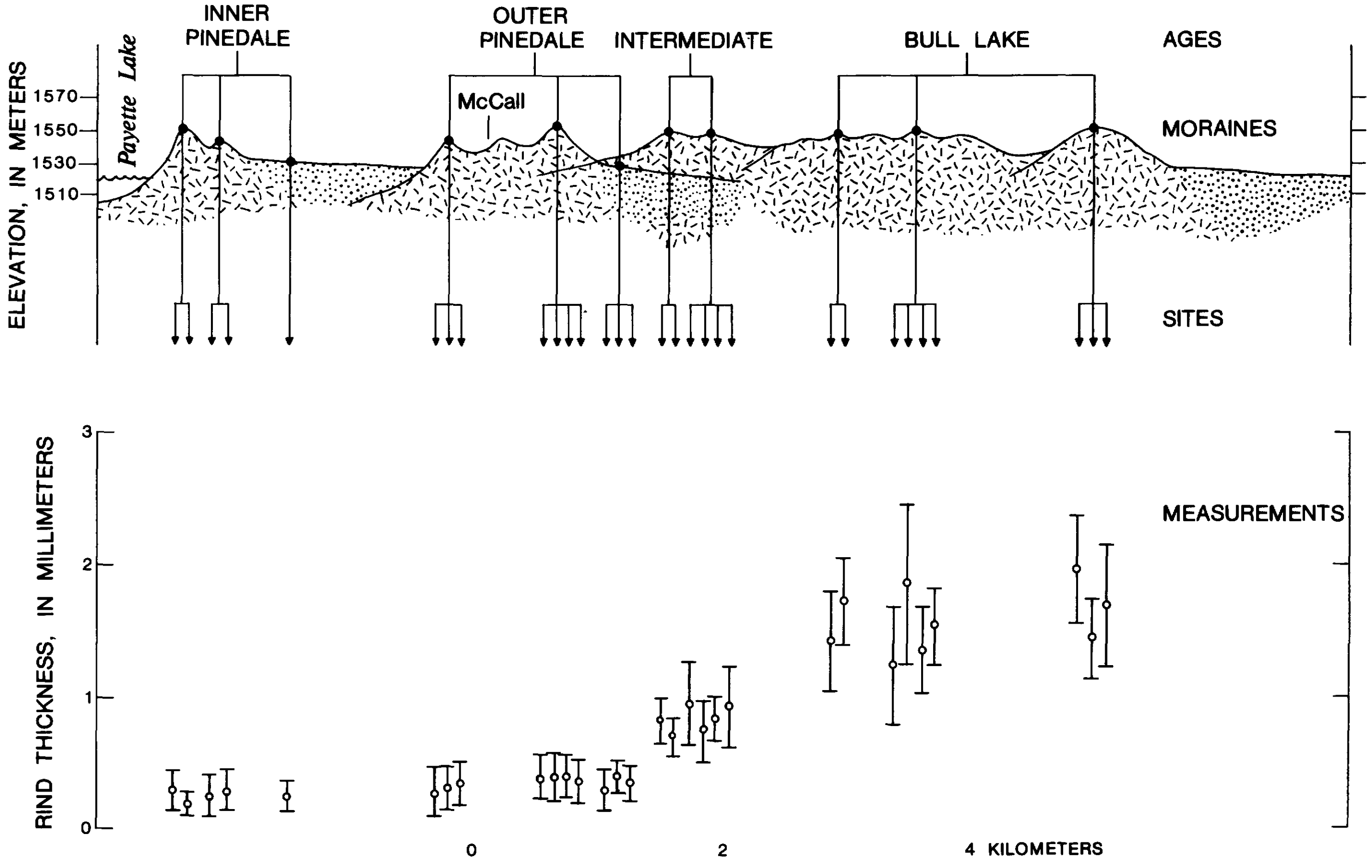

FIGURE 16.—Diagrammatic sketch of the nested sampling design for the deposits near McCall, Idaho. Sampling was based on mapping by Schmidt and Mackin (1970). Short line pattern, till; stipple, outwash. Measurements are summarized as the mean ±1 standard deviation rather than the branches for the 30-60 measurements at each sampling site. Kilometer scale is approximate.

TABLE 3.—*Analysis of variance, McCall and Lassen Peak data*

Analysis of variance				Components of variance				Test of hypothesis	
Source	Sum of squares	Degrees of freedom	Mean square	Level	Unit size	Variance component	Percent	F-Ratio	Estimated p[1]
				McCall (basalt)					
Among ages-----	314.040	2	104.680	1	3	0.36185	78.62	182.060	0.00018
Among moraines-	4.025	5	.575	2	8	.00513	.00	.544	.378
Among sites----	21.132	18	1.057	3	26	.02646	5.75	14.690	1.8x10^{-18}
Within sites---	81.633	958	.072	4	984	.07192	15.63		
Total--------	420.830	983				0.46024	100.00		
				Lassen Peak (fine-grained andesite)					
Among ages-----	44.323	3	14.774	1	4	0.11971	64.74	29.719	2.1x10^{-6}
Among sites----	6.462	13	.497	2	17	.01494	8.08	9.891	3.2x10^{-12}
Within sites---	24.778	493	.050	3	510	.05026	27.18		
Total--------	75.563	509				0.18491	100.00		
				Lassen Peak (coarse-grained andesite)					
Among ages-----	167.360	3	55.788	1	4	0.37108	70.55	31.969	7.3x10^{-7}
Among sites----	22.686	13	1.745	2	17	.04968	9.45	16.585	1.3x10-16
Within sites---	60.396	574	.105	3	591	.10522	20.00		
Total--------	250.452	590				0.52598	100.00		

[1] p, probability that the null hypothesis is true.

measurements). However, the variation among moraines is small (F=0.5) compared to that among sites. For both the Lassen Peak fine- and coarse-grained data, the variation among ages is large (F=30 and 32) compared to that between sites, and the variation among sites is large (F=10 and 17) compared to that within a site (among measurements). All comparisons, except that between moraines and sites at McCall, allow for only a slight possibility that the null hypothesis is true.

The most important conclusion from the analysis of variance is that, within a given study area, the variation in rind thickness between different ages of deposits is more important than all other sources of variation, including variation due to differences in rock type, climate, and vegetation. The components-of-variance analyses in table 3 suggest that differences in age contribute about 65–80 percent of the total rind-thickness variance. Another important conclusion is that, at McCall at least, any differences in rind thickness between moraines of one stratigraphic unit are not important compared to other sources of variation in rind thickness.

MULTIPLE COMPARISONS

The analysis of variance indicates that important differences in average rind thickness exist among sites and among ages of deposits, but it does not indicate *which* differences are important. Multiple comparison tests allow direct comparisons of differences in rind thickness and determine which differences are important.

The method used in this study is that of Scheffé (1959). The derived statistic for comparison is

$$D_s = ((S^2)\left(\frac{C^2_t}{N_t}\right)(k-1)\,(F_{k-1},\,N_o-k,\,1-\alpha))^{1/2}$$

where

D_s is the significant, or critical, difference for the comparison;

S^2 is the mean square residual (error mean square in the analysis of variance);

C_t is the coefficient of comparison of sample mean t;

N_t is the number of observations in sample t;
k is the number of samples in the class being examined;
F is the F-ratio for the given probability and degrees of freedom;
N_o is the total number of observations in the class being examined; and
α is the probability level.

For comparison of two means, the statistic reduces to

$$D_s = \left((S^2)\left(\frac{1}{n_1} + \frac{1}{n_2}\right)(k-1)\,(F_{k-1,\, N_o-k,\, 1-\alpha})\right)^{1/2}$$

The multiple comparison tests (table 4) prove the importance of age (time) in weathering-rind development. All differences in mean rind thickness between stratigraphic ages of deposits exceed the critical differences (D_s) calculated for a probability of 0.05 by Scheffé's method. Differences in mean rind thickness between closest pairs of ages exceed D_s by factors ranging from 1.4 to 13.3. Clearly, weathering-rind thickness effectively discriminates between different ages of deposits.

For moraines within one age of deposit, the conclusions are the opposite of those for ages. None of the differences in mean rind thickness between moraines of one stratigraphic age at McCall (the only area where moraines were tested) exceed D_s, except for one case. This indicates that at McCall, moraines of each stratigraphic unit are all similar in age. The exception is the outermost Bull Lake moraine, which has a mean rind thickness that exceeds D_s in comparisons with the other two Bull Lake moraines by factors of 2.0 and 3.4. Because this moraine cannot be distinguished from the other two by any method other than weathering rinds, it remains grouped with the other two Bull Lake moraines as a map unit.

For sites within one stratigraphic age of deposit, comparisons of mean rind thicknesses yield mixed results (table 4). Generally, for relatively young deposits, the differences between sites of one age do not exceed D_s, suggesting that the samples come from a single age population. In contrast, differences in mean rind thickness for sites of the same stratigraphic age within older deposits exceed D_s in some cases. However, the majority of comparisons do not exceed D_s, and those that do commonly contradict the stratigraphic sequence of moraines within the deposit. In some cases, sites on different moraines have differences in rind thickness that do not exceed D_s, whereas the differences that exceed D_s are commonly for sites on the same moraine. Therefore, the different populations suggested by the differences in rind thickness that exceed D_s are probably not produced by differences in age but by local differences in other factors such as climate, rock type, or surface stability.

SUMMARY OF STATISTICAL ANALYSIS

Statistical analysis demonstrates that weathering rinds are an excellent quantitative indicator of age. The rind measurements can be closely reproduced, and they tend to be nearly normally distributed, with a tendency for positive skewness. Analysis of variance indicates that, within a sampling area, the age of the deposit sampled is the most important source of variation in rind thickness. Multiple comparison tests demonstrate that, within a sampling area, (1) all differences in mean rind thickness between different stratigraphic ages of deposits are important, (2) differences in mean rind thickness between different moraines of the same stratigraphic age are generally

TABLE 4.—*Summary of results of Scheffé's multiple comparison test (α=0.05)*

Comparison group[1]	Number exceeding D_s	Number not exceeding D_s
Comparisons between sites		
McCall inner Pinedale---	0	10
McCall outer Pinedale---	0	45
McCall intermediate-----	6	15
McCall Bull Lake--------	17	19
Lassen (fg) Tioga-------	0	6
Lassen (fg) early Tioga-	2	4
Lassen (fg) Tahoe-------	3	12
Lassen (fg) pre-Tahoe---	2	1
Lassen (cg) Tioga-------	0	6
Lassen (cg) early Tioga-	0	6
Lassen (cg) Tahoe-------	1	14
Lassen (cg) pre-Tahoe---	2	1
Comparisons between moraines		
McCall inner Pinedale---	0	3
McCall outer Pinedale---	0	3
McCall intermediate-----	0	1
McCall Bull Lake--------	2	1
Comparisons between ages		
McCall------------------	6	0
Lassen (fg)-------------	6	0
Lassen (cg)-------------	6	0

[1] fg, fine grained; cg, coarse grained.

negligible, and (3) differences in mean rind thickness between sites of the same stratigraphic age may be important, but the differences are largely due to factors other than age.

NUMERICAL MODELS OF WEATHERING-RIND DEVELOPMENT WITH TIME

The extraction of numerical-age information from weathering-rind measurements can be done in two ways: (1) rind-thickness ratios, and (2) rate curves. Although the ratio of the rind thicknesses for two deposits does not provide numerical ages for the deposits, such ratios can provide very useful information on the magnitude of the age difference between the deposits. In addition, if the numerical age of one deposit is known, rind-thickness ratios provide limits to the possible ages of other deposits in the same area. Rate curves have the major advantage of allowing numerical ages to be calculated directly from the data, but the rate curves need to be defined and calibrated. Because of the paucity of independent age determinations, definition of rate curves based on several deposits within a sequence requires major assumptions whose validity cannot at present be proven. In the following sections, we will first examine rind-thickness ratios as a means of estimating minimum and maximum probable age differences between deposits, and then we will attempt to develop rate curves using dated sequences from West Yellowstone and elsewhere.

RIND-THICKNESS RATIOS

The ratio of rind thicknesses from two deposits in the same sequence provides a simple index to their age relations. We can estimate with considerable confidence the minimum and maximum *age* ratios indicated by these *rind* ratios. Therefore, from the rind-ratio data for two deposits, we can infer either limits on their age ratio, or, if one age is known or assumed, we can infer the minimum and maximum value for the other age.

Within a given local sequence of deposits, the factors of climate, vegetation, topography, and parent material at the sampling sites were generally held nearly constant; time is the only remaining major variable affecting rind thickness. However, because Quaternary climate has fluctuated, the rate of weathering-rind development may also have changed, especially between glacial and interglacial times. Therefore, deposits of different ages have been subjected to different climatic histories and may have weathered under different average climates. With our present information, we are not able to calculate this effect. However, the decrease in the rate of rind formation due to colder temperatures during glacial times would tend to be compensated for by an increase in rate due to a probable concomitant increase in soil moisture. Assuming that the total effect of climatic change on the rate of rind development is minor, and for present purposes can be neglected, we now attempt to bracket the maximum and minimum age relations indicated by the rind ratios.

Three basic types of functions can be postulated for the relationship between rind thickness and time:

1. linear: $d = kt$ or $t = kd$
2. logarithmic[1]: $d = k \log t$ or $t = k(10)^d$
3. power function: $d = kt^{1/n}$ or $t = kd^n$

where d = rind thickness, t = time, n is an unspecified exponent, and k is a rate factor due to variables other than time. In each case, calculation of rind thickness ratios (d_1/d_2) eliminates k by division and leaves the age ratios (t_1/t_2) as a function of rind thicknesses only:

4. linear: $d_1/d_2 = t_1/t_2$
5. logarithmic: $d_1/d_2 = \log t_1/\log t_2$
6. power function: $d_1/d_2 = (t_1/t_2)^{1/n}$

Rind thickness ratios for deposits sampled in this study (table 5) can therefore be used to estimate age ratios within each sampling area, where the value of the rate factor k is approximately constant.

In the past, the rate of change of features due to weathering has been assumed by some workers (for example, Birkeland, 1973) to be constant, especially in the absence of independent age estimates; but many workers now believe that the rate of change of most weathering features decreases with time (Cernohouz and Solc, 1966; Ollier, 1969, p. 252; Carrara and Andrews, 1975; Birkeland, 1974, p. 176; Winkler, 1975, p. 151; Pierce and others, 1976; Porter, 1976). A constant rate corresponds to a linear function (eq. 1), whereas a decreasing rate can be represented by either a logarithmic curve (eq. 2), or a power function curve (eq. 3(with $n > 1$. The rate of change of some weathering features may decrease to values approaching zero, in which case a steady state is reached.

In table 5, the rind-thickness ratios are presented in two forms: (1) the simple rind-thickness ratio, which is appropriate for estimating the age ratio if rind thickness is a linear function of age, and (2) the rind ratio squared, which is appropriate for estimating the age ratio if rind-thickness is a power function ($n=2$) of age.

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[1] Use of the base 10 is convenient but arbitrary; the natural base (e) or other bases would be equally valid for the general case.

TABLE 5.—*Rind-thickness ratios*

Deposits	Rind ratio (d_1/d_2) (minimum age ratio)	Rind ratio squared $(d_1/d_2)^2$ (maximum(?) age ratio)
West Yellowstone (Deckard Flats/Pinedale/Bull Lake)		
* Deckard Flats-Pinedale terminus	4.0	16
* Deckard Flats-Bull Lake	7.8	61
Pinedale terminus-Bull Lake	2.0	3.8
McCall (Pinedale/Intermediate/Bull Lake)		
* Inner Pinedale-intermediate Pinedale	1.2	1.5
* Intermediate Pinedale-outer Pinedale	1.3	1.6
Pinedale average-Intermediate	3.0	8.8
Pinedale average-Bull Lake average	5.0	25
Intermediate-Bull Lake average	1.7	2.9
Inner Bull Lake-outer Bull Lake	1.1	1.3
Yakima Valley (Domerie/Ronald/Bullfrog/Indian John/Swauk Prairie/Thorp/pre-Thorp(?))		
* Domerie-Ronald	2.1	4.3
* Domerie-Bullfrog	2.8	8.1
Ronald-Bullfrog	1.4	1.9
Bullfrog-Indian John	1.5	2.2
Indian John-Swauk Prairie[1]	1.1	1.2
Swauk Prairie-Thorp	1.8	3.2
Thorp-pre-Thorp(?)	1.4	2.0
Mount Rainier (Evans Creek/Hayden Creek/Wingate Hill/Logan Hill)		
* Evans Creek-Hayden Creek	9.1	82
* Evans Creek-Wingate Hill	19	354
Hayden Creek-Wingate Hill	2.1	4.3
Wingate Hill-Logan Hill	1.9	3.6
Puget Lowland (Vashon-Low Fraser terrace/High Fraser terrace/Salmon Springs)		
* Low Fraser terrace-Vashon	1.1	1.2
* Low Fraser terrace-High Fraser terrace	3.4	11
* Vashon-Salmon Springs	4.4	19
High Fraser terrace-Salmon Springs	1.4	2.0
Lassen Peak (Tioga/"Early Tioga"/Tahoe/pre-Tahoe)		
* Tioga-"early" Tioga	1.9	3.8
* Tioga-Tahoe	4.2	18
* Tioga-pre-Tahoe	6.2	39
"Early Tioga"-Tahoe	2.2	4.8
"Early Tioga"-pre-Tahoe	3.2	10
Tahoe-pra-Tahoe	1.5	2.2
Truckee (Tioga/Tahoe/Donner Lake)		
Tioga-Tahoe	1.3	1.7
Tioga-Donner Lake	5.8	34
Tahoe-Donner Lake	4.4	20

[1] Swauk Prairie deposits may have anomalously thin rinds due to a thick loeas cover.

