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THE INFLUENCE OF FLOTATION ON THE RATE OF RECOVERY OF WOOD CHARCOAL FROM ARCHAEOLOGICAL SITES

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ABSTRACT.—This paper explores the extent to which quantitative data produced by the analysis of archaeological wood charcoal are biased as a result of the flotation process. After considering the formation and physical properties of charcoal, and the stresses characterizing the flotation process, a model depicting the rate of recovery of charcoal as a function of bulk density is developed. The results of flotation trials using modern, nonarchaeological charcoal fragments reveal that most samples are recovered at rates in excess of 90%, despite differences in density. The magnitude of stresses generated during flotation apparently are insufficient to produce an observable differential rate of recovery among samples. However, because fossil and modern charcoal fragments likely differ considerably in density and strength, further investigations are necessary to evaluate the effects of flotation on the quantification of archaeological remains.

RESUMEN.—Esta ponencia examina el punto al cual los datos cuantitativos que son producidos por el análisis del carbón de leña arqueológico son parcial de resultas del proceso de flotación. Después de análisis de la formación y las propiedades físicas del carbón de leña, y los esfuerzos que caracterizan el proceso de flotación, un modelo es desarrollado que representa la proporción de recobro del carbón de leña como una función de la densidad volumétrica. Los resultados de las pruebas de flotación empleando los fragmentos del carbón de leña moderno y no arqueológico revelan que la mayor parte de las muestras es recobrada en exceso de 90%, a pesar de las diferencias en la densidad. Los esfuerzos que son causados por la flotación aparentemente son insuficiente en magnitud producir una diferencia en la proporción de recobro entre las muestras que pode observar. Sin embargo, hay probablemente unas diferencias considerables en la densidad y la fuerza entre los fragmentos del carbón de leña fósil y moderno. Unas investigaciones adicionales son necesarias por lo tanto para evaluar los efectos de flotación en los intentos cuantificar los restos argueológicos.

RÉSUMÉ.—Ce papier explore la mesure à laquelle les données quantitatives qui sont produit par l'analyse du charbon de bois archéologique sont biaisés par suite du procédé de flottaison. Après analyse de la formation et des propriétés physiques du charbon de bois, et des efforts qui caractérisent la flottaison, un modèle est développé qui dépeint la proportion de recouvrement du charbon de bois comme une fonction de densité volumétrique. Il résulte des essais de flottaison qui sont réalisés en utilisant les fragments du charbon de bois moderne et non archéologique que la plupart des échantillons sont recouvrés dans une proportion de plus de 90%, en dépit des différences de densité. Les efforts qui sont causés par la flottaison en apparence sont insuffisant pour produire une différence de la proportion de recouvrement entre les échantillons qu'on peut observer. Cependant, il y a probablement des différences considérables de la densité et la résistance entre les fragments du charbon de bois fossile et moderne. Des investigations supplémentaires sont nécessaire par conséquent pour évaluer les effets de la flottaison sur les buts de quantifier les restes archéologiques.

INTRODUCTION

Since its popularization by Struever (1968), the flotation technique has made possible the recovery of voluminous samples of floral remains from archaeological sites. The availability of large samples, along with an increasing emphasis on the formulation of processual interpretations (Dennell 1978; Ford 1979:297-298; Minnis and LeBlanc 1976; Renfrew 1973:29, 1979:263; Struever 1968; van der Veen and Fieller 1982; Yarnell 1970:215), has resulted in the appearance in the archaeological literature of economic and environmental studies based upon the quantitative analysis of plant remains retrieved by flotation. Although the majority of such studies have involved the examination of seeds, several investigations have included a consideration of charred wood macrofossils (e.g., Adovasio *et al.* 1979-1980, Asch *et al.* 1972, Johannessen 1983, Miller 1985, Minnis 1978, and Zalucha 1983).

All such studies entail several assumptions regarding the composition of charcoal samples obtained by flotation: (1) The wood charred by human or nonhuman agencies and deposited at a site is representative of the botanical component of the economy or environment, (2) the remains preserved and present within the sedimentary matrix prior to excavation are representative of the charcoal deposited, and (3) the charcoal recovered by flotation is representative of that *in situ*. The successive failure of these assumptions results in an increasing restriction on the information content of archaeobotanical data.