Because the rate of rind formation almost certainly decreases with time, as is argued in the next section, the simple rind-thickness ratio (thicker rind to thinner rind) is a minimum estimate of the age ratio. The exponent of $n=2$ is appropriate for simple diffusion reactions, such as obsidian hydration (Friedman and Smith, 1960). Rinds appear to form by a combination of oxidation, hydrolysis, and solution processes (Colman, 1977), for which an exponent of two is probably a maximum; thus the rind ratio squared is probably near the upper limit of the age ratio. Therefore, table 5 provides the probable upper and lower limits of the age ratios of the listed deposits.

As an example of the utility of table 5, Pinedale and Bull Lake terminal moraines near West Yellowstone have rind thicknesses of 0.40 and 0.78 mm respectively, for a ratio of about 2, and a ratio squared of about 4. Their ages, independently determined by Pierce and others (1976), are about 35,000 and 140,000 yr, respectively, for an age ratio of 4.0. Thus table 5 can be used to place limits on the age difference between the West Yellowstone Pinedale and Bull Lake deposits independently of other age estimates. Our best estimate for rind thickness versus time functions, derived in the next section, almost invariably produces age ratios between the limits of the rind ratio and the rind ratio squared proposed in table 5.

The rind ratio approach to extracting numerical age information from rind data is presented before we give our preferred rate-curve model. The assumptions used in estimating the maximum and minimum age ratios are few, and, we think, readily justified. Thus, the age constraints provided by rind ratios are relatively definitive data. Age inferences or correlations incompatible with the constraints provided by the rind ratios are therefore open to serious question.

TIME-STRATIGRAPHIC NOMENCLATURE

Because of lack of agreement in the usage of time terminology for the Quaternary, we will define the time terms that will be used in the following sections on numerical ages and correlations. Our primary reference is the marine oxygen-isotope record (Emiliani, 1955, 1966; Broeker and van Donk, 1970; Emiliani and Shackleton, 1974; Shackleton, 1977a), which has been shown to be dominantly a record of worldwide ice volume (Shackleton and Opdyke, 1973). Figure 20 (p. 32) shows four such oxygen-isotope records plotted on a common time scale. We consider the last interglaciation to be equivalent to all or part of isotope stage 5, the period independently dated as between about 75,000 and 125,000 yr ago. The Toba Tuff in North Sumatra has been dated by K-Ar as 75,000 yr old, and occurs in deep-sea cores at the stage 4–5 boundary (Ninkovich and others, 1978); oxygen-isotope values for stage 5e and for the corals at the high sea stand in Barbados (dated by U-series methods as 125,000 yr old) demonstrate their equivalence (Shackleton, 1977b).

The isotopic record demonstrates that there were fluctuations in ice volume during stage 5, and some workers have argued that only the earliest part, stage

5e, represents the last interglaciation, and that stages 5b and (or) 5d represent early phases of the last glaciation, especially at high latitudes (see references in Suggate, 1974). For temperate latitudes, such as the locations of the sampling areas in this study, we provisionally accept the arguments of Suggate (1974) that the last major interglacial-to-glacial transition occurred at the boundary between stages 5 and 4, about 75,000 yr ago. This agrees with the estimates of Willman and Frey (1970) and Dreimanis and Karrow (1972) for the beginning of the Wisconsin Glaciation. The temperate-latitude Wisconsin thus encompasses isotope stages 2–4. In our usage, early Wisconsin refers to glacial culmination(s) within stage 4, about 60,000 to 70,000 yr ago, and late Wisconsin refers to glacial culmination(s) within stage 2, about 12,000 to 22,000 yr ago. Our mid-Wisconsin glacial advances occurred during the middle part of stage 3, between about 30,000 and 50,000 yr ago, and would be approximately correlative with the late Altonian advance in the mid-continent, which culminated about 32,000 yr ago (Willman and Frey, 1970; Dreimanis and Karrow, 1972).

Most oxygen-isotope records indicate that ice volume during stage 6 (about 130,000–150,000 yr ago) was at least as great as that during any time since. We consider glacial deposits correlating with stage 6 to be latest pre-Wisconsin, sometimes called the penultimate glaciation.

RATE CURVES FOR WEATHERING-RIND THICKNESS

The paucity of independent numerical ages for Quaternary deposits in the Western United States presents a major obstacle to determining the exact relation between rind thickness and time. The only glacial sequence examined in this study for which there are numerical ages older than the last major advance is that at West Yellowstone. This sequence has been dated by Pierce and others (1976) using combined obsidian-hydration and K-Ar dating.

A curve for the development of weathering rinds with time has been constructed for basalts in Bohemia by Cernohouz and Solc (1966), using seven ages ranging from 600 yr to about 2,000,000 yr. They do not state the basis for the ages, so it is difficult to evaluate their data; but their curve fits their data points extremely well (fig. 17). This rate curve is of the form

$$d=A \log (1+Bt)$$

where d=rind thickness, t=time, and A and B are constants.

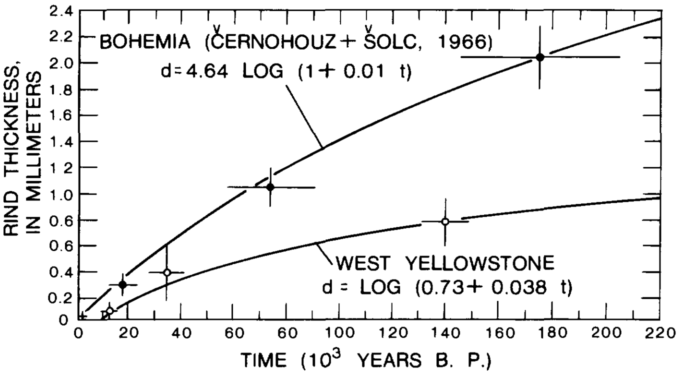

FIGURE 17.—Weathering-rind thickness versus time curves for Bohemia and West Yellowstone. The Bohemia curve is from Černohouz and Šolc (1966), and is based on the four points shown in addition to three points with ages greater than 220,000 yr. The West Yellowstone curve is based on the logarithmic form of the Bohemia curve, on obsidian-hydration ages (Pierce and others, 1976), and on rind-thickness data from this study. The difference between the two curves results from differences in rock type, climate, and other factors between the two areas. Error bars on data points are from Černohouz and Šolc (1966) for Bohemia; for West Yellowstone, time error bars are from Pierce and others (1976) and rind-thickness error bars are ±1 standard deviation (this study, table 1).

The West Yellowstone data (fig. 17) demonstrate that rind thickness is not a linear function of time; the rate of rind formation clearly decreases with time. We attempted to fit (by inspection) various types of power function and logarithmic curves to the data, and of these curves, a logarithmic curve of the same form as the curve for Bohemia (Černohouz and Šolc, 1966) appeared to fit the data best.

A date of about 35,000 yr was used for the Pinedale deposits at West Yellowstone, rather than about 30,000 yr as calculated by Pierce and others (1976) using a maximum temperature correction. The rind thickness for the terminal Pinedale deposits is somewhat higher than would be expected for a logarithmic curve through the data for the other West Yellowstone deposits. This may be due to the fact that, unlike Deckard Flats (recessional Pinedale) and Bull Lake deposits, which are basalt rich, the terminal Pinedale deposits consist of scattered basalt clasts in a rhyolite-rich deposit. The rhyolitic material appears to alter very slowly, and the weathering in these deposits seems to be concentrated in the scattered basaltic clasts, which may thus exhibit slightly thicker than expected rinds.

Unlike the Bohemia curve, which intercepts the origin, the West Yellowstone curve has been constructed with the zero rind-thickness intercept at 7,000 yr (fig. 17). The curve with this intercept is meant to approximate a curve with two segments; that is, one whose rate begins slowly but which eventually attains a logarithmic form (fig. 18). Three arguments suggest that a curve similar to curve *C* in figure 18 is appropriate. First, some time is necessary for weathering processes, especially oxidation, to reach the depths sampled in this study. Second, because weathering rinds are initially a surface phenomenon, it is reasonable to expect that much of the early surface weathering will take place on grains in the soil matrix, which have a much greater surface area than the larger clasts. Third, the fact that most of the late glacial deposits, on the order of 12,000–15,000 yr old, have very thin weathering rinds (for example, 0.1 mm for Deckard Flats (recessional Pinedale) deposits near West Yellowstone) suggests that the early stages of rind formation are very slow at the depths sampled. The figure of 7,000 yr for the intercept may not be precisely applicable to all sampling areas because of differences in climate and soil parent material, but in many cases variations due to these factors tend to offset each other. Also, the ages estimated from the rind curves for deposits older than the last major glacial advance change only slightly if the intercept value is changed. Therefore, 7,000 yr was used as the intercept for all the rate curves; inaccuracies in age estimates due to the intercept value are small compared with other uncertainties in the rate curves.

Birkeland (1974, p. 176) presented several inflected curves similar to curve *B* (fig. 18) as models for weathering and soil development processes. Winkler (1975, p. 148–151) reviewed several weathering studies and concluded that weathering rates may initially increase exponentially, and probably eventually decrease exponentially. The fact that the distributions of weathering-rind measurements tend to be log normal supports the logarithmic form of the rate curve.

Because climate affects rind development, fluctuations in climate in the past have had an effect on the rate of rind formation. Because data for evaluating this effect are not available, the rate curves that will be constructed instead average the climate in each area through time. The sampling areas are all in the same basic weather pattern today, and the parallelism of past and present snowlines in southern Washington State (Porter, 1964) suggests that general climatic patterns have not changed drastically. If climatic change has been approximately concordant for the areas sampled, the rind curves are valid for comparison and correlation purposes.

The pluvial lake record of the Western United States indicates that precipitation during glacial times could not have been much less than that of the present interglacial (G. I. Smith, oral commun., 1977). Similar precipitation and colder temperatures would have resulted in greater effective soil moisture in glacial times than in interglacial times. The effects of lower temperatures and the effects of higher effective soil moisture (or vice versa) on weathering-rind development are offsetting.

These arguments suggest that, if the actual rate curves could be plotted in detail, they probably would fluctuate around the average rate curves that will be presented, but the fluctuations probably would be small and concordant between curves.

The fact that the two curves in figure 17 indicate different rates of rind formation is reasonable because of differences in climate, rock type, and other variables between the two areas. Because factors affecting rind-development rates are different for each area, a separate curve of rind thickness versus time will be developed for each sampling area in this study. The form of these curves will be the same as that for the dated model for West Yellowstone (fig. 17). The curves will be calibrated using one deposit in each area as a calibration point whose age will be independently inferred from other data. The resulting rate curves will then be used to estimate the ages of the other deposits in each area. The calibration procedure empirically eliminates the need to account for the variation due to factors other than time, assuming that these factors are reasonably constant within each area.

In the absence of independent numerical ages, the calibration point for each curve must be inferred by correlation. The ages of the deposits representing the last glacial maximum (oxygen-isotope stage 2) are known or inferred with greater certainty than those of

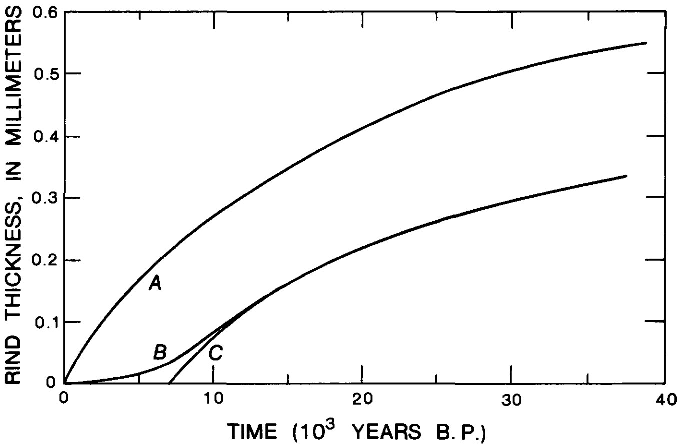

FIGURE 18.—Conceptual models of the weathering-rind thickness versus time function. *A*, model used by Černohouz and Šolc (1966); *B*, conceptual model used in this study for early stages of rind development; *C*, simple log function, similar to *A*, used to approximate *B*. Rind thickness scale approximate.

any other deposits in the areas sampled. Numerical age estimates exist for some of these deposits, and their correlation is relatively straightforward. However, these deposits were unsuitable for use as calibration points for the following reasons: (1) the uncertainty of individual rind measurements (±0.1-0.2 mm) is of the same magnitude as the average rind thickness for these deposits (0.1-0.4 mm), and (2) the age of these deposits is relatively close to zero, so that a small uncertainty in their position as a calibration point results in large uncertainty in the position of the rest of the curve.

A more useful calibration point is the deposits representing the glacial maximum about 135,000-140,000 yr ago, just prior to the last interglaciation. These deposits correspond to oxygen-isotope stage 6, and to dated times of glacial maxima in Hawaii (Porter and others, 1977) and at West Yellowstone (Pierce and others, 1976). Most oxygen-isotope records indicate that ice volumes during stage 6 were at least as great as those during any time since. (For example, see fig. 20.) Therefore, it seems reasonable that moraines or terraces representing stage 6 should be preserved in most areas, although exceptions are known (for example, Pierce, 1979). Deposits of about this age also appear to have a minimum percent-error in weathering-rind measurements, and are near the middle of the apparent useful range of rind thickness (table 2); they are thus a convenient calibration point. We have assigned this age to a number of sampled deposits based on soil development, morphology, sequence of deposits, loess distribution, terrace heights, and other relative-age indicators (table 6), in addition to stratigraphic relations. These data are primarily those described by previous workers in each of the study areas (references, fig. 3), supplemented by our own observations.

On the basis of the criteria listed in the preceding paragraph, the following deposits are considered correlative: Bull Lake at West Yellowstone, Bull Lake near McCall, Indian John in the Yakima Valley, pre-Tahoe near Lassen Peak, and Donner Lake near Truckee. These correlations appear to be relatively sound, but correlations in the Puget Lowland and near Mount Rainier are less certain for reasons that will be discussed later, in the section on correlations. Two interpretations will be presented for these areas, corresponding to a calibration age of either early Wisconsin (65,000 yr) or pre-Wisconsin (140,000 yr) for the Salmon Springs and the Hayden Creek deposits.

The correlations used for calibrating ages are for the most part consistent with the opinions of previous workers in these areas, as expressed both in the original references (fig. 3) and in later communications (S. C. Porter, written commun., 1976; K. L. Pierce, written commun., 1976; P. W. Birkeland, written com-

TABLE 6.—*Characteristics of deposits considered to be about 140,000 yr old (oxygen-isotope stage 6)*

[Starred entries, observations of authors; other entries from references, figure 3]

Area (MAT, MAP)[1]	Deposit	Depth of oxidation (m)	Maximum hue	Bt horizon	Loess[2]	Morphology
West Yellowstone (1.7, 50).	Bull Lake-------	*1-2	7.5-10*YR*	Moderately developed, 15-30 cm thick.	0.3-1 m (b).	Subdued.
McCall (4.4, 65).	---do-----------	*2	*5-7.5*YR*	Well developed, 50 cm thick.	Locally 2 m* (b).	Subdued.*
Yakima Valley (7.9, 55).	Indian John (Porter, 1975).	1-3+	7.5*YR*	Well developed, 20-30 cm thick,	1-3 m (b).	Very subdued.*
Truckee (6.0, 80).	Donner Lake-----	3	7.5*YR*	Well developed, 50 cm thick.	None--------	Do.
Lassen Peak (7, 120).	Pre-Tahoe-------	5	5*YR*	Well developed----	---do-------	Very subdued.
Mt. Rainier (9, 130).	Hayden Creek[3]---	2	7.5-10*YR*	Weakly developed--	Locally >3 m (b?).*	Subdued.
Puget Lowland (10, 150).	Salmon Springs[3]	3	7.5*YR*	Well developed(?)*	Up to 6 m locally.*	Very subdued.

[1] MAT, mean annual temperature (°C); MAP, mean annual precipitation (cm).

[2] (b), buried soil at least as well developed as the surface soil is locally recognizable beneath loess.

[3] An optional interpretation, discussed later, is that Hayden Creek and Salmon Springs deposits are early Wisconsin (60,000-70,000 yr) in age.

mun., 1976; D. R. Crandell, oral commun., 1976). Crandell and Miller (1974) favored a latest pre-Wisconsin age for the Wingate Hill Till, an age that appears to be too young based on its very thick weathering rinds. Crandell (1972) implied that Tahoe Till at Lassen Peak could be either early Wisconsin or latest pre-Wisconsin; we consider either correlation possible, but favor assigning the pre-Tahoe to the latest pre-Wisconsin.

Weathering-rind thickness versus time curves were constructed for each area (fig. 19), using the inferred ages of the deposits discussed above as calibration points (one point per curve). The logarithmic form of the curves is based on the model for the dated West Yellowstone sequence (fig. 17). The West Yellowstone curve appears in figure 19 as it did in figure 17, and each of the other curves was obtained by simply multiplying the West Yellowstone curve by a rate factor (table 7) so that it would pass through the appropriate calibration point. For example, the Bull Lake deposits at West Yellowstone, average rind thickness 0.78 mm, are correlated with the Indian John deposits in the Yakima Valley, average rind thickness 1.05 mm. The Yakima Valley curve was obtained by multiplying the West Yellowstone curve by 1.05/0.78, or 1.35. The rate factor of 1.35 accounts for the difference in the rate of rind formation between West Yellowstone and the Yakima Valley, and for the difference in rind thickness between Bull Lake and Indian John deposits, which are thought to be about the same age. Finally, the rind thicknesses for the other deposits in each area were plotted on the curve constructed for that area.

Thus, the numerical age of *one* deposit in each area has been inferred using multiple correlation methods and stratigraphic relations, and the ages of the other deposits have been estimated from weathering-rind curves. The ages estimated by this method for the glacial deposits from the different areas of this study appear to be concentrated in discrete time intervals, indicated by the histogram in figure 19.

The usefulness of weathering rinds as a dating technique decreases towards both ends of the time scale in figure 19. For young ages, the method is limited by the ability to measure very thin rinds. The thinnest rinds that could be measured using the procedures in this study were 0.1 mm thick, which limits the usefulness of the method for deposits less than about 10,000 yr old. The decreasing rate of change with time implied by the logarithmic form of the weathering-rind curves limits the ability of weathering-rind thickness to discriminate between older deposits. In addition, few deposits older than about 0.5 m.y. in the Western United States have well-preserved weathering profiles. Consequently, the use of weathering rinds for age estimates is generally limited to deposits younger than about 0.5 m.y., although weathering rinds may be useful in separating different ages of deposits up to about 1.0 m.y. if relatively stable (uneroded) sites can be found.

TABLE 7.—*Deposits used as calibration points, and derivation of the rate of factors used in the weathering-rind equation* $d = a \log (0.73+0.038t)$

Deposit used for calibration	Age (10^3 yr)	Rind thickness (mm)	Rate factor (*a*) [2]
W. Yellowstone Bull Lake	140	0.78	1.00
McCall Bull Lake	140	1.61	2.06
Indian John	140	1.05	1.35
Pre-Tahoe (Lassen)	140	1.06	1.36
Donner Lake	140	.93	1.19
Hayden Creek (option 1)	65	1.37	2.71
Hayden Creek (option 2)	140	1.37	1.76
Salmon Springs (option 1)	65	1.01	2.00
Salmon Springs (option 2)	140	1.01	1.29

[1] Bull Lake deposits near West Yellowstone are about 140,000 yr old, based on combined obsidian hydration and K-Ar methods (Pierce and others, 1976). Other deposits are inferred to be the same age based on relative-age methods and stratigraphic relations. The Hayden Creek and the Salmon Springs deposits may be younger than 140,000 yr; if so they are probably early Wisconsin (about 65,000 yr old).

[2] Rate factors are derived from the calibrated West Yellowstone curve. Rate factors are computed by dividing the rind thickness for a given deposit by the rind thickness for the equivalent age at West Yellowstone.

The curves in figure 19 are a major result of this study. Before discussing the conclusions that can be drawn from the curves, it seems appropriate to review the assumptions upon which the curves are based. These assumptions include (1) that in each sampling area, the sampling procedures, and the mapping upon which the sampling plan was based, produce measurements that are representative of the principal ages of deposits present, (2) that factors other than age are relatively constant throughout each sampling area, (3) that the form of the curves for rind thickness versus time based on the West Yellowstone data is correct and can be applied to other areas, and (4) that the age estimates and correlations used for calibration are correct. All of the conclusions based on the weathering-rind curves are qualified by the validity of these assumptions; however, these assumptions appear to be reasonable based on the evidence presented earlier.

The rind thickness versus time curves are presented not because we are absolutely sure that they are correct, but to provide a reasonable model that can be tested. Because of the consistency of the rind measurements, we believe that approximations of the numerical ages of the different deposits are contained

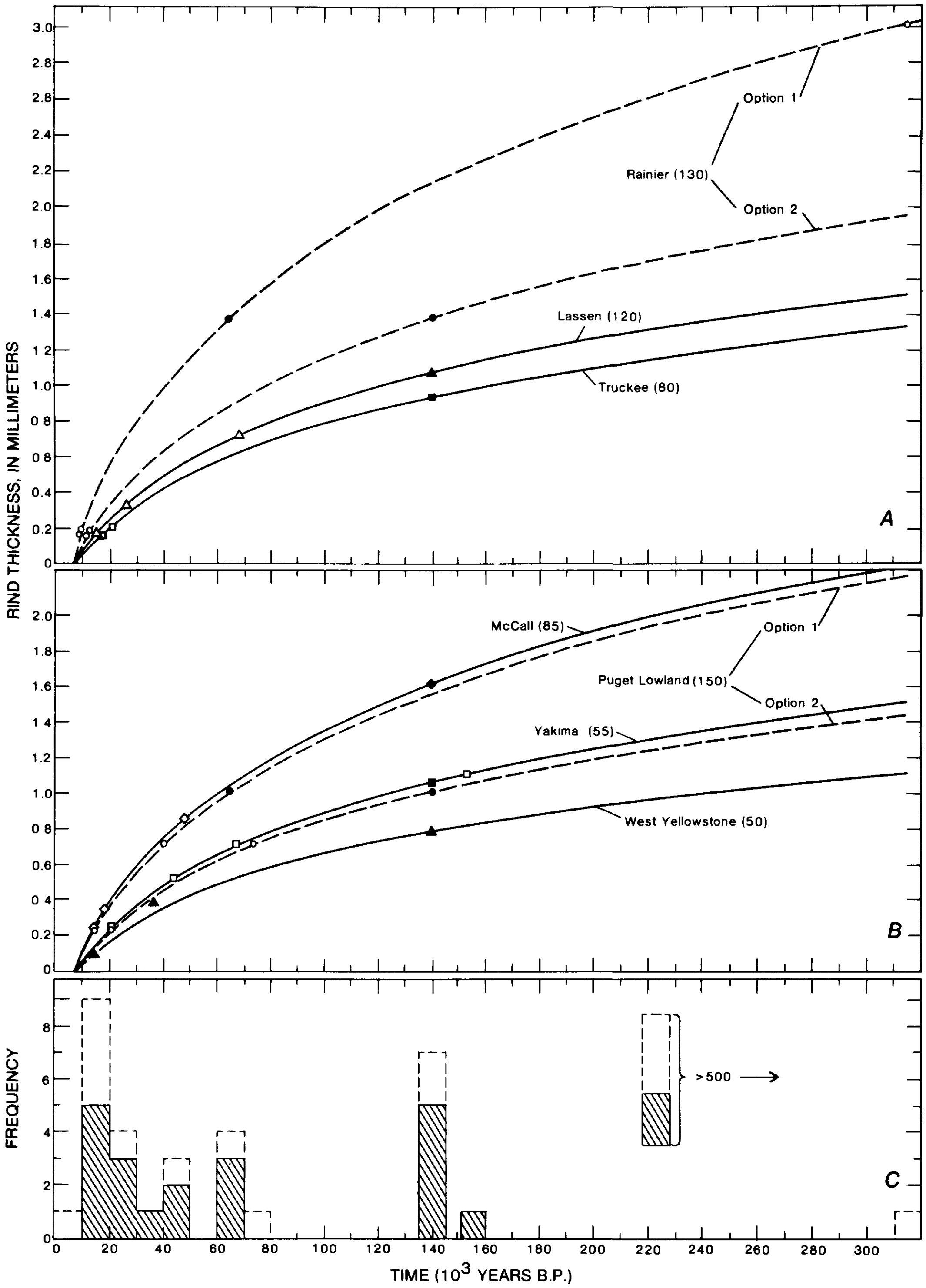

FIGURE 19.—Weathering-rind thickness versus time curves for each of the principal sampling areas. *A*, areas containing andesitic rocks; *B*, areas containing basaltic rocks. Numbers in parentheses after area name are the approximate mean annual precipitation (cm) for that area. Calibration points (solid symbols) for West Yellowstone are based on obsidian hydration ages by Pierce and others (1976); other calibration points are by correlations to deposits of known age. Open symbols represent deposits plotted on the rind curves according to their mean rind thickness. Because of uncertainties as to the age of the Hayden Creek and the Salmon Springs deposits, which were used as calibration points, two interpretations (options 1 and 2) are presented for the Puget Lowland and Mount Rainier areas. Different symbol shapes correspond to different sampling areas. *C*, histogram of age estimates. Dashed, unshaded areas represent estimates from both options for the Puget Lowland and for Mt. Rainier, and thus include two estimates for each deposit.

in the rind data; although independent numerical age estimates do not at present exist to test our model, they may in the future. We feel an obligation to offer a model that may make it possible to extract the age information from the rind data and to offer age estimates for different deposits in the sequences studied.

A number of independent observations can be made from figure 19 that support both the method used to construct the curves and the assumptions upon which the method is based. First, the ages determined from the weathering-rind curves for the last major glacial advance in each area generally are consistent with radiocarbon age estimates for those advances. Second, the curves show that the rate of weathering-rind formation generally increases with increasing mean annual precipitation. An exception is in the Puget Lowland, where the basalt is significantly different from other basalts used in the study (see Appendix C). Finally, the pattern of times of glacial advance, shown by the histograms in figure 19, is consistent with most marine oxygen-isotope records (fig. 20).

REGIONAL CORRELATIONS BASED ON AGES ESTIMATED FROM WEATHERING-RINDS

The data in figure 19 can be transformed easily into a correlation chart (fig. 21) by simply labeling the data points. Some of the correlations in figure 21, however, are in conflict with earlier interpretations. The following discussion examines those conflicts, along with other pertinent conclusions concerning the ages of the deposits. The deposit names used in this discussion are those used by previous workers and are used primarily to identify specific deposits. The conclusions and correlations we suggest apply to the deposits we sampled, but not necessarily to all deposits to which a given name has been applied.

CASCADE RANGE–PUGET LOWLAND

Weathering-rind methods do not resolve the age difference between the Evans Creek advance from Mount Rainier and the Vashon advance of the Cordilleran ice sheet. Stratigraphic relations between deposits related to the two advances demonstrate that the Evans Creek advance is somewhat older than the Vashon advance (Crandell, 1963), whereas the weathering-rind data, if anything, suggest the reverse. The discrepancy is probably due to differences in the rocks and climate of the two areas and to the inability of weathering rinds to resolve differences of only a few thousand years. The numerical age estimates of Crandell and Miller (1974, table 3) are retained for the two advances.

Considerable controversy persists regarding the correlation of all but the youngest glacial advances in the Puget Lowland–Cascades area (for example, Porter, 1976). Much of this controversy results from difficulties in interpreting very old (50,000 yr or more) radiocarbon ages, and from differing concepts of the amounts of weathering and morphologic change expectable from the range of deposits of Wisconsin age. In addition, strong climatic gradients, variability of rock types, and variable thickness and extent of eolian mantles in the area make the interpretation of most relative-age criteria extremely difficult. These factors also hinder the interpretation of weathering-rind data, but weathering rinds are probably at least as good as any other age criterion available for determining the ages of deposits near or beyond the limit of the radiocarbon method. The following discussion examines the problems of age estimates in the Puget Lowland and the Cascade Range (including the Mount Rainier area and the Yakima Valley) and discusses the correlations between these areas. We will present the interpretations that we favor, from weathering-rind thickness and other weathering data.

Crandell and Miller (1974, p. 55–56) favored a 40,000 to 80,000 yr age (oxygen-isotope stage 4) for the Hayden Creek advance and suggested that the Wingate Hill advance occurred just before 125,000 yr ago (during oxygen-isotope stage 6). Hayden Creek deposits exhibit large variations in weathering-rind thicknesses between sites (Appendix A), due in part to burial by eolian deposits at some sites and to erosion at others. Sites C76–40 and C78–116 were chosen as representative of the weathering interval since Hayden Creek time, because they were the only stable, loess-free sites examined. Rinds at these sites, which are several kilometers upvalley from the Hayden Creek terminus (Crandell and Miller, 1974, pl. 1), average 1.37 mm on fine-grained andesite.

In general, the soils in Hayden Creek deposits contain 10*YR* to 7.5*YR* colors, and a weakly developed argillic B horizon. Locally, these deposits are covered by thick (>2 m) eolian deposits (loess?), which are reddish (7.5*YR*), clayey, and weathered to depths of more than 2 m. We did not find any unambiguous exposures of a buried soil beneath the surface loess on Hayden Creek deposits, but the overall weathered appearance of the loess may make it difficult to recognize a buried soil. However, the following facts indirectly suggest that a buried weathered zone may exist beneath the loess on Hayden Creek deposits: (1) locally, the presence of relatively thick weathering rinds (as much as 1.0 mm average) beneath loess more than 2 m thick, (2) rapid lateral variation in weathering-rind thickness beneath the loess in places, suggesting erosion of a weathered zone, and (3) the common occurrence of a zone of increased compaction (Bt horizon?) near the