In fact, various researchers have argued that the meaning of data derived from the quantification of floral remains, including wood charcoal, is obscure because the relationship between human activities or the environment and the charring and deposition of plant materials is exceedingly complex (Dennell 1972:149-151, 1976, 1978; Ford 1979:304; Hally 1981; Hillman 1973; Hubbard 1975, 1976; Munson *et al.* 1971; Willcox 1974). The effects of differential preservation following deposition among broad classes of plant remains (Dennell 1978; Dimbleby 1977:19-21, Ford 1979:299, Green 1979, Levy 1963), and among taxa of seeds (Gasser and Adams 1981), on the validity of quantitative data has received some attention. Although the implications of the charring process for the preservation and identification of wood charcoal have been examined (Lopinot 1984:Chapters III-IV, Rossen and Olsen 1985, Zalucha 1983), the potential for differences among taxa in the rate of survival of wood charcoal *in situ* given such environmental variables as temperature and water table fluctuations, sediment chemistry, and biogenic disturbance have not been addressed.

Casual observations by Pals and Voorrips (1979:228) indicated that the collection of samples from the trench by hand results in the overrepresentation of taxa having particularly tough charcoal. This paper explores, in greater depth, the question of whether or not a charcoal sample recovered by flotation is representative of the remains embedded in the site matrix prior to excavation. After briefly considering the formation process and physical properties of charred wood, and examining the stresses characterizing the flotation process, a model depicting the influence of flotation on the rate of recovery of charcoal is developed. The results of a series of experiments designed to test the utility of the model are presented, and implications of the current findings for palaeoethnobotanical research are discussed.

THE FORMATION AND PHYSICAL CHARACTERISTICS OF CHARCOAL

Charcoal is produced by the thermal decomposition, or pyrolysis, of wood (e.g., Goos 1952, Hawley 1952, Lopinot 1984:Chapter III, Tillman 1981). The formation of various volatile substances and a solid residue (charcoal) commences when the temperature of wood rises above ambient levels. As the temperature continues to increase (and in the absence of oxygen after the ignition temperature has been reached), volatiles are given off, and the charcoal component becomes more stable and enriched in carbon.

The conversion of wood to charcoal is associated with dramatic structural alteration of the cell wall. Scanning electron microscope studies show a transition from the fibrillar structure of the cell wall in wood to a smooth, amorphous wall in the charred state (McGinnes *et al.* 1971). Attendant upon transformation of the cell wall are a number of gross physical changes including mass loss, a decrease in bulk density, anisotropic shrinkage, cracking, and distortion or loss of certain anatomical details routinely employed in identification (Baileys and Blankenhorn 1982, Beall *et al.* 1974, Lopinot 1984:Chapters III-IV, McGinnes *et al.* 1971, Rossen and Olson 1985, Zalucha 1983, Zicherman and Williamson 1981). As a result of the physical alterations induced by the pyrolytic process, charcoal typically is markedly brash and friable in comparison to uncharred wood.

THE EFFECTS OF FLOTATION ON CHARCOAL

From the point at which the sediment sample is added to the water medium until the resultant light and heavy fractions are dried, flotation appears to be a violent process. The destruction of delicate plant remains during flotation has been observed by a number of authors (Bohrer 1970; Ford 1979:302; French 1971; French *et al.* 1972:186; Jarman *et al.* 1972:45; Lange and Carty 1975; Munson *et al.* 1971; Renfrew 1973:15; Struever 1968; Wagner 1982; Yarnell 1963, 1974:113). Indeed, all flotation systems currently in use (cf. French 1971; Jarman *et al.* 1972; Lange and Carty 1975; Limp 1974; Minnis and LeBlanc 1976; Schock 1971; Stewart and Robertson 1973; Struever 1968; Watson 1974, 1976; Williams 1973) are characterized by a variety of mechanical stresses that may degrade charred wood macrofossils. Stresses relevant to the destruction of charcoal are those that result in a decrease in the amount of quantifiable remains that can be assigned to any taxonomic category. Thus, stresses of importance here are those that produce fracture in the material, and thereby cause a reduction in fragment size beyond that of the smallest screen mesh used in the flotation apparatus, or otherwise render the charcoal unidentifiable. Fracture occurs when the strain limit of the charcoal is reached, i.e., when the charcoal no longer can dissipate the energy acquired through stress application by deformation (Kollmann and Côté 1968:292, and Panshin and de Zeeuw 1980:221-222). Crushing and smearing represent extreme cases of fracture. Two types of potentially destructive mechanical stresses common to the flotation schemes described in the literature may be recognized: (1) A suite of *impact stresses* that impinge upon charcoal fragments as they are separated from the sediment matrix, and (2) *internal static stresses* that are associated with the wetting and drying of charcoal.