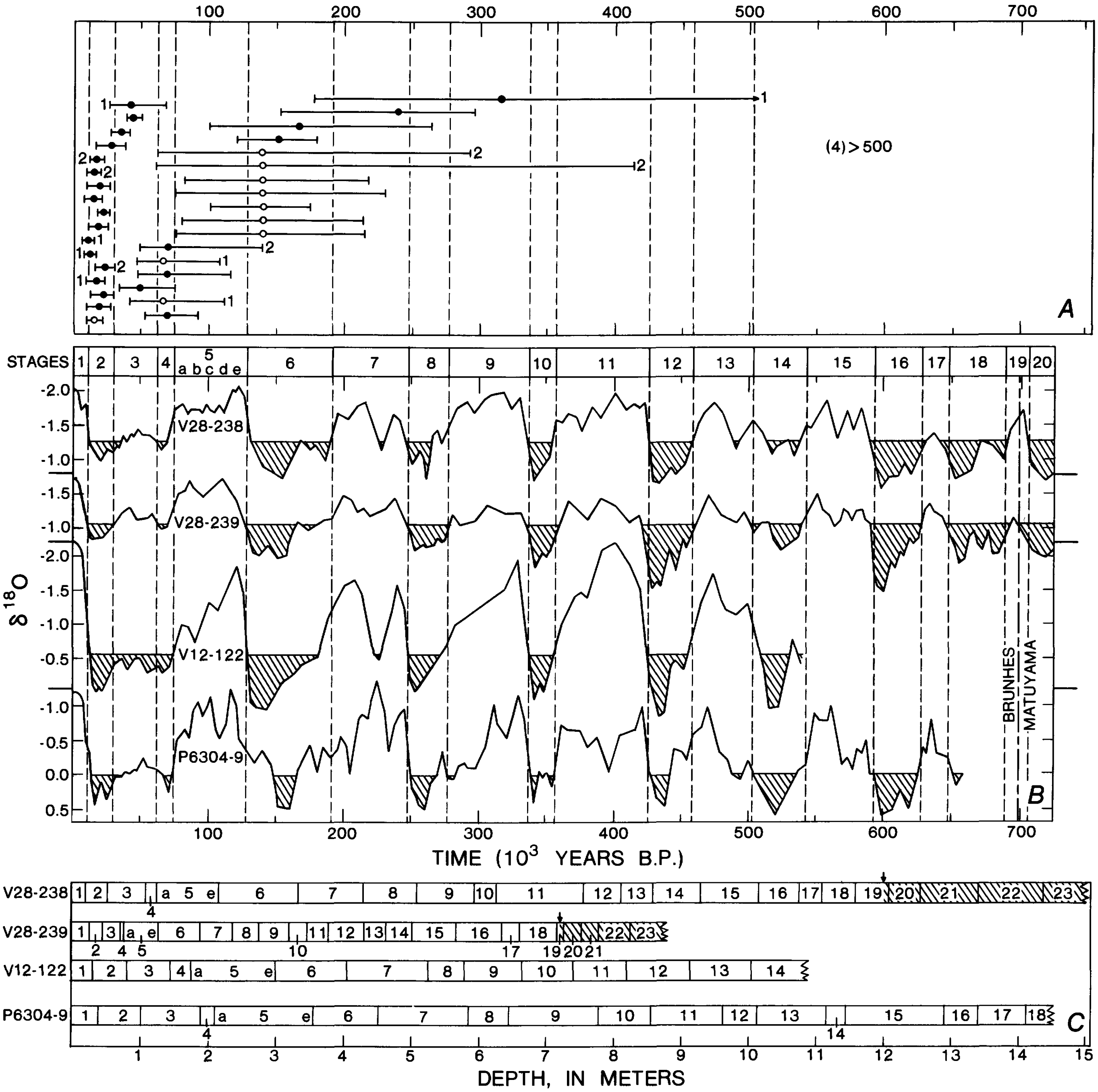

FIGURE 20.—Comparison of ages estimated from weathering rinds in glacial deposits in this study with the deep-sea oxygen-isotope record. *A*, ages of glacial deposits estimated from figure 19. Error bars on ages were obtained by projecting ±1 standard deviation of the weathering-rind measurements to the curves in figure 19. Closed circles are the calibration points of figure 19, whose ages are known from independent age estimates or are inferred by correlation; open circles represent ages estimated from weathering-rind thicknesses (fig. 19). Numbers at the ends of the error bars refer to the optional interpretations for the Puget Lowland and Mount Rainier areas in figure 19. *B*, oxygen-isotope records of four deep-sea cores (V28-238 and 239, Shackleton, 1977a; V12-122, Broeker and van Donk, 1970; and P6304-9, Emiliani, 1966). The isotope records have been plotted on a common time scale according to the estimated ages of stage boundaries given by Hays and others (1976) for stages 1 to 13, and by Shackleton and Opdyke (1973) for stages 13 to 20. Shaded portions of the curves represent isotope values heavier than an arbitrary value (the low value of stage 2 plus 25 percent of the difference between stage 1 and stage 2). the shaded areas are intended to highlight times of high ice volumes. *C*, The four cores plotted on a common depth scale, with the oxygen-isotope stages numbered. Shaded portions are those that are magnetically reversed (below the Brunhes- Matuyama boundary (arrow in *C*, and long dash-short dash line in *B*)).

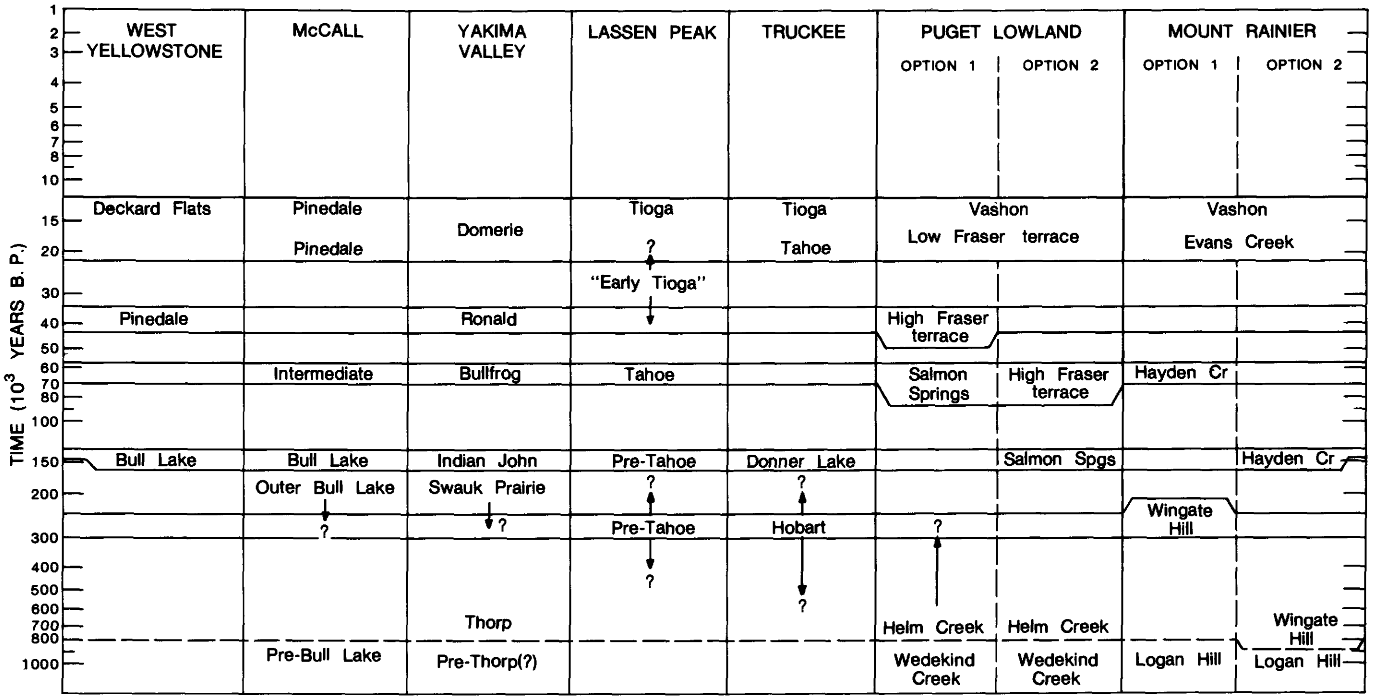

FIGURE 21.—Correlation chart for deposits sampled in this study. The chart was produced from the age estimates in figure 19. Horizontal lines enclose deposits thought to be about the same age. Arrows suggest other possible correlations, queried where uncertain, discussed in the text. Stratigraphic names are those of previous workers. (See fig. 3 for references.) Vashon deposits (Mount Rainer) are slightly younger than Evans Creek deposits (Crandell, 1963); weathering-rind thicknesses are not consistent with this difference. Rinds in Swauk Prairie deposits are only slightly thicker than those in Indian John deposits. However, Swauk Prairie deposits are thickly mantled with loess, and therefore may be significantly older than the rind thickness suggests (S. C. Porter, oral commun., 1977). Pre-Tahoe deposits at Lassen Peak probably include deposits of more than one age. Rinds were measured only for the youngest (innermost) of these deposits.

base of the loess. Although the soils and weathering characteristics of the Hayden Creek deposits vary considerably due to the eolian mantle and to erosion, no systematic change suggestive of discrete ages within the Hayden Creek was noted.

In estimating the age of the Hayden Creek advance, the rind thicknesses of both younger (Evans Creek) and older (Wingate Hill) deposits and also the fact that the rate of rind development decreases with time must be considered. Because weathering rinds are so thick (and soft) an Wingate Hill deposits (>3.0 mm average), Crandell and Miller's (1974) correlation of the Wingate Hill deposits with isotope stage 6 (about 140,000 yr old) implies an extremely rapid rate of weathering rind development. This rate is *not* supported by the very thin rinds (0.1-0.2 mm) on Evans Creek deposits. Because the age of the Wingate Hill deposits is uncertain but probably much greater than 140,000 yr, the data for the Hayden Creek deposits were used for the calibration points in figure 19. Two interpretations (options) of the age of the Hayden Creek deposits are shown in figure 19: (1) early Wisconsin (about 65,000 yr old) as suggested by Crandell and Miller (1974) and (2) latest pre-Wisconsin (about 140,000 yr old).

An age of 140,000 yr for the Hayden Creek deposits (fig. 19, option 2) is considerably older than Crandell and Miller's (1974) estimate, and it leaves the much less extensive Evans Creek end moraines as the sole representative of the Wisconsin Glaciation. However, this option is favored by (1) the thickness (1.37 mm average) of weathering rinds at the few undisturbed sites sampled on the Hayden Creek deposits, (2) the large ratio, about 9:1, in weathering-rind thickness between the Hayden Creek and the Evans Creek deposits (table 2; fig. 12), (3) the development of an argillic B horizon on the Hayden Creek deposits, in contrast to the lack of clay enrichment in the weak soil on the Evans Creek deposits, (4) thick, weathered loess on some Hayden Creek deposits, and (5) some suggestion of a buried weathering zone beneath the loess on Hayden Creek deposits.

On the other hand, if the Hayden Creek deposits are about 65,000 yr old (isotope stage 4), then the Wingate Hill deposits must be 250,000 or more yr old, if the rate of weathering-rind formation is logarithmic. These ages imply the absence of any recognized glacial deposit (end moraine or outwash terrace) representing an advance about 140,000 yr ago; this advance appears to be widely represented elsewhere. In addition, an age of about 65,000 yr (isotope stage 4) for the Hayden Creek deposits leads to the conclusion that the glacial advance representing isotope stage 4 was nearly twice as extensive as that representing isotope stage 2 (Evans Creek). However, Crandell and Miller (1974) favored an early Wisconsin age for the Hayden Creek deposits, primarily because of the weak development of an argillic B horizon, and correlation with the Salmon Springs deposits in the Puget Lowland, which were thought to be early Wisconsin.

In summary, the age of the Hayden Creek advance(s?) remains unresolved but is probably either about 65,000 or 140,000 yr. The possibility remains that the Hayden Creek deposits include deposits of both ages, but no data supporting this hypothesis have been found. Based on weathering data, an age of about 140,000 yr rather than 65,000 yr seems more probable. The Wingate Hill deposits are surely pre-Wisconsin, and are probably much older than 140,000 yr. If the Hayden Creek deposits are about 140,000 yr old, then our rind development curve (fig. 19) places Wingate Hill at more than a half million years old.

An analogous situation exists in the Puget Lowland, where the age of the Salmon Springs Drift is the subject of controversy. Traditionally, it has been considered early Wisconsin (Birkeland and others, 1970), but Porter (1976) suggested that it could be pre-Wisconsin, at least in part. The arguments for these alternative interpretations are much the same as those presented earlier for the Hayden Creek deposits. One difference between the two areas is that the Salmon Springs and Vashon advances were similar in size, whereas the Hayden Creek and Evans Creek advances were markedly different in extent.

Salmon Springs Till appears to have a moderately well developed argillic B horizon and has weathering rinds about 1 mm thick on basalts. It is commonly capped by thin, weathered eolian deposits, and both the till and eolian deposits are oxidized to 7.5*YR* colors. On the other hand, the equivalent outwash terrace (middle Salmon Springs; Carson, 1970) is covered by thick, relatively unweathered eolian deposits (loess?), locally as much as 6 m thick. The gravels at the gravel-loess contact are oxidized, but in most places the oxidation appears to be ground-water alteration rather than a buried soil. At one locality (C76-37B) on the terrace margin where the loess is thin, weathering rinds in the gravel are comparable to those on stones in Salmon Springs Till (1.07 mm average thickness).

The Puget Lowland receives considerably more precipitation than the other sampling areas in this study, but the basalt in the deposits there contains almost no olivine or vitric glass, and therefore it probably weathers more slowly than the basalt in other areas sampled. The net effect of these rock type and precipitation factors on weathering-rind-development rates is uncertain, but the two factors have opposite effects, and thus tend to cancel each other. In any case, average rind thicknesses on stones from the Salmon Springs deposits are about the same as those on stones from deposits considered to be 140,000 yr old in the Yakima Valley. The latter area receives one-half to one-third as much precipitation as the Puget Lowland but contains basalt that apparently weathers faster than that in the Salmon Springs deposits.

Two buried drifts are exposed in the type section of the Salmon Springs Drift. The relation of the Salmon Springs surface till examined in this study to the two drifts in the type area is uncertain. The two drifts in the type area are separated by a peat tentatively estimated to be about 50,000 yr old on the basis of radiocarbon determinations (Crandell and Miller, 1974, p. 18). However, a more recent determination of about 71,500 yr has been obtained by ^{14}C enrichment techniques (Stuiver and others, 1978). No evidence was found, either in this study or in Carson (1970), to suggest that more than one age of Salmon Springs Till exists at the surface. Carson also argued against an earlier, less extensive Salmon Springs advance being represented by one of the multiple outwash terraces emanating from the Salmon Springs Till margin. He argued that the three terraces are related to one main Salmon Springs advance, a recessional stage of that advance, and a slightly older advance from the Olympic Mountains.

Marine deposits in the area of Gray's Harbor, Wash., provide useful information concerning the age of the Salmon Springs deposits. Three sampling sites on the first marine terrace, about 20-25 m above sea level, produced an average weathering-rind thickness of 0.79±0.42 mm, although basalts in these deposits were scarce and the measurements ranged more widely than those for most other sample sites. These deposits have not been mapped or studied in detail, and sea level curves for areas this close to the continental ice margin are different from those for areas where high sea stands have been dated. However, it seems unlikely that the terrace sampled could be younger than the last series of high sea stands, associated with isotope stage 5 (see fig. 20). At Willapa Bay, about 60 km south of Gray's Harbor, Kvenvolden and others (1977) suggested that the first (20-m) marine terrace is Sangamon in age based on amino acid enantiomeric ratios. In addition, samples we collected of clayey deposits overlying the lower Salmon Springs Terrace near Grays Harbor have pollen spectra suggestive of an interglacial climate (L. E. Heusser, oral commun., 1979). These data suggest that Salmon Springs deposits, with an average rind thickness of 1.01±0.40 mm, may be older than the last interglaciation and the first marine terrace, and thus may be about 140,000 yr old.

Two different interpretations (options) of the chronology in the Puget Lowland are presented in figures 19 and 21. The similarity in weathering data for the Hayden Creek and the Salmon Springs deposits suggests that the two are at least partially equivalent. We interpret the available data as favoring an age of about 140,000 yr (option 2) rather than 65,000 yr (option 1) for both of these deposits.

In the Yakima Valley, Porter (1976) considered all members of the Lakedale Drift (Hyak, Domerie, Ronald, and Bullfrog Members) to be late Wisconsin, equivalent to the Vashon and Evans Creek advances on the other side of the Cascades. He also considered the Kittitas Drift (Indian John and Swauk Prairie Members) to be pre-Wisconsin (written commun., 1976) and to correlate with the Salmon Springs Drift; hence he suggested that the latter may be pre-Wisconsin at least in part (Porter, 1976). A pre-Wisconsin age for the Kittitas Drift is strongly supported by evidence based on soil development, buried soils, loess stratigraphy, morphology, terrace profiles, and position of this drift in the stratigraphic sequence. These data also suggest that the younger of the two Kittitas members (Indian John) is latest pre-Wisconsin in age, or about 140,000 yr old. Relative-age criteria for the Indian John deposits are very similar to those of the 140,000-yr-old Bull Lake deposits at West Yellowstone (table 6).

Porter (1976) grouped the two members of the Kittitas Drift because they have similar weathering and erosional characteristics. Weathering rinds on stones in the Swauk Prairie Member are only slightly thicker than those on stones from the Indian John Member. However, Porter (1976; oral commun., 1977) also indicated that the Swauk Prairie Member may conceivably be at least one full glacial cycle (about 10^5 yr in the marine record) older than the Indian John Member. If that is the case, then the rinds in the Swauk Prairie Member are anomalously thin, probably due to burial by a thick mantle of loess. Data that suggest a major age difference between the Swauk Prairie and Indian John Members include the following: (1) Our observations suggest that the Swauk Prairie Member locally may contain two buried soils (one in the till and one within the overlying loess) indicating three episodes of weathering separated by two episodes of loess deposition. No more than one buried soil was observed associated with the Indian John Member. (2) The Swauk Prairie terrace is twice the height of the Indian John terrace above present drainage and is more than 25 m above the level of the Indian John terrace.

Differences in weathering-rind thickness indicate that significant age differences exist between the members of the Lakedale Drift. The three older members (Domerie, Ronald, Bullfrog) have average rind thicknesses differing by factors of about 1, 2, and 3 (0.25, 0.52, 0.71 mm) respectively. As discussed earlier, the rate of weathering-rind development decreases with time, so the three members must differ in age by factors of *more* than 1, 2, and 3, respectively. Therefore, because the Domerie Member is about 14,000 yr old (Porter, 1976), the three members probably span the entire time of the last glaciation, and the Bullfrog Member probably dates from early in that glaciation (early Wisconsin).

CALIFORNIA MOUNTAINS

Tahoe and Tioga deposits traditionally have been considered to be early and late Wisconsin in age, respectively (Birkeland and others, 1970). The weathering-rind data suggest that, for two areas examined in this study, these previous interpretations need to be reexamined. In the Truckee, Calif., area, Tahoe deposits have only slightly thicker rinds than Tioga deposits. Soils and other weathering data for the two deposits are also similar according to recent work by Burke and Birkeland (1979). They have now considered much of what was originally mapped as Tahoe (Birkeland, 1964) to be equivalent to Tioga, so that much of what was previously mapped as Tahoe near Truckee may not be correlative with Tahoe deposits mapped elsewhere in the east-central Sierra Nevada region. However, Burke and Birkeland (1979) have also discovered a more intensely weathered deposit that could be early Wisconsin. Weathering-rind thicknesses measured by Burke (1979) for this deposit appear to be similar to those of Donner Lake deposits. Thus, this newly recognized deposit in the Truckee area that is possibly intermediate in weathering characteristics and age between the Tioga and the Donner Lake may be the equivalent of the Tahoe of the east-central Sierra Nevada.

In the Lassen Peak area, deposits originally mapped as Tahoe by Crandell (1972) were subdivided into Tahoe and "early Tioga" by Kane (1975). This subdivision appears to be valid because the two deposits were shown to have distinctly different soil colors, depths of oxidation, and weathering-rind thicknesses. The weathering-rind data presented here suggest that the Tahoe deposits of this area are early Wisconsin, and the "early Tioga" deposits are intermediate between late and early Wisconsin (fig. 19).

The Tahoe deposits near Lassen Peak could possibly be pre-Wisconsin (Crandell, 1972), but this interpretation creates several problems. First, a pre-Wisconsin age for the Tahoe would demand an exceptionally slow rate of weathering-rind formation (fig. 19). This rate would be anomalous considering the large amount of precipitation in the Lassen Peak area. No lithologic reason was noted that could account for such a slow rate of rind formation. Second, a pre-Wisconsin age for the Tahoe (and the Wisconsin age of the "early Tioga") would place the last interglacial *within* what Crandell (1972) mapped as a single unit (Tahoe). Crandell (1972) recognized that his Tahoe unit probably contained deposits of more than one age, but evidently considered other age differences to be more important. Therefore, although characteristics such as subdued morainal form, oxidation to more than 1 m, and 7.5*YR* colors suggest that the Tahoe at Lassen Peak could be as old as the Bull Lake deposits at West Yellowstone, we consider the Tahoe deposits at Lassen Peak to be early Wisconsin in age. The wetter climate at Lassen Peak appears to increase the rate at which weathering and erosional characteristics are attained.

Cursory observations of weathering and erosional features suggest that pre-Tahoe deposits in the Lassen Peak area could encompass more than one pre-Wisconsin age. However, all pre-Tahoe sampling sites were located immediately beyond the limit of Tahoe deposits in order to sample the youngest deposit in case of multiple ages. Rind thicknesses from these sites suggest that the pre-Tahoe deposits sampled are latest pre-Wisconsin in age (about 140,000 yr old).

ROCKY MOUNTAINS

The age of the Bull Lake Glaciation has been the subject of considerable controversy because of the lack of numerical-age determinations. Also, correlations based on differing relative-age criteria in areas of differing climates and rock types have proved problematical. The term Bull Lake was originally defined by Blackwelder (1915) to designate the older, morphologically muted moraines of the two sets of well-preserved moraines at Bull Lake, Wyo., on the flanks of the Wind River Range. Since that time, a conceptual definition of the characteristics of Bull Lake deposits, based on terrace heights, moraine morphology, and soil development appears to have evolved. These characteristics were thought to represent an early Wisconsin to intra-Sangamon age (Richmond, 1965).

The belt of moraines that wrap around Horse Butte in the West Yellowstone Basin have been described as Bull Lake by all workers who have examined them (Pierce and others, 1976, references). Apparently, these deposits fit the concept of the Bull Lake rather well, although no outwash terraces associated with the moraines are preserved in the subsiding West Yellowstone Basin. Problems of correlation and nomenclature arose when the deposits near West Yellowstone were dated at about 140,000 yr old by combined K-Ar and obsidian-hydration methods (Pierce and others, 1976). Obviously, this age is not compatible with an early Wisconsin age for the Bull Lake. Although Richmond (1976, 1977) has recently favored correlation of the West Yellowstone deposits with the late stade of the Sacajawea Ridge Glaciation, he stated (1976, p. 373) that "surficial and weathering characteristics***do not exclude possible correlation with the broad smooth moraines of the early stade of the Bull Lake as locally developed at Bull Lake." In addition, "type" Sacajawea Ridge deposits on the east side of the Wind River Range are associated with the 600,000-yr-old Pearlette "type-O" ash (Pierce, 1979). Also, Bull Lake deposits in the type area remain undated, and their correlation with deposits in other areas is uncertain. Therefore, the belt of moraines that wrap around Horse Butte are here called the Bull Lake deposits at West Yellowstone because of their well-established similarity to the type Bull Lake deposits. In view of the present conceptual difficulties, the use of the name Bull Lake for deposits near West Yellowstone and McCall does not *necessarily* imply that the conclusions reached for these deposits are applicable to all the Bull Lake deposits in the type area, or to all deposits mapped as Bull Lake in the Rocky Mountains.

In the McCall area, the pronounced development of an argillic B horizon and the thickness of the weathering rinds in most of the Bull Lake deposits strongly suggests that they are at least as old as the West Yellowstone Bull Lake. A younger age for the Bull Lake deposits at McCall would require an unreasonably rapid rate of weathering-rind formation (fig. 19). However, small portions of the deposits at McCall mapped as Bull Lake by Schmidt and Mackin (1970) appear to be early Wisconsin. Weathering-rind measurements at sampling sites on the moraines mapped partly as the innermost of the large group of Bull Lake moraines and partly as the outermost of the Pinedale moraines were consistently thinner than those at sites on the rest of the Bull Lake moraines. The average rind thickness for these moraines (here called "intermediate") results in an age of about 60,000 yr on the McCall curve in figure 19.

Thus, in the two areas examined in this study, the deposits that have been mapped as Bull Lake and that fit the conceptual definition of Bull Lake, with the exception of the innermost moraine at McCall, evidently are pre-Wisconsin. This age is contrary to that usually assigned to the Bull Lake Glaciation (Richmond, 1965, 1976; Birkeland and others, 1970). In addition, the Bull Lake–Tahoe correlation (Birkeland and others, 1970) appears to be uncertain because (1) most of the Bull Lake deposits examined in this study are believed to be pre-Wisconsin, although some deposits grouped with Bull Lake are probably early Wisconsin, and (2) the Tahoe deposits examined in this study are probably early Wisconsin or younger, although Tahoe deposits in some areas may be pre-Wisconsin (Burke and Birkeland, 1979).

SUMMARY

A large number of environmental factors, including climate, parent material, vegetation, position in the weathering profile, and time affect weathering-rind development, just as they do soil development and other near-surface weathering processes. Because the focus of this paper is on the influence of time, sampling procedures were designed to reduce, eliminate, or isolate the variation due to all the factors other than time.

Even though much of the variation in rind thickness due to factors other than time was eliminated, that remaining is clearly important, although difficult to evaluate quantitatively. Of the remaining variation, that due to lithologic variation in the rocks sampled appears to be the most important, even within the limited range of lithologies and textures studied. Variation in rind thickness due to differences in climate is also important, especially that due to differences in precipitation. The effect of temperature could not be evaluated independently; it may have a considerable influence on rind thickness. Variations in soil matrix texture, vegetation, and erosion and (or) deposition also contribute small amounts of variation in rind thickness.

More than 7,335 weathering-rind measurements at about 150 sampling sites in the Western United States were analyzed to demonstrate the usefulness of weathering-rind thickness as a relative-age criterion. Of the 17 areas examined, 7 had the most favorable rock types and climates and were studied in detail. Weathering-rind measurements can be closely reproduced by different workers if they adhere to the same procedures. The distribution of weathering-rind measurements at individual sites tends to be log normal, with a tendency for positive skewness. Within a sampling area, deposit age (the time factor) is by far the most important source of variation in weathering-rind thickness. All differences in mean rind thickness between stratigraphic ages within a sampling area are important. Differences in mean rind thickness between moraines are generally negligible, whereas such differences between sites may be important, but are largely due to factors other than time. Therefore, weathering rinds are an excellent quantitative indicator of relative age.

Two approaches can be used to extract numerical age information from the weathering-rind data for a given area: (1) age constraints provided by rind-thickness ratios, and (2) estimation of the precise rind thickness versus time function. With only few and minor assumptions, rind-thickness ratios can be used to determine with near certainty the minimum and maximum age ratios between two deposits. Thus, if the age of one deposit in a sequence is known or postulated, the minimum and maximum age of another unit can be determined. This ratio method, although not precise, provides both useful information on ages and constraints on correlations. Thus, even if a reader is unable to accept the assumptions necessary for the construction of our thickness versus time curves, more certain but less definitive information on age relations can still be obtained from the rind-ratio data (table 5).

A logarithmic model of weathering-rind development with time appears to be most consistent with the processes involved and with independent age controls. The rind thickness versus time curves (figs. 17, 19) are our best approximation of the age information contained in the rind-thickness data; they are presented as a model to be evaluated, refined, or rejected as more information on radiometric ages and rates of weathering processes is obtained.

The model of weathering-rind development with time, based on several assumptions, can be used to estimate numerical ages. On the basis of rind data for deposits of known age at West Yellowstone and in Bohemia, rind thickness increases with time according to a logarithmic function. Because of differences in rock type and climate, individual logarithmic curves were constructed for each area, using one deposit in each area as a calibration point. The ages of the calibration points in areas other than West Yellowstone were inferred by correlation using traditional relative-age methods and stratigraphic relations. The correlations are based on data from previous workers and on our own observations. The ages of all deposits other than the calibration points were estimated from the weathering-rind curves in figure 19.

The curves in figure 19 depend on a number of assumptions, including: (1) that the sampling procedures produced representative data, (2) that factors other than time are relatively constant within each sampling area, (3) that the form of the curves is correct, and (4) that the age estimates for the deposits used for calibration are correct. To the degree to which these assumptions are valid, the model of weathering-rind development results in a number of important conclusions:

1. The Wisconsin Glaciation in the Western United States appears to be complex. Convincing evidence exists for a mid-Wisconsin glacial advance between about 35,000 and 50,000 yr ago in several areas, including West Yellowstone (Pinedale) and the Yakima Valley (Ronald). The "early Tioga" deposits in the Lassen Peak area appear to be younger than 35,000 yr, but are clearly older than the late-Wisconsin Tioga deposits. In the Puget Lowland, the high Fraser terrace may represent a mid-Wisconsin advance from the Olympic Mountains. At West Yellowstone, this mid-Wisconsin advance was the largest one in Wisconsin time (Pierce and others, 1976). These advances are similar in age to the late Altonian advances in the midcontinent (Willman and Frey, 1970; Dreimanis and Karrow, 1972).
2. Age estimates based on weathering rinds indicate an advance about 60,000–70,000 yr ago (early Wisconsin) in several areas, including the McCall area, the Yakima Valley, the Lassen Peak area, and possibly the Puget Lowland and Mount Rainier areas. This advance is probably correlative with oxygen-isotope stage 4 of the marine record, a time of high worldwide ice volumes.
3. In the seven principal areas examined in this study, the rind data (fig. 19) do not indicate any end moraines dating from the period between about 75,000 and 130,000 yr ago, based on our age estimates, and the attendant assumptions. We found no stratigraphically distinct deposits with rinds in the range of 5–25 percent thinner than the deposits we correlate with oxygen-isotope stage 6. Lack of end moraines does not imply that glacial expansions did not occur during this interval 75,000–130,000 yr ago, which is generally equivalent to stage 5 of the oxygen-isotope record, a time of relatively low worldwide ice volumes. Richmond (1976) identified and approximately dated glacial events in the Yellowstone area that he correlated with oxygen-isotope stages 5b and 5d (fig. 20); however, these events are not directly related to preserved end moraines. On the basis of ice-contact features of the West Yellowstone rhyolite flow (R. L. Christiansen, written commun., 1972), glaciers were sizable 115,000±7,000 yr ago (Pierce and others, 1976; Richmond, 1976). In the areas examined in this study, glacial advances during oxygen-isotope stage 5 apparently were not sufficiently extensive to leave a preserved end-moraine record.
4. Our correlations suggest that an advance about 140,000 yr ago is widely represented. These correlations are based on traditional relative-age criteria, and are the basis for calibrating the weathering-rind model. However, the ages of the Hayden Creek and Salmon Springs deposits in the Mount Rainier-Puget Lowland area are uncertain. These deposits may date either from about 65,000 or from about 140,000 yr ago; if they are 65,000 yr old, then no representatives of a 140,000-yr-old advance has been found in these areas. Weathering data and stratigraphic relations with interglacial deposits appear to favor an age of about 140,000 yr for Salmon Springs and Hayden Creek. A widespread occurrence of glacial deposits about 140,000 yr old is consistent with the marine oxygen-isotope record (stage 6), which indicates that worldwide ice volumes were at a maximum during that time. Most oxygen-isotope records indicate that ice volumes during stage 6 were equal to or greater than those of any subsequent time.
5. End moraines in some areas were deposited during times that are not represented by such features in other areas. This probably results from differences in glacier response due to local climatic variations in different areas, although it could result from inadequate sampling or from inadequate mapping on which the sampling was based. Deposits of one glacial advance may be preserved in some areas, or eroded or buried in others by a succeeding advance of about the same size, depending on relatively small differences in the response of the glaciers to local climatic conditions. As a result, correlation by sequence of deposits alone (finger-matching) will inevitably lead to errors.

The approximate ages estimated from weathering rinds conflict with some previous interpretations and agree with others. Weathering rinds appear to be particularly helpful in distinguishing early Wisconsin deposits from latest pre-Wisconsin deposits in many areas. Relatively few deposits older than 140,000 yr have weathering profiles preserved well enough to be useful for numerical age estimates from weathering rinds. The decreasing rates of weathering-rind formation with time also limits their use for very old (>0.5 m.y.) deposits.

In the Mount Rainier-Puget Lowland area, Hayden Creek and Salmon Springs deposits are probably at least partially correlative, but whether they are early Wisconsin, pre-Wisconsin, or include both is uncertain. The available weathering and stratigraphic data favor a pre-Wisconsin age. Wingate Hill and Helm Creek deposits are certainly pre-Wisconsin and are probably at least several hundred thousand years old.

On the east side of the Cascade Range, Kittitas Drift is almost certainly pre-Wisconsin, and the Indian John Member is probably latest pre-Wisconsin. The Lakedale Drift appears to span most of the Wisconsin, with the Bullfrog Member probably being early Wisconsin.

In the Sierra Nevada-southern Cascades region, Tahoe deposits at Lassen Peak appear to be at least as old as early Wisconsin, but the Tahoe sampled at Truckee is considerably younger, unlike most Tahoe deposits in the Sierra Nevada-southern Cascades region. The two areas sampled in this region contain some of the few deposits in the Sierra Nevada-southern Cascades that can be convincingly correlated with late pre-Wisconsin (Donner Lake and pre-Tahoe, respectively).

In the Rocky Mountains, most deposits mapped and commonly accepted as being Bull Lake at McCall and West Yellowstone are pre-Wisconsin in age. A moraine intermediate between the Pinedale and the Bull Lake moraines at McCall is probably early Wisconsin. Pinedale deposits at West Yellowstone are somewhat older than the late Wisconsin Pinedale deposits at McCall.

In conclusion, weathering rinds have been shown to be an excellent indicator of relative age. As is the case with all relative-age criteria, factors other than time cause variation in rind thickness. However, time is much more important than any other factor in determining rind thickness. With weathering rinds, variation due to factors other than time is easier to isolate, account for, or eliminate than with many other relative-age criteria. By calibrating the curves of weathering-rind thickness versus time with independent age estimates, the influence of factors other than time can be eliminated, and weathering-rind thickness can be used to estimate the numerical ages of deposits. The wide applicability of weathering rinds and the numerical age estimates that can be made from them make weathering rinds a useful correlation tool for Quaternary deposits in the Western United States.