An impact stress acts over a short interval of time and arises as a consequence of a collision between two bodies (Kollmann and Côté 1968:379). As the flotation sample is poured into the water medium, each piece of charcoal collides with the water surface, matrix particles of various sizes and densities, and other charred fragments. Following immersion of the sample, the resulting suspension is agitated by the action of water currents or air bubbles, and in some systems, by manual stirring. Charcoal is subject to breakage through collisions with suspended matter, the sides of the flotation chamber, the stirring implement, and the catch screen or strainer. Damage due to impact stresses also may occur as the remains contained in the light and heavy fractions are transferred to the paper or cloth on which they are to be dried.

Extensive breakage occurs as a result of the wetting and drying of charred plant remains, including charcoal, as has been pointed out by Barghoorn (1944), Bohrer (1970), Ford (1979:299), French *et al.* (1972:186), and Jarman *et al.* (1972:45). Such destruction, which typically is manifested as exfoliation along growth rings or rays, is effected by internal static stresses that accompany changes in the moisture content of the material. Wood swells and shrinks in relation to the amount of water adsorbed onto, or lost from, the cell wall (Forest Products Laboratory 1974, Kollmann and Côté 1968:204, Siau 1984:31, and Skaar 1972:82). Beall *et al.* (1974) allude to the fact that charcoal behaves in a similar manner. Thus, one is justified in assuming that, during changes in moisture content, the behavior of charcoal is approximated, at least qualitatively, by that of wood. When the quantity of hygroscopic water present in a sample of whole wood is increased or decreased, a moisture gradient develops, which, given the effects of differential swelling or shrinkage, results in the generation of the static stresses compression and tension (Kollmann and Côté 1968:422, and Skaar 1972:118-119). Skaar (1972:119-120) has described the stress regime characteristic of a drying wood specimen: As its surface begins to dry, the outer layers of the wood fragment shrink relative to the wet inner core; while the inner layers are influenced by weak compressive stresses, the outer layers become set in tension. As the drying of deeper layers commences, compression increases in the interior, and the region of high tensile stress migrates from the outermost layers toward the center of the fragment. During the final stages of drying, the outer layers acquire a compression set, whereas the internal portions of the sample are subjected to mild tensile stresses. A stress pattern essentially the reverse of that for drying is observed when wood is immersed in water (Skaar 1972:123). Presumably, the scheme outlined here for wood is applicable to the response of charcoal to wetting and drying as well.

A MODEL: THE RATE OF RECOVERY OF CHARCOAL AS A FUNCTION OF BULK DENSITY

The cell wall imparts to wood its strength, i.e., its ability to resist an applied stress. Both the mass per unit volume of cell wall substance *(true density)* and the mass of cell wall substance in a given volume of whole wood *(bulk density)* contribute to the strength properties of uncharred wood (Panshin and de Zeeuw 1980:221-223, Wangaard 1950:152-153). However, differences among wood samples in true density are negligible (Forest Products Laboratory 1974, Kollmann and Côté 1968:161, Panshin and de Zeeuw 1980:214, Stamm 1929, Wangaard 1950:153). Hence, bulk density is of primary importance in considering the strengths of various woods. The general relationship between bulk density and wood strength, obtained empirically, is given by a power function:

$$s = x\, d_b{}^y \quad (1)$$

where s is any strength property, x is a proportionality constant, d_b is the bulk density of the wood tested, and y is a positive exponent (Forest Products Laboratory 1974, Markwardt and Wilson 1935, Newlin and Wilson 1919, Panshin and de Zeeuw 1980:223, Wangaard 1950:153-156). Actually, specific gravity (the bulk density of the material tested relative to the density of a standard substance, usually pure water) traditionally has been used in the wood science literature to predict the strength properties of wood. Since bulk density is more appropriate, in terms of physical meaning, as a measure of the proportion of cell wall material in wood, it is used in preference here as an indicator of wood strength. In fact, when pure water is used as the standard substance, bulk density and specific gravity assume identical absolute values.