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APPENDIXES A-C

APPENDIX A.—WEATHERING-RIND THICKNESS MEASUREMENTS

[a, fine-grained andesite; b, coarse-grained andesite; c, andesite, undivided; d, granular basalt; e, dense, glassy basalt; f, basalt, undivided; g, quartizite; h, other; N in measurement columns, not measured or not given]

Sample No.	Measurements (mm)			Deposit	Rock type	Remarks
	Mean	Standard deviation	Number			
				West Yellowstone, Mont., Wyo.		
C76-74	0.11	0.08	34	Deckard Flats	d	Pinedale recessional deposits.
-74	.10	.06	31	---do-------	f	
-74	.13	.13	32	---do-------	h	Gallatin intrusives.
-75	.10	.07	21	---do-------	f	
C75-97	.35	.23	39	Pinedale----	d	Pinedale terminal deposits.
-98	.44	.22	41	---do-------	d	
-98	.67	.21	25	---do-------	d	Surface stones.
-99	.67	.24	11	---do-------	f	Do.
-101	.59	.21	15	---do-------	f	Varying rock types, poor site.
-94	.25	.14	35	Bull Lake---	d	Eroding site.
-95	.76	.17	56	---do-------	d	
-96	.78	.21	51	---do-------	d	
-100	.81	.20	55	---do-------	d	
-102A	1.04	.18	34	---do-------	d	Wetter site.
-102B	.93	.19	30	---do-------	d	Do.
				McCall, Idaho		
C78-125	.74	.13	36	Pinedale----	e	Side-valley recessional moraine.
-124	.60	.20	39	---do-------	e	Do.
C75-106	.29	.14	40	---do-------	e	Inner moraine.
C76 -51	.20	.08	63	---do-------	e	Do.
-52	.26	.16	22	---do-------	e	Do.
-69	.29	.14	39	---do-------	e	Do.
C78-141	.24	.12	39	---do-------	e	Outwash from inner moraine.
C76 -62	.27	.19	33	---do-------	e	Intermediate moraine.
-63A	.31	.16	25	---do-------	e	Do.
-63B	.45	.21	28	---do-------	e	Intermediate moraine, angular stones.
-64	.35	.16	39	---do-------	e	Intermediate moraine.
C75-105	.39	.17	50	---do-------	e	Outer moraine.
C76 -65	.39	.18	33	---do-------	e	Do.
-68	.40	.16	34	---do-------	e	Do.
C78-134	.35	.16	38	---do-------	e	Do.
C75-107	.30	.15	31	---do-------	e	Outwash.
C76 -66	.40	.11	36	---do-------	e	Do.
-67	.35	.13	35	---do-------	e	Do.
-59	.97	.32	38	Intermediate	e	Innermost moraine.
-60	.75	.24	40	---do-------	e	Do.
-61	.53	.23	47	---do-------	e	Innermost moraine, stones from loess above till.
-71	.93	.30	56	---do-------	e	Innermost moraine.

Sample No.	Measurements (mm) Mean	Standard deviation	Number	Deposit	Rock type	Remarks
McCall, Idaho--Continued						
C78-121	.84	.19	39	---do-------	e	Do.
-135	.84	.16	32	---do-------	e	Do.
-137	.71	.15	33	---do-------	e	Do.
-136	.59	.22	36	---do-------	e	Innermost moraine, eroding site, reworked stones.
[1]C75-108A	1.41	.28	44	Bull Lake---	e	Inner moraine, no loess.
[1] -108B	1.71	.32	30	---do-------	e	Inner moraine, beneath 2 m loess.
[1] -104A	1.23	.45	43	---do-------	e	Intermediate moraine.
[1]C76 -54B	1.85	.61	32	---do-------	e	Intermediate moraine, SMC[3] measurements.
[1] -54B	2.13	.65	32	---do-------	e	Intermediate moraine, KLP[3] measurements.
-54A	.02	.05	24	---do-------	e	Intermediate moraine, unoxidized till.
[1] -57	1.35	.33	36	---do-------	e	Intermediate moraine.
[1] -58	1.52	.29	38	---do-------	e	Do.
[2]C75-109	1.96	.40	36	---do-------	e	Outer moraine.
[2]C76 -55	1.44	.30	31	---do-------	e	Do.
[2] -56	1.69	.47	32	---do-------	e	Do.
[1]C75-104B	1.18	.35	38	Not known---	e	C horizon of soil buried by Bull Lake Till.
[1]C76 -54C	1.42	.29	40	---do-------	e	B horizon of soil buried by Bull Lake Till, SMC[3] measurements.
[1] -54C	1.50	.26	40	---do-------	e	Soil buried by Bull Lake Till, B horizon, KLP[3] measurements.
Yakima Valley, Wash.						
C75-131	0.25	0.04	225	Domerie-----	e	Data from Porter (1975).
-130	.52	.06	193	Ronald------	e	Do.
-130	.43	.21	31	---do-------	e	This study.
-133	.71	.12	279	Bullfrog----	e	Data from Porter (1975).
C76 -43	.78	.19	31	---do-------	e	End moraine, this study.
-42	.71	.16	30	---do-------	e	Outwash terrace.
-44	.65	.15	34	---do-------	e	Do.
-45	.68	.22	41	---do-------	e	Do.
-46	.30	.14	36	---do-------	e	Outwash terrace, variable lithologies, thick loess cover.
-47	.40	.18	38	---do-------	e	Outwash terrace.
C75-134	1.05	.17	287	Indian John-	e	Data from Porter (1975).
-135	1.10	.11	413	Swauk Prairie	e	Do.
-140	1.96	.24	346	Thorp--------	e	Do.
None	2.78	.23	70	Pre-Thorp(?)-	e	Do.
Mount Rainier, Wash.						
C75-123	0.23	0.16	34	Vashon------	a	
-123	.27	.17	28	---do-------	b	
-124	.16	.11	38	---do-------	a	
-116	.13	.09	27	Evans Creek-	a	
-116	.08	.06	27	---do-------	b	

Sample No.	Measurements (mm) Mean	Standard deviation	Number	Deposit	Rock type	Remarks
Mount Rainer, Wash.--Continued						
-119	.15	.12	11	---do-------	a	
-119	.17	.11	32	---do-------	b	
-129	.14	.08	24	---do-------	a	
-129	.12	.09	38	---do-------	b	
C76 -41	.21	.15	18	---do-------	a	
-41	.24	.24	26	---do-------	b	
C78-118	.17	.12	22	---do-------	a	Outwash.
C77 -44	1.03	.18	21	Hayden Creek	a	
C75-120	.63	.25	16	---do-------	a	Slightly eroding site.
-120	.84	.33	28	---do-------	b	Do.
-122	.53	.29	33	---do-------	a	Deposit buried by about 1 m of loess.
-122	.65	.29	35	---do-------	b	Do.
-128	1.05	.39	36	---do-------	a	Slightly eroding site, may be mixed with older till.
[1]C76-40	1.45	.56	41	---do-------	a	Inner moraine.
-40	1.95	.54	38	---do-------	b	Do.
C78-115	.78	.20	38	---do-------	a	Outwash, stones from within loess.
-115	.82	.21	31	---do-------	b	Do.
[1] -116	1.03	.31	34	---do-------	a	Stones from within thin loess.
-116	.99	.24	26	---do-------	b	Do.
[1] -116	1.29	.30	43	---do-------	a	Stones from within till beneath thin loess.
-117	.34	.29	43	---do-------	a	Recessional outwash.
-117	.31	.28	19	---do-------	b	Do.
[2] -119	2.09	.68	33	Hayden Creek(?)	a	Oldest of three Hayden Creek(?) terraces downstream from terminus.
[2]C75-121	3.99	.71	36	Wingate Hill	a	
[2] -121	3.50	.69	39	---do-------	b	
[2] -126	2.69	.71	44	---do-------	a	
[2] -125	4.66	1.19	35	Logan Hill--	a	
[2] -118	7.38	1.43	21	---do-------	a	
[2] -118	8.63	1.88	15	---do-------	b	
Puget Lowland, Wash.						
C76 -29	0.86	0.53	27	Not known---	f	First marine terrace(?), Grays Harbor.
-30	.90	.53	13	---do-------	f	Do.
C78-110	.68	.28	32	---do-------	f	Do.
C76 -22	.26	.17	31	Vashon------	f	
-24	.21	.14	37	---do-------	f	
-28	.16	.09	44	Lower Fraser terrace.	f	
-32	.24	.14	31	---do-------	f	
-39	.25	.19	45	---do-------	f	Replicate of C76-32.
-38	.71	.30	40	High Fraser terrace.	f	
[1] -26	1.13	.38	56	Salmon Springs	f	
[1] -27	.87	.35	68	---do-------	f	
-33	.34	.22	55	Middle Salmon Springs terrace.	f	Buried beneath 5 m of loess.

Sample No.	Measurements (mm)			Deposit	Rock type	Remarks
	Mean	Standard deviation	Number			
				Puget Lowland, Wash.--Continued		
-37A	.57	.48	37	---do-------	f	Buried beneath 3 m of loess.
[1] -37B	1.07	.53	38	---do-------	f	
None--	3.3	2.0	N	Helm Creek--	f	Data from Carson (1970).
Do--	2.6	2.5	N	---do-------	f	Data from Carson (1970); outwash.
Do--	6	3	N	Wedekind Creek	f	Data from Carson (1970).
				Lassen Peak, Calif.		
C75 -84	0.19	0.10	15	Tioga	a	
-84	.20	.18	50	---do-------	b	
-92	.15	.10	23	---do-------	a	
-92	.11	.11	46	---do-------	b	
C76 -07	.17	.10	23	---do-------	a	
-07	.14	.10	22	---do-------	b	
-12	.18	.07	17	---do-------	a	
-12	.17	.08	38	---do-------	b	
-06	.52	.35	10	---do-------	a	Probably thin, older deposit.
-06	.57	.38	21	---do-------	b	Do.
C75 -89	.40	.16	35	"early Tioga"	a	
-89	.48	.21	32	---do-------	b	
C76 -08	.24	.11	38	---do-------	a	
-08	.27	.12	34	---do-------	b	
-13	.42	.22	23	---do-------	a	
-13	.39	.22	60	---do-------	b	
-11	.30	.15	27	---do-------	a	SMC[3] measurements, replicate of C75-89.
-11	.29	.14	27	---do-------	a	KLP[3] measurements, replicate of C75-89.
-11	.35	.18	33	---do-------	b	SMC measurements, replicate of C75-89.
-11	.31	.18	33	---do-------	b	KLP measurements, replicate of C75-89.
C75 -87	.61	.22	32	Tahoe-------	a	
-87	.81	.21	33	---do-------	b	
-88	.84	.27	44	---do-------	a	
-88	1.01	.36	31	---do-------	b	
-85	.57	.20	43	---do-------	a	
-85	.62	.26	26	---do-------	b	
C76 -10	.70	.24	39	---do-------	a	
-10	.61	.29	7	---do-------	b	
-09	.77	.24	45	---do-------	a	
-09	.71	.27	11	---do-------	b	
-14	.74	.23	17	---do-------	a	SMC measurements.
-14	.86	.20	17	---do-------	a	KLP measurements.
-14	.84	.27	77	---do-------	b	SMC measurements.
-14	.84	.22	77	---do-------	b	KLP measurements.
[1]C75 -86	.96	.27	32	pre-Tahoe---	a	
[1] -86	1.45	.49	31	---do-------	b	
[1] -90	1.37	.48	26	---do-------	a	
[1] -90	2.23	.92	31	---do-------	b	

Sample No.	Measurements (mm)			Deposit	Rock type	Remarks
	Mean	Standard deviation	Number			
Lassen Peak, Calif.--Continued						
[1] -91	.91	.23	31	---do-------	a	
[1] -91	1.53	.46	27	---do-------	b	
Truckee River, Calif., Nev.						
C75 -75	0.15	0.06	17	Tioga-------	a	
-75	.16	.07	40	---do-------	b	
-81	.16	.08	21	---do-------	a	Outwash.
-81	.16	.08	40	---do-------	b	Do.
-76	.24	.11	38	Tahoe-------	a	
-76	.35	.23	36	---do-------	b	
-80	.19	.09	43	---do-------	a	Outwash.
-80	.20	.13	37	---do-------	b	Do.
-83	.22	.10	32	---do-------	a	Do.
-83	.16	.09	40	---do-------	b	Do.
C76 -04	.18	.08	42	---do-------	a	
-04	.18	.09	25	---do-------	b	
[1]C75 -79	1.06	.29	41	Donner Lake-	a	
[1] -79	1.16	.31	37	---do-------	b	
[1] -78	.89	.22	32	---do-------	a	Outwash.
[1] -78	.89	.22	27	---do-------	b	Do.
[1] -82	.80	.21	33	---do-------	a	Do.
[1] -82	.85	.17	39	---do-------	b	Do.
[1] -77	.75	.22	31	Hobart------	a	Buried.
[1] -77	1.00	.30	39	---do-------	b	Do.
C76 -05	.36	.16	23	Not known---	a	Buried beneath Donner Lake Till.
-05	.60	.33	33	---do-------	b	Do.
Bighorn River, Mont. (Mapping of Hamilton and Paulson (1968))						
C75 -62	0	N	N	First terrace	h	Miscellaneous metavolcanics.
-58	.26	0.26	33	Second terrace	h	Do.
-60	.32	.31	32	Third terrace	h	Do.
-59	.28	.29	35	Fourth terrace	h	Do.
-61	.46	.33	30	Fifth terrace	h	Do.
Mammoth, Calif. (mapping of Curry (1971) and Burke (1979))						
C75 -72	0.23	0.17	42	Tioga-------	f	Inner moraine.
-72	.21	.10	21	---do-------	g	Do.
-63	.25	.11	20	---do-------	g	Outer moraine.
-63	.22	.12	17	---do-------	h	Outer moraine, quartz latite.
-63	.17	.08	7	---do-------	f	Outer moraine.
-73	.18	.11	25	Tahoe-------	g	
-73	.26	.17	15	---do-------	f	
-65	.50	.29	32	Casa Diablo-	g	
-65	.50	.39	26	---do-------	f	

Sample No.	Measurements (mm)			Deposit	Rock type	Remarks
	Mean	Standard deviation	Number			
West Walker River, Calif. (mapping of Clark (1967))						
C75 -69	0.18	0.15	34	Tioga-------	c	
-68	.26	.31	40	Tahoe-------	c	
-70	.25	.23	41	---do-------	c	
-67	.40	.27	36	Deep Creek--	c	
-66	.43	.27	36	Grouse Meadows	c	
-66	.37	.22	30	---do-------	g	
-71	.38	.34	25	Huntoon Gravel	c	
-71	1.72	.92	15	---do-------	f	
Wallowa Lake, Ore. (mapping of Crandell (1967)[4])						
C75-115	0.26	0.19	29	Wt[4]---------	f	
-113	.38	.33	33	Tto---------	f	
-114	.63	.37	43	Jt----------	f	
-112	.94	.36	38	Cto----------	f	
Grand Mesa, Colo. (mapping of Yeend (1969))						
C76 -01	0.08	0.06	39	Late Pinedale	f	Grand Mesa Formation.
-03	.95	.23	42	Pinedale-----	f	Do.
[1] -02	1.39	.37	56	Bull Lake----	f	Land's End Formation.
Siletz River, Ore.						
C76 -18	1.87	0.78	27	Not known---	e	Buried gravel below second(?) terrace.
-19	.44	.14	40	---do-------	e	15-m (first?) terrace.
-21	.27	.09	26	---do-------	e	Do.
-21	2.38	.80	14	---do-------	f	15-m (first?) terrace, diffuse inner rinds.
Spokane, Wash.						
C76 -50	0.06	0.06	27	Not known---	e	Gravel from last Missoula flood.
-50	.07	.06	21	---do-------	d	Do.
South Fork Shoshone River, Wyo.						
C76 -76	0.08	0.07	24	Pinedale(?)-	a	
-76	.08	.08	20	---do-------	b	
Warm River Butte Area, Idaho, Wyo. (mapping of Richmond (1973a, b))						
C78-100	0.32	0.13	36	Middle Pinedale	f	
-101	.29	.13	31	---do---------	f	
-102	.29	.12	36	Early Pinedale	f	
-108	.24	.10	34	---do---------	f	
-109	.32	.11	30	---do---------	f	

Sample No.	Measurements (mm)			Deposit	Rock type	Remarks
	Mean	Standard deviation	Number			
Warm River Butte Area, Idaho, Wyo. (mapping of Richmond (1973a, b))--Continued						
-103	.26	.10	33	Bull Lake-----	f	
-106	.34	.13	42	---do---------	f	
-107	.32	.13	25	---do---------	f	
[1] -98	1.04	.20	32	Sacagawea Ridge	f	
[1] -99	.99	.16	34	---do---------	f	
[1] -104	.76	.16	37	---do---------	f	
- 97	.14	.19	27	---do---------	f	In calcareous soil, buried by 3 m of loess.
-105	.53	.21	25	---do-------	f	Buried by 2.5 m of loess.

[1] Outer part of weathering rind is soft.
[2] Outer part of weathering rind is very soft.
[3] SMC, S. M. Colman; KLP, K. L. Pierce.
[4] W, T, J, C, arbitrary letter designations of units from Crandell (1967); t, till; o, outwash.

APPENDIX B.—SAMPLE LOCATIONS AND SITE DATA

[Climatic data for principal sampling areas given in headings in the form (Station, MAP, MAT), where MAP is mean annual precipitation (cm) and MAT is mean annual temperature (°C); N/A, not applicable. Data from U.S. Weather Bureau (1959). Where all topographic maps are in the same State as sampling area, State name not given]

Site No.	Location	Topographic map	Vegetation	Altitude (m)	Soil pH[1]
West Yellowstone, Mont., Wyo. (West Yellowstone, 53.7, 1.7)					
C76- 74	1.0 km NW. of Indian Creek Campground-----	Mammoth 15′, Wyo.--	Pine--------	2,245	--
- 75	Junction, Grand Loop and Bunsen Peak Roads	---do--------------	Grass, sage-	2,115	--
C75- 97	0.3 km SW. of Cougar Creek Patrol Cabin---	Madison Junction 15′, Wyo.	Pine, grass-	2,110	5.0
- 98	0.6 km SSW. of Cougar Creek Patrol Cabin--	---do--------------	---do-------	2,100	--
- 99	0.7 km NNE. of Madison Range Overlook-----	---do--------------	---do-------	2,080	--
-101	1.0 km SSW. of Madison Range Overlook-----	---do--------------	---do-------	2,065	--
- 94	NW1/4SW1/4NW1/4, sec. 25, T. 12 S., R. 4 E.	Tepee Creek 15′, Mont.	Grass, sage-	2,015	--
- 95	NW1/4NW1/4NW1/4, sec. 15, T. 12 S., R. 4 E.	---do--------------	---do-------	2,015	5.8
- 96	NW1/4SW1/4SW1/4, sec. 15, T. 12 S., R. 5 E.	---do--------------	---do-------	2,020	--
-100	SW1/4SE1/4SE1/4, sec. 10, T. 12 S., R. 5 E.	---do--------------	Grass, fir--	2,090	5.6
-102	NE1/4SE1/4NE1/4, sec. 6, T. 14 S., R. 5 E.	West Yellowstone 15′, Wyo.	Pine, grass-	2,050	5.7
McCall, Idaho (McCall, 69.4, 4.4)					
C78-125	Center sec. 12, T. 15 N., R. 2 E.---------	Cascade 15′--------	Grass, fir--	2,050	--
C78-124	SW1/4SW1/4NW1/4, sec. 7, T. 15 N., R. 3 E.	---do--------------	Fir, grass--	1,970	--
C75-106	NW1/4SW1/4NW1/4, sec. 3, T. 18 N., R. 3 E.	McCall 7 1/2′------	Pine--------	1,540	5.7
C76- 51	NW1/4NW1/4SW1/4, sec. 2, T. 18 N., R. 3 E.	---do--------------	Pine-fir----	1,545	--
- 52	NE1/4NE1/4SE1/4, sec. 3, T. 18 N., R. 3 E.	---do--------------	---do-------	1,540	--
- 69	NW1/4NW1/4NE1/4, sec. 3, T. 18 N., R. 3 E.	---do--------------	---do-------	1,540	--
C78-141	SW1/4NW1/4SE1/4, sec. 3, T. 18 N., R. 3 E.	---do--------------	---do-------	1,530	--
C76- 62	NW1/4SE1/4SW1/4, sec. 9, T. 18 N., R. 3 E.	---do--------------	---do-------	1,540	--

Site No.	Location	Topographic map	Vegetation	Altitude (m)	Soil pH[1]
McCall, Idaho (McCall, 69.4, 4.4)--Continued					
- 63	NE1/4SE1/4SE1/4, sec. 8, T. 18 N., R. 3 E.	---do--------------	Fir, pine---	1,535	--
- 64	NW1/4SW1/4SE1/4, sec. 8, T. 18 N., R. 3 E.	---do--------------	Pine-fir----	1,540	--
C75-105	SW1/4NE1/4NW1/4, sec. 16, T. 18 N., R. 3 E.	---do--------------	Pine--------	1,540	6.1
C76 -65	SW1/4NW1/4NW1/4, sec. 16, T. 18 N., R. 3 E.	---do--------------	Pine, fir---	1,545	--
-68	NW1/4NE1/4NE1/4, sec. 16, T. 18 N., R. 3 E.	---do--------------	---do-------	1,555	--
C78-134	NE1/4NE1/4SW1/4, sec. 7, T. 18 N., R. 3 E.	Meadows 7 1/2'-----	---do-------	1,550	--
C75-107	SE1/4NW1/4SE1/4, sec. 16, T. 18 N., R. 3 E.	McCall 7 1/2'------	Grass, sage-	1,535	5.5
C76- 66	SW1/4NW1/4SW1/4, sec. 16, T. 18 N., R. 3 E.	---do--------------	---do-------	1,525	--
- 67	SE1/4SE1/4NE1/4, sec. 16, T. 18 N., R. 3 E.	---do--------------	---do-------	1,540	--
- 59	NE1/4SW1/4NW1/4, sec. 15, T. 18 N., R. 3 E.	---do--------------	Pine, aspen-	1,560	--
- 60	SW1/4NE1/4NW1/4, sec. 15, T. 18 N., R. 3 E.	---do--------------	---do-------	1,560	--
- 61	SW1/4NE1/4NW1/4, sec. 15, T. 18 N., R. 3 E.	---do--------------	---do-------.	1,560	--
- 71	SE1/4NE1/4NW1/4, sec. 15, T. 18 N., R. 3 E.	---do--------------	---do-------	1,560	--
C78-121	SW1/4NE1/4SW1/4, sec. 7, T. 18 N., R. 3 E.	Meadows 7 1/2'-----	Grass, sage, pine.	1,550	--
-135	NW1/4NE1/4SW1/4, sec. 7, T. 18 N., R. 3 E.	---do--------------	Grass, pine, fir.	1,550	--
-137	NE1/4NW1/4NW1/4, sec. 15, T. 18 N., R. 3 E.	McCall 7 1/2'------	Pine--------	1,570	--
-136	SE1/4NW1/4NE1/4, sec. 16, T. 18 N., R. 3 E.	---do--------------	Pine, fir---	1,555	--
C75-108	NW1/4NW1/4SW1/4, sec. 15, T. 18 N., R. 3 E.	---do--------------	Grass, aspen	1,550	6.0
-104	NW1/4SE1/4SW1/4, sec. 22, T. 18 N., R. 3 E.	---do--------------	Pine--------	1,585	5.9
C76- 54	NW1/4SE1/4SW1/4, sec. 22, T. 18 N., R. 3 E.	---do--------------	---do-------	1,585	--
- 57	SW1/4SE1/4NW1/4, sec. 22, T. 18 N., R. 3 E.	---do--------------	Pine-fir----	1,585	--
- 58	NW1/4NW1/4NE1/4, sec. 22, T. 18 N., R. 3 E.	---do--------------	---do-------	1,585	--
C76-109	SW1/4SE1/4NE1/4, sec. 33, T. 18 N., R. 3 E.	Lake Fork 7 1/2'---	Grass-------	1,550	5.6
- 55	NW1/4NE1/4SE1/4, sec. 33, T. 18 N., R. 3 E.	---do--------------	---do-------	1,550	--
- 56	NW1/4SW1/4NW1/4, sec. 34, T. 18 N., R. 3 E.	---do--------------	---do-------	1,555	--
Yakima Valley, Wash. (Cle Elum, 56.0, 7.9; Ellensburg, 23.0, 8.3)					
C75-131	SW1/4NW1/4SE1/4, sec. 2, T. 20 N., R. 14 E.	Kachess Lake-------	Pine, grass-	690	5.8
-130	SW1/4NW1/4SW1/4, sec. 18, T. 20 N., R. 15 E.	Easton 15'---------	---do-------	675	6.0
-133	NW1/4NW1/4SE1/4, sec. 29, T. 20 N., R. 15 E.	Cle Elum 15'-------	---do-------	655	6.0
C76- 42	-----do-------------------------------	---do--------------	---do-------	655	--
- 43	SW1/4NE1/4SW1/4, sec. 19, T. 20 N., R. 15 E.	Easton 15'---------	Pine, fir---	695	--
- 44	SE1/4SE1/4NE1/4, sec. 34, T. 20 N., R. 15 E.	Cle Elum 15'-------	Pine, grass-	625	--
- 45	NE1/4SW1/4SE1/4, sec. 33, T. 20 N., R. 16 E.	---do--------------	Pine-grass--	570	--
- 46	NW1/4NE1/4NE1/4, sec. 14, T. 18 N., R. 17 E.	Thorp 15'----------	Grass-sage--	505	--
- 47	NE1/4SW1/4SW1/4, sec. 35, T. 18 N., R. 18 E.	---do--------------	Grass-sage?-	470	--
C75-134	SE1/4SW1/4SE1/4, sec. 1, T. 19 N., R. 15 E.	Cle Elum 15'-------	Grass-------	645	6.2
-135	SW1/4SW1/4NW1/4, sec. 29, T. 20 N., R. 17 E.	Thorp 15'----------	-----do-----	750	6.3
Mount Rainier, Wash. (Puyallup, 103, 10.5; Buckley, 126, N/A; Longmire, 209, N/A; Stampede Pass, 234, 4.2)					
C75-123	NE1/4NW1/4NW1/4, sec. 8, T. 17 N., R. 4 E.	Ohop Valley 15'----	Mixed forest	200	5.2
-124	NE1/4NE1/4NE1/4, sec. 16, T. 20 N., R. 6 E.	Lake Tapps 15'-----	Grass-------	200	--
-116	NE1/4NW1/4NE1/4, sec. 28, T. 12 N., R. 6 E.	Mineral 15'--------	Fir---------	280	5.8
-119	NW1/4SE1/4NE1/4, sec. 28, T. 15 N., R. 6 E.	Kapowsin 15'-------	Mixed forest	515	5.8
-129	1.6 km E. of Ranger Creek Camp-------------	Greenwater 15'-----	---do-------	905	--
C76- 41	NW1/4SE1/4SE1/4, sec. 11, T. 16 N., R. 6 E.	Kapowsin 15'-------	---do-------	590	--
- 40	SW1/4NE1/4NE1/4, sec. 31, T. 16 N., R. 6 E.	---do--------------	---do-------	610	--
C78-118	NE1/4NW1/4NE1/4, sec. 23, T. 12 N., R. 1 E.	Onalaska 15'-------	---do-------	110	--
C77- 44	SE1/4NE1/4NW1/4, sec. 9, T. 12 N., R. 2 E.	---do--------------	---do-------	165	--
C75-120	SE1/4SW1/4NW1/4, sec. 11, T. 15 N., R. 4 E.	Ohop Valley 15'----	---do-------	380	5.4
-122	NE1/4SE1/4NW1/4, sec. 9, T. 14 N., R. 5 E.	Mineral 15'--------	---do-------	445	--
-128	NE1/4NE1/4NE1/4, sec. 5, T. 19 N., R. 8 E.	Enumclaw 15'-------	---do-------	465	--

Site No.	Location	Topographic map	Vegetation	Altitude (m)	Soil pH^1
Mount Rainer, Wash. (Puyallup, 103, 10.5; Buckley, 126, N/A; Longmire, 209, N/A; Stampede Pass, 234, 4.)--Cont.					
C78-115	NE1/4SW1/4SE1/4, sec. 10, T. 12 N., R. 2 E.	Onalaska 15′	---do---	165	--
-116	NW1/4NW1/4NW1/4, sec. 15, T. 12 N., R. 3 E.	Morton 15′	---do---	270	--
-117	NW1/4NE1/4NE1/4, sec. 2, T. 11 N., R. 5 E.	Spirit Lake 15′	---do---	260	--
-119	NE1/4SW1/4NE1/4, sec. 21, T. 12 N., R. 1 E.	Onalaska 15′	---do---	135	--
C75-121	Center sec. 2, T. 15 N., R. 4 E.	Ohop Valley 15′	---do---	425	5.6
-126	NW1/4SE1/4NW1/4, sec. 35, T. 20 N., R. 7 E.	Enumclaw 15′	---do---	475	--
-125	NW1/4SW1/4NE1/4, sec. 35, T. 20 N., R. 7 E.	---do---	---do---	490	--
-118	Center border sec. 26-35, T. 13 N., R. 1 E.	Onalaska 15′	---do---	200	5.5
Puget Lowland, Wash. (Oakville, 139, 10.5; Blue Glacier, 397, 1.6)					
C76- 29	NE1/4SE1/4NE1/4, sec. 27, T. 19 N., R. 12 W.	Copalis Beach 7 1/2′.	Mixed forest	20	--
- 30	SW1/4NE1/4NE1/4, sec. 29, T. 20 N., R. 12 W.	Moclips 7 1/2′	---do---	25	--
C78-110	NW1/4NE1/4SW1/4, sec. 14, T. 19 N., R. 12 W.	---do---	---do---	20	--
C76- 22	SW1/4NW1/4NW1/4, sec. 11, T. 20 N., R. 6 W.	Elma 15′	Fir	140	--
- 24	NW1/4SE1/4NE1/4, sec. 8, T. 20 N., R. 5 W.	---do---	Mixed forest	150	--
- 28	SE1/4SW1/4SE1/4, sec. 18, T. 19 N., R. 6 W.	---do---	Fir	65	--
- 32	NE1/4NW1/4NE1/4, sec. 2, T. 17 N., R. 7 W.	Montesano 15′	Mixed forest	10	--
- 39	---do---	---do---	---do---	10	--
- 38	NE1/4SE1/4NW1/4, sec. 33, T. 18 N., R. 8 W.	Wynoochee Valley 15′.	---do---	25	--
- 26	NE1/4NE1/4SE1/4, sec. 6, T. 19 N., R. 6 W.	Elma 15′	Fir	105	--
- 27	SW1/4SW1/4SW1/4, sec. 3, T. 19 N., R. 6 W.	---do---	Mixed forest	130	--
- 33	SE1/4NW1/4SE1/4, sec. 25, T. 18 N., R. 7 W.	---do---	---do---	35	--
- 37	NW1/4NW1/4SW1/4, sec. 28, T. 18 N., R. 8 W.	Wynoochee Valley 15′.	---do---	50	--
Lassen Peak, Calif. (Mineral, 131, 8.0; Manzanita Lake, 108, 6.5)					
C75- 84	SW1/4NW1/4NW1/4, sec. 34, T. 30 N., R. 4 E.	Lassen Peak 15′	Pine, grass	1,995	5.1
- 92	NW1/4SE1/4NE1/4, sec. 10, T. 31 N., R. 4 E.	Manzanita Lake 15′	Pine	1,790	5.2
C76- 07	SW1/4SE1/4SE1/4, sec. 4, T. 29 N., R. 6 E.	Mt. Harkness 15′	Pine, grass	1,560	--
- 12	SE1/4SW1/4SW1/4, sec. 35, T. 31 N., R. 3 E.	Lassen Peak 15′	Fir	1,855	--
- 06	NE1/4NE1/4NW1/4, sec. 4, T. 29 N., R. 6 E.	Mt. Harkness 15′	Pine	1,560	--
C75- 89	NW1/4SE1/4SE1/4, sec. 22, T. 29 N., R. 4 E.	Lassen Peak 15′	---do---	1,525	5.9
C76- 08	SE1/4SE1/4NE1/4, sec. 21, T. 29 N., R. 6 E.	Mt. Harkness 15′	---do---	1,540	--
- 13	NW1/4SW1/4SE1/4, sec. 35, T. 31 N., R. 3 E.	Lassen Peak 15′	Fir	1,900	--
- 11	NW1/4SE1/4SE1/4, sec. 22, T. 29 N., R. 4 E.	---do---	Pine	1,525	5.9
C75- 87	SW1/4NE1/4NE1/4, sec. 28, T. 29 N., R. 4 E.	---do---	---do---	1,625	--
- 88	SW1/4SW1/4SW1/4, sec. 22, T. 29 N., R. 4 E.	---do---	---do---	1,575	--
- 85	SW1/4SW1/4NE1/4, sec. 20, T. 29 N., R. 4 E.	---do---	---do---	1,605	5.9
C76- 10	SW1/4SE1/4SW1/4, sec. 27, T. 29 N., R. 6 E.	Mt. Harkness 15′	Pine, fir	1,485	--
- 09	NE1/4SE1/4NE1/4, sec. 34, T. 29 N., R. 6 E.	---do---	Pine	1,480	--
- 14	NW1/4NE1/4NE1/4, sec. 3, T. 30 N., R. 3 E.	Lassen Peak 15′	Fir, pine	715	--
C75- 86	SE1/4SW1/4NE1/4, sec. 20, T. 29 N., R. 6 E.	---do---	Pine	1,625	6.1
- 90	NE1/4NW1/4NE1/4, sec. 28, T. 29 N., R. 6 E.	---do---	---do---	1,660	5.3
- 91	SW1/4SW1/4SE1/4, sec. 16, T. 29 N., R. 6 E.	---do---	---do---	1,705	--
Truckee River, Calif., Nev. (Truckee, 80.0, 6.0; Reno, 18.0, 9.5)					
C75- 75	SW1/4SW1/4NW1/4, sec. 16, T. 17 N., R. 16 E.	Truckee 15′, Calif.	Pine	1,800	6.1
- 81	NE1/4SE1/4NW1/4, sec. 16, T. 17 N., R. 16 E.	---do---	---do---	1,795	5.8
- 76	NE1/4NW1/4SW1/4, sec. 16, T. 17 N., R. 16 E.	---do---	---do---	1,825	--
- 80	NW1/4NW1/4SW1/4, sec. 5, T. 17 N., R. 17 E.	---do---	Sage, grass	1,775	--
- 83	NE1/4SE1/4SE1/4, sec. 7, T. 19 N., R. 18 E.	Verdi 7 1/2′, Nev.	Grass, pine	1,485	6.2
C76- 04	SW1/4SE1/4NW1/4, sec. 9, T. 17 N., R. 16 E.	Truckee 15′, Calif.	Pine	1,900	--