The true density of charcoal does not vary significantly from species to species nor among samples of a single species charred at different final temperatures (Bailey and Blankenhorn 1982, Blankenhorn *et al.* 1978). Moreover, the rôle of bulk density as an indicator of the relative amount of cell wall material in a given specimen remains unchanged when wood is charred (though, as noted previously, its absolute value decreases). Therefore, the relationship between bulk density and the strength properties of charcoal should be similar in form to that embodied in equation (1) for wood. Accordingly, any strength property of charcoal, S, including shock resistance (the strength property associated with impact stresses) and compressive and tensile strengths, may be expressed as follows:

$$S = XD_b{}^Y \quad (2)$$

where X and Y are constants, and D_b is the bulk density of charcoal. If R is the rate, or probability, of recovery of charcoal following the application of a particular stress, then

$$R = 1 - e^{-w\,S} \tag{3}$$

where e and w are constants, the former being the base of natural logarithms with an approximate value of 2.72. Explicit in the equation is the fact that R increases hyperbolically with S. Charcoal entirely lacking in strength would be associated with a probability of recovery of zero; as charcoal strength increases, R tends, asymptotically, toward unity. The actual shape of the curve is specified by the constant, w. Substituting equation (2) into (3), and given that K is a constant equivalent to the product of X and w,

$$R = 1 - e^{-KD_b^{\,Y}}. \tag{4}$$

The last equation clearly implies that the probability of recovery of charcoal subjected to any stress associated with flotation is a function of the bulk density of the material. The model predicts that a high-density charcoal, such as that of Oregon white oak *(Quercus garryana)*, is more likely to survive any stress characterizing the flotation process than is a light charcoal, of which charred western redcedar *(Thuja plicata)* is a notable example. The actual shape of the graph of the function is specified by the constants, K and Y. When the latter factor equals one, the function will be hyperbolic in form; the function will be sigmoid when Y exceeds one.

One might wish to construct a separate model of the relationship between the probability of recovery and the bulk density of charcoal for each stress encountered in the flotation process. However, as indicated previously, charred wood fragments are acted upon concurrently by impact and static stresses associated with collisions and hygroscopic swelling, respectively, while immersed in water in the flotation receptacle. In addition, the static stresses compression and tension work in concert during both the wetting and drying of charcoal. Hence, because flotation stresses act simultaneously, and perhaps synergistically, in causing the degradation of charcoal, a model depicting the destructive effects of the entire flotation process (i.e., of all of its stresses) would be of more use to archaeologists in assessing the respresentativeness of flotation samples. By determining, experimentally, the values of R and D_b for a series of charcoal samples submitted to the flotation operation, the constants K and Y can be derived, allowing such a model, in the form of a hyperbolic or sigmoid function, to be set forth.

MATERIALS AND METHODS

The charcoal used in the present experiments was obtained from wood specimens representing 18 species common in the Pacific Northwest (Table 1). Samples were taken from various parts of one or two individuals of each species. Material obtained from stems less than about 1 cm in diameter include both pith and xylem; samples from larger stems consist entirely of xylem. Thus, from this point onward, the term "wood" includes pith as well as xylem; use of the term is not restricted to the latter tissue, as is usually the case. The arguments up to

TABLE 1.—*Rate of Recovery of Charcoal Samples Submitted to Flotation.*

Species	Source	Mean R	Range	n
Acer circinatum (vine maple)	A	1.00	0.99–1.00	3
	B	0.97	0.96–0.99	3
	C	0.62	0.00[a]–1.00	3
Alnus rubra (red alder)	A	0.94	0.93–0.95	3
	D	0.97	0.94–1.00	3
	C	0.73	0.62–0.80	3
Arctostaphylos uva-ursi (kinnikinnick)	B	0.71	0.41–0.86	3
Corylus cornuta (hazelnut)	B	0.92	0.85–0.99	3
	C	0.95	0.85–1.00	3
Gaultheria shallon (salal)	A	1.00	1.00	2
	B	1.00	1.00	1
	C	0.99	0.96–1.00	3
Holodiscus discolor (creambush oceanspray)	A	0.99	0.99–1.00	3
	B	0.97	0.92–1.00	3
	C	0.99	0.96–1.00	3
Philadelphus lewisii (mockorange)	A	0.93	0.84–0.99	3
	B	0.96	0.91–0.99	3
	C	0.71	0.50–0.86	3
Picea sitchensis (Sitka spruce)	D	0.95	0.91–0.99	3
	C	0.92	0.85–0.95	3
Pinus ponderosa (ponderosa pine)	A	0.98	0.96–1.00	3
	D	1.00	1.00	3
	C	1.00	1.00	3
Pseudotsuga menziesii (Douglas fir)	D	0.86	0.70–0.96	3
Purshia tridentata (antelope-brush)	A	0.99	0.99–1.00	3
	B	0.97	0.94–1.00	2
	C	1.00	1.00	2
Quercus garryana (Oregon white oak)	A	0.78	0.71–0.86	3
	D	0.96	0.89–1.00	3