Site No.	Location	Topographic map	Vegetation	Altitude (m)	Soil pH[1]
Truckee River, Calif., Nev. (Truckee, 80.0, 6.0; Reno, 18.0, 9.5)--Continued					
C75- 79	SE1/4NW1/4SW1/4, sec. 11, T. 17 N., R. 16 E.	---do---------------	---do-------	1,785	6.4
- 78	SE1/4SE1/4SE1/4, sec. 25, T. 18 N., R. 16 E.	---do---------------	Sage, grass-	1,755	--
- 82	NE1/4SW1/4SE1/4, sec. 18, T. 19 N., R. 18 E.	Verdi 7 1/2′, Nev.-	---do-------	1,510	6.2
- 77	SW1/4SW1/4SE1/4, sec. 10, T. 17 N., R. 16 E.	Truckee 15′, Calif.	Pine--------	1,800	6.0
C76- 05	SE1/4NW1/4SW1/4, sec. 11, T. 17 N., R. 16 E.	---do---------------	---do-------	1,785	--
Bighorn River, Mont.					
C75- 62	NE1/4SE1/4SE1/4, sec. 33, T. 5 S., R. 31 E.	Yellowtail Dam 7 1/2′.	Grass-------	970	--
- 58	NE1/4SE1/4SW1/4, sec. 1, T. 6 S., R. 31 E.	Mountain Pocket Creek 7 1/2′.	Grass, sage-	990	--
- 60	SW1/4SE1/4SE1/4, sec. 19, T. 4 S., R. 31 E.	Lemonade Springs 7 1/2′.	Grass-------	1,005	--
- 59	SW1/4SE1/4SW1/4, sec. 19, T. 4 S., R. 31 E.	---do---------------	---do-------	1,025	--
- 61	NE1/4SE1/4SE1/4, sec. 2, T. 4 S., R. 31 E.	Woody Creek Camp 7 1/2′.	Sage, grass-	1,085	--
Mammoth, Calif.					
C75- 72	SW1/4SE1/4NE1/4, sec. 2, T. 4 S., R. 27 E.	Mt. Morrison 15′---	Sage, manzanita.	2,390	--
- 63	SE1/4SE1/4SE1/4, sec. 2, T. 4 S., R. 27 E.	---do---------------	---do-------	2,450	--
- 73	SE1/4SE1/4SE1/4, sec. 36, T. 3 S., R. 27 E.	---do---------------	Sage, grass-	2,305	--
- 65	SE1/4NE1/4SW1/4, sec. 31, T. 3 S., R. 28 E.	---do---------------	---do-------	2,270	--
West Walker River, Calif.					
C75- 69	SW1/4NE1/4SW1/4, sec. 21, T. 6 N., R. 23 E.	Fales Hot Springs 15′.	Sage, grass-	2,105	--
- 68	SE1/4NW1/4SE1/4, sec. 21, T. 6 N., R. 22 E.	Sonora Pass 15′----	---do-------	2,635	--
- 70	NW1/4SW1/4NE1/4, sec. 23, T. 6 N., R. 23 E.	Fales Hot Springs 15′.	---do-------	2,195	--
- 67	NE1/4SW1/4NE1/4, sec. 22, T. 7 N., R. 23 E.	---do---------------	---do-------	2,220	--
- 66	NW1/4NW1/4NW1/4, sec. 5, T. 6 N., R. 23 E.	---do---------------	---do-------	2,610	--
- 71	SE1/4SW1/4SW1/4, sec. 35, T. 6 N., R. 24 E.	---do---------------	---do-------	2,105	--
Wallowa Lake, Ore.					
C75-115	SE1/4NW1/4NE1/4, sec. 5, T. 3 S., R. 45 E.	Joseph 15′---------	Grass-------	1,340	--
-113	SE1/4SW1/4NE1/4, sec. 9, T. 3 S., R. 45 E.	---do---------------	Grass, sage-	1,535	--
-114	NW1/4SE1/4NE1/4, sec. 9, T. 3 S., R. 45 E.	---do---------------	---do-------	1,500	--
-112	NW1/4SW1/4NW1/4, sec. 15, T. 3 S., R. 45 E.	---do---------------	Pine, grass-	1,455	--
Grand Mesa, Colo.					
C76- 01	0.2 km N. of Bonham Reservoir---------------	Grand Mesa 7 1/2′.	Spruce-fir--	2,980	--
- 02	SE1/4NW1/4SW1/4, sec. 4, T. 12 S., R. 96 W.	Lands End 7 1/2′.	Grass, spruce	3,140	--
- 03	NE1/4SE1/4SW1/4, sec. 3, T. 12 S., R. 96 W.	Skyway 7 1/2′------	Spruce, grass	3,185	--
Siletz River, Ore.					
C76- 18	NE1/4SE1/4SW1/4, sec. 24, T. 8 S., R. 11 W.	Euchre Mt. 15′-----	Mixed forest	15	--
- 19	NE1/4SW1/4SE1/4, sec. 21, T. 9 S., R. 10 W.	---do---------------	---do-------	20	--
- 21	NW1/4NE1/4SW1/4, sec. 33, T. 9 S., R. 9 W.	Toledo 15′---------	---do-------	65	--
Spokane, Wash.					
C76- 50	SE1/4SW1/4NE1/4, sec. 29, T. 25 N., R. 42 E.	Medical Lake 15′---	Grass-------	705	--

Site No.	Location	Topographic map	Vegetation	Altitude (m)	Soil pH[1]
		South Fork Shoshone River, Wyo.			
C76- 76	1.5 km E. of mouth of Ishawooa Creek-------	Ishawooa 15'-------	Grass-------	1,890	--
		Warm River Butte Area, Idaho, Wyo.			
C78-100	0.6 km NNW. of Bechler River Ranger Station	Warm River Butte 15', Idaho-Wyo.	Pine--------	1,966	--
-101	1.0 km NNW. of Bechler River Ranger Station	---do---------------	---do-------	1,969	--
-102	NE1/4NW1/4NE1/4, sec. 11, T. 9 N., R. 45 E.	---do---------------	Pine, aspen-	1,868	--
-108	NW1/4NE1/4NW1/4, sec. 3, T. 47 N., R. 118 W.	---do---------------	Pine, grass-	1,960	--
-109	NW1/4SE1/4NW1/4, sec. 4, T. 47 N., R. 118 W.	---do---------------	Grass, pine-	1,966	--
-103	NE1/4NE1/4NW1/4, sec. 19, T. 9 N., R. 45 E.	---do---------------	Fir, aspen, sage.	1,743	--
-106	NE1/4NW1/4NW1/4, sec. 3, T. 8 N., R. 45 E.	---do---------------	Pine, aspen, grass.	1,902	--
-107	NW1/4NE1/4NE1/4, sec. 2, T. 8 N., R. 45 E.	---do---------------	---do-------	1,935	--
- 98	NW1/4NE1/4NW1/4, sec. 33, T. 47 N., R. 118 W.	McReynolds Res. 7 1/2', Idaho-Wyo.	Pine--------	2,109	--
- 99	NE1/4SW1/4SW1/4, sec. 28, T. 47 N., R. 118 W.	Warm River Butte 15', Idaho-Wyo.	---do-------	2,097	--
-104	NW1/4NW1/4SE1/4, sec. 24, T. 10 N., R. 44 E.	---do---------------	Aspen, grass-	1,878	--
- 97	SE1/4NE1/4SE1/4, sec. 32, T. 8 N., R. 44 E.	Drummond 7 1/2', Idaho.	Sage, grass--	1,783	--
-105	SW1/4SW1/4NW1/4, sec. 5, T. 8 N., R. 45 E.	Warm River Butte 15', Idaho-Wyo.	Grass, pine--	1,993	--

[1] 1:1 soil-water mixture, <0.2 mm fraction; leaders (--), not measured.

APPENDIX C.—GENERALIZED PETROGRAPHIC DESCRIPTIONS

The following are generalized petrographic descriptions of the rock types in each of the major study areas on which weathering rinds were measured.

BASALTS

WEST YELLOWSTONE

Basalts examined near West Yellowstone, Mont., were derived from the Madison River Basalt (Christiansen and Blank, 1972). The rocks contain scattered phenocrysts of plagioclase as much as 1 mm long, and less commonly phenocrysts of olivine as much as 0.5 mm in diameter, locally in glomeroporphyritic clusters. The matrix consists of plagioclase, in laths 0.1-0.2 mm long; crystals of clinopyroxene, olivine, and opaque minerals, about 0.05-0.1 mm in diameter; and irregular-shaped masses of basaltic glass and chlorophaeite. Matrix textures are mostly intergranular to intersertal, and less commonly subophitic. Visual estimates of the modal composition are: plagioclase, 45-55 percent; pyroxene, 25-30 percent, olivine, 5-10 percent; glass and chlorophaeite, 5-10 percent; and opaque minerals about 10 percent.

McCALL

Rocks examined near McCall, Idaho, are extremely uniform in texture and composition and are probably derived from the upper part of the Yakima Basalt Subgroup of the Columbia River Basalt Group (John Bond, oral commun., 1976). The rocks are mostly aphanitic, consisting of plagioclase laths 0.1 to 0.2 mm long (with scattered microphenocrysts up to 0.5 mm long); crystals of clinopyroxene, olivine, and opaque minerals 0.05-0.01 mm in diameter; and irregular-shaped masses of glass, chlorophaeite, and calcite. The textures are mostly intersertal to hyaloophitic; less commonly intergranular to subophitic. Visual estimates of the modal composition are plagioclase, 45-55 percent; pyroxene, 20-30 percent; olivine, 0-5 percent; calcite, 0-5 percent; glass and chlorophaeite, 15-20 percent; opaque minerals, 10-15 percent.

YAKIMA VALLEY

Rocks examined from the Yakima Valley are derived from the Eocene Teanaway Basalt (Foster, 1958; Porter, 1975). They are mostly aphanitic, but some contain scattered phenocrysts of plagioclase or opaque minerals 0.3-0.5 mm in longest dimension. Grain size generally ranges between 0.05 and 0.2 mm, and textures are mostly intersertal; less commonly textures are intergranular, hyaloophitic, and subophitic. Visual estimates of the modal composition are: plagioclase, some of which is zoned, 45-55 percent; clinopyroxene, 25-35 percent; olivine, 0-10 percent; opaque minerals, 5-10 percent; glass, chlorophaeite, and (or) chlorite, 10-20 percent; and rare (<1 percent) potassium feldspar.

PUGET LOWLAND

The precise source of the basalt in the Puget Lowland drifts is not known, but it is probably mostly derived from the Eocene Crescent Formation in the Olympic Mountains. The basalt contains microphenocrysts of plagioclase, 0.5-0.8 mm long, and clinopyroxene, 0.3-0.5 mm in diameter. The matrix consists mostly of thin plagioclase laths (0.3-0.5 mm long); equant clinopyroxenes (0.05-0.1 mm in diameter); and irregular-shaped masses of devitrified glass, chlorophaeite, and chlorite. Glass is rarely present. Textures are mostly intersertal, less commonly hyaloophitic. Visual estimates of the modal composition are: plagioclase, 40-55 percent; clinopyroxene, 25-35 percent; olivine, 0-1 percent; opaque minerals, 5-10 percent; and altered glass and chlorite, 10-20 percent.

ANDESITES

Weathering rinds from sampling areas containing andesitic rocks were measured on two groups of stones: "coarse grained" and "fine grained." The two textural groups represent an arbitrary field classification based on phenocryst content and matrix texture. See p. 12 for definition of these textural groups.

MOUNT RAINIER

Most of the rocks examined from the Mount Rainier area were derived from andesite of the Mount Rainier volcano (Fiske and others, 1963), although some weathering rinds were measured on stones derived from older volcanic rocks. The andesite of the Mount Rainier volcano is a hypersthene andesite and is remarkably uniform in composition.

The fine-grained andesites contain scattered phenocrysts 0.5-1.5 mm in largest dimension, whereas microphenocrysts 0.1-0.3 mm long are more abundant. Plagioclase is the most abundant phenocryst, with lesser amounts of pyroxene, and a few crystals of amphibole and olivine. Both the plagioclase and the pyroxene are typically zoned, with plagioclase showing a wide range in degree of zoning. Both ortho- and clinopyroxenes are present; slightly pleochroic orthopyroxene (hypersthene?) is more abundant. Amphiboles and some pyroxenes exhibit reaction rims of iron oxides. The matrix is very fine grained (0.01-0.05 mm in size) and appears to consist mostly of plagioclase, pyroxene, opaques, and glass. Visual estimates of the modal composition are: plagioclase, 45-50 percent; pyroxene, 30-35 percent; opaques, 5-10 percent; glass, 5-10 percent; amphibole, 0-1 percent; and olivine 0-1 percent. Textures are primarily hyaloopilitic.

Coarse-grained andesites are similar compositionally to fine-grained andesites. The grain size is highly bimodal, with abundant large (0.5-3.0 mm) phenocrysts of plagioclase and pyroxene, and rare phenocrysts of olivine and opaque minerals, in a very fine grained (0.01-0.03 mm) matrix. The pyroxene phenocrysts commonly occur in glomeroporphyritic clusters. Textures range from hyaloopilitic to pilotaxitic.

LASSEN PEAK

Rocks examined from the Lassen Peak area were derived from a variety of andesitic flows which make up the volcanic complex around Lassen Peak (Williams, 1932). The mineralogy of these andesites is moderately variable.

The fine-grained andesites are nonporphyritic to weakly porphyritic. Phenocrysts, if present, range from 0.3 to 1.5 mm in size; plagioclase (some of which is zoned) is generally the largest and most abundant phenocryst; phenocrysts of clino- or orthopyroxenes and olivine are less common. The matrix is typically fine grained (0.08-0.1 mm) and consists of plagioclase, pyroxene, opaque minerals, glass, and rarely calcite, potassium feldspar, and olivine. In rocks containing calcite or olivine, clinopyroxene is more abundant than orthopyroxene. Textures are mainly pilotaxitic to intergranular. Visual estimates of the modal composition are: plagioclase, 40-60 percent; pyroxene, 25-40 percent; opaques, 5-10 percent; glass, 0-15 percent; potassium feldspar, 0-10 percent; calcite, 0-5 percent; and olivine, 0-15 percent.

The coarse-grained andesites have similar mineralogy, except that they contain very little glass.

Phenocrysts are abundant, the most common being plagioclase (1.0-2.0 mm long), which is commonly zoned. Pyroxene (clino- more abundant than ortho-) and olivine phenocrysts range from 0.6 to 1.2 mm in size. The matrix grain-size is about 0.1-0.2 mm. Textures are mostly intergranular to pilotaxitic.

TRUCKEE

The rocks examined from near Truckee, Calif., were derived mostly from the late Tertiary andesites that are abundant in the area. A few basalt clasts (those without olivine phenocrysts) from the Pliocene and Pleistocene Lousetown Formation (Birkeland, 1963) may have been included with the fine-grained andesites.

The fine-grained andesites contain microphenocrysts 0.1-0.3 mm in size and a few scattered phenocrysts up to 2 mm in size. The phenocrysts are plagioclase, pyroxene, olivine, and amphibole in varying proportions; the microphenocrysts are plagioclase (most abundant) and pyroxene. A few of the plagioclase and pyroxene phenocrysts are zoned. Clinopyroxene is commonly more abundant than orthopyroxene. The matrix is very fine grained (0.02-0.07 mm) and consists mostly of plagioclase, pyroxene, and opaque minerals. Glass is scarce. Visual estimates of the modal composition are: plagioclase, 50-65 percent; pyroxene, 20-35 percent; opaques, 5-10 percent; olivine, 0-10 percent; amphibole, 0-5 percent; glass, 0-5 percent. Textures are primarily pilotaxitic to trachytic.

The coarse-grained andesites are similar mineralogically and texturally to the fine-grained andesites. They contain abundant phenocrysts of plagioclase and pyroxene 0.5-2.0 mm in size, in a matrix whose grain size is generally 0.01-0.1 mm.

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