TABLE 1.—*Rate of Recovery of Charcoal Samples Submitted to Flotation (continued).*

Species	Source	Mean R	Range	n
Ribes sanguineum (red currant)	A	0.98	0.97–0.99	3
	C	0.98	0.95–1.00	3
Rubus spectabilis (salmonberry)	A	0.98	0.97–0.98	3
	B	0.97	0.95–1.00	3
	C	0.88	0.65–1.00	3
Sorbus scopulina (Cascade mountain-ash)	A	0.95	0.90–0.97	3
	B	0.95	0.89–1.00	2
	C	0.39	0.00[a]–0.93	3
Thuja plicata (western redcedar)	D	0.98	0.95–1.00	3
	C	0.97	0.90–1.00	3
Tsuga heterophylla (western hemlock)	D	0.88	0.71–0.97	3
	C	0.91	0.81–1.00	3
Vaccinium parvifolium (red huckleberry)	A	0.95	0.88–1.00	3
	B	0.97	0.97–0.98	3
	C	0.72	0.54–0.83	3

Note: Source of wood samples: A, base of dominant stem; B, midlength of dominant stem; C, new distal stem growth; D, midlength of lateral branch. Wood samples were derived from a single individual for each species, with the exception of ponderosa pine, in which case the wood from source A was obtained from one tree, and the samples from sources D and C were collected from a second tree. R is the calculated rate of recovery of a sample (m_{after} divided by m_{before}), and n is the number of samples.

[a]Some charcoal was recovered from all of the flotation samples; however, in the case of two species, one of three samples derived from source C contained insufficient mass for measurement by the balance employed.

this point are not altered by the inclusion of pith in some of the samples. Pith, being composed of thin-walled parenchyma cells, merely acts to lower the bulk density of a given sample. The specimens were stored at room temperature for two months, after which they were charred as follows: Each piece of wood was tightly wrapped in heavy-duty aluminum foil so as to decrease the supply of oxygen to its surface, heated for several hours over commercial charcoal briquettes until uniformly black in color, and allowed to cool while remaining enclosed in foil. Each charred specimen then was shattered by hand or with the use of a hammer. The resultant fragments were divided to form four samples. Three of the samples, each composed of 10-20 fragments, were employed as spikes for flotation trials; the fourth sample, composed of 2-3 fragments, was used for bulk density determinations. The charcoal fragments used were highly variable in shape; their minimum diameters varied from approximately 0.25 to 1.5 cm.

Determination of Recovery Rates.—The following formula was used to compute the rate of recovery of each charcoal fragment sample:

$$R = \frac{m_{after}}{m_{before}} \qquad (5)$$

where m_{before} is the mass of charcoal present prior to flotation, and m_{after} is the mass of charcoal subsequently retrieved. The mass of each charcoal sample was measured to the nearest 0.01 g with an electronic balance.

Each of 126 mock flotation samples was prepared by combining a charcoal fragment sample of known mass (m_{before}) with 0.5l of clean sand. The samples were processed using a machine-assisted flotation device similar to the SMAP unit described by Watson (1976): Water, under pressure, was brought into a 200l plastic drum by a pipe that terminated at an upward-directed shower head. A flotation sample was poured into the water-filled barrel within a basket fashioned from 1.6 mm mesh fiberglass screen and suspended from the rim of the barrel. Agitation was provided by jets of water issuing from the shower head and by manual stirring. While the sand particles sank and passed through the mesh basket, the light fraction was carried through a sluice to an attached box where it could be caught in a suspended 1.6 mm mesh fiberglass net. However, to increase the speed of the operation, the light fraction was caught in a tea strainer as it was discharged from the sluice. Each charcoal-bearing light fraction was dried at room temperature in a paper bag for 28 days, at which point it was re-weighed to obtain m_{after}. The operation produced no heavy fraction. i.e., no charcoal fragments sank. Some actual archaeological charcoal fragments typically are denser than water, and consequently form a heavy fraction upon flotation. The heavy nature of such fragments likely stems from the presence of water and encrusting minerals acquired while in situ. The lack of heavy fractions in the flotation trials described here may be attributed to the fact that the charcoal was completely dry and free of mineral particles prior to processing. The flotation system employed is diagrammed in Fig. 1.

Extraordinary care was taken during the conduct of the flotation trials to avoid the loss of charcoal fragments due to factors other than damage (e.g., to loss resulting from fragments being washed over the sides of the flotation apparatus), and to prevent intersample contamination. Moreover, because the hygroscopic water content, and thus, the mass of charcoal, is dependent upon relative humidity, several samples were re-weighed at various times during the weighing procedure, in fact, no change in mass was observed for any of these

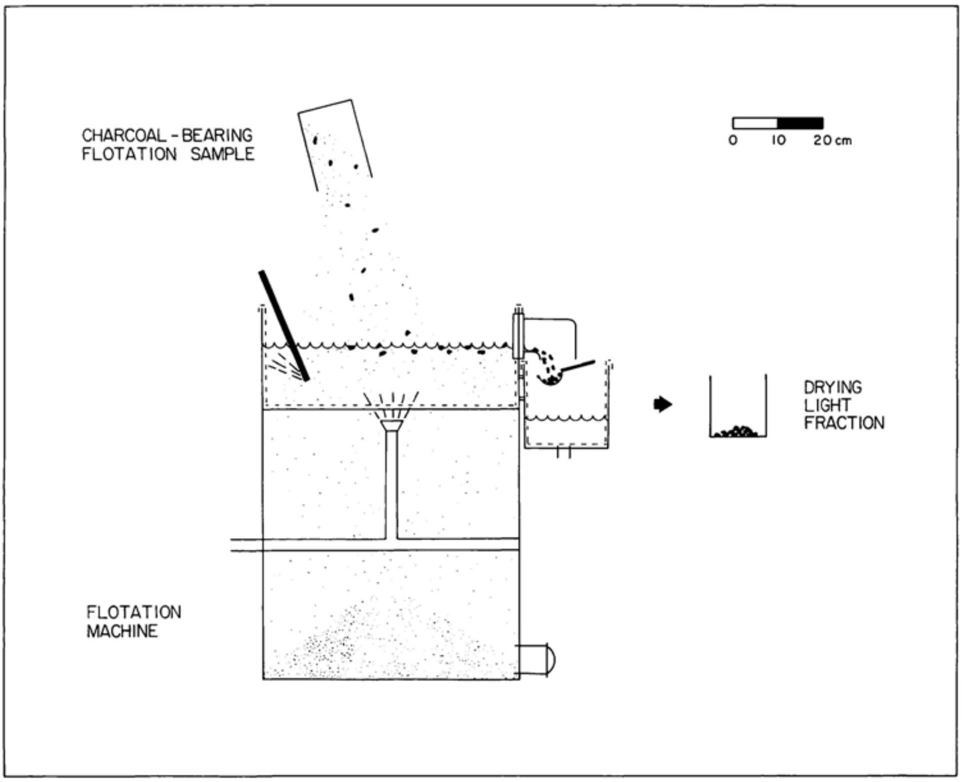

FIG. 1.—Diagrammatic representation of the flotation system employed in the present study for the retrieval of charcoal fragment samples.

samples. Hence, one can be reasonably confident that any reduction in charcoal mass is attributable exclusively to stress-induced degradation.

The quantification of charcoal abundance may be accomplished through fragment counts or by the measurement of sample mass. Mechanical stresses tend to increase the number of fragments through subdivision of those contained in the sediment sample prior to flotation. Some proportion of the resultant fragments will be too small to be recovered in the flotation screens. In terms of counts, the fraction of unrecoverable fragments cannot be ascertained. Hence, the number of fragments retrieved may bear no discernible relationship to those originally comprising a sample. Consequently, fragment counts may not be used appropriately in the calculation of charcoal recovery rates. On the other hand, the fraction of unrecoverable fragments can be quantified with respect to mass. As a result, meaningful recovery rates may be calculated on the basis of any flotation-induced reduction in sample mass. Although sensitive only to breakage resulting in the production of unrecoverable fragments, the measurement of sample mass clearly provides the most appropriate means of calculating charcoal recovery rates in an experimental setting where m_{before} is known for each sample.

Determination of Bulk Densities.—The bulk density of each charred wood specimen was calculated as the average of the measurements obtained for two or (usually) three fragments. The bulk densities of a total of 129 charcoal fragments were determined using the maximum moisture content technique developed by Smith (1954) for small wood samples. The following equation allows the calculation of the bulk density (D_b) of a given charcoal fragment:

$$D_b = \frac{1}{\dfrac{V_{water}}{m_{dry}} + \dfrac{1}{D_t}} \tag{6}$$

where m_{dry} is the mass of the fragment when dry, D_t is a constant corresponding to the true density of charcoal, and V_{water} is the volume of water contained in the fragment when saturated. In Smith's paper, the constant, here designated D_t, represented the specific gravity of cell wall substance. Density may be substituted validly for specific gravity in Smith's equation, since both parameters carry the same absolute value, and the dimensions associated with density are consistent with the equation. The variable, V_{water} is equal to the difference between m_{sat}, the saturated mass of the specimen, and m_{dry}. To determine m_{sat}, a test fragment was placed with distilled water in a desiccator flask, and a vacuum was applied for 28 days. The fragment, which was assumed to be saturated, was then weighed after eliminating any excess surface water with a damp towel. The constant, D_t, in equation (6) was assigned a value of 1.43 g cm^{-3}, which corresponds to the mean of 32 mercury porosimeter measurements made by Baileys and Blankenhorn (1982) of the true density of the wood of red oak, southern yellow pine, black cherry, and hybrid poplar charred at various final temperatures.

RESULTS AND DISCUSSION

The data generated by the flotation experiments and density determinations are summarized in Tables 1 and 2, respectively. A histogram is presented in Fig. 2, in which the relative frequencies (fractions of 126 total samples) of 10 fragment sample classes, each representing a particular interval of recovery rates, are depicted. The results seem to warrant optimism as regards the destructive nature of the flotation process. Seventy-six percent of the samples were recovered at rates $\geq$90%.

A plot of bulk density (D_b) versus rate of recovery (R) is shown in Fig. 3. A model of the form given in equation (4) was fitted to these data by an iterative Taylor series technique (see Draper and Smith 1966: Chapter 10) using the program SIGFIT (computer programs referenced in this paper were written by the author in BASIC, and were executed on an Apple Macintosh 512K). The procedure rendered the following parameter estimates, rounded to two significant figures: K = 2800, and Y = 4.1. The fitted sigmoid curve and the associated equation are given in Figure 3. Obviously, the data are approximated very poorly by a sigmoid curve. In fact, the results fail to uphold any correlation between bulk density and the rate of recovery of charcoal.

TABLE 2.—*Charcoal Bulk Density Values Determined by Maximum Moisture Content Technique.*

Species	Source	Mean D_b (g/cm^3)	Range (g/cm^3)	n
Acer circinatum (vine maple)	A	0.40	0.35–0.47	3
	B	0.31	0.29–0.32	3
	C	0.24	0.24–0.25	3
Alnus rubra (red alder)	A	0.32	0.30–0.33	2
	D	0.34	0.30–0.40	3
	C	0.39	0.33–0.51	3
Arctostaphylos uva-ursi (kinnikinnick)	B	0.76	0.76	2
Corylus cornuta (hazelnut)	A	0.33	0.29–0.38	3
	B	0.29	0.27–0.30	3
	C	0.31	0.13–0.48	2
Gaultheria shallon (salal)	A	0.36	0.34–0.38	2
	B	0.91	0.80–1.03	3
	C	0.41	0.36–0.44	3
Holodiscus discolor (creambush oceanspray)	A	0.53	0.51–0.57	3
	B	0.36	0.34–0.40	3
	C	0.28	0.26–0.29	3
Philadelphus lewisii (mockorange)	A	0.46	0.32–0.58	3
	B	0.46	0.41–0.50	3
	C	0.87	0.67–1.11	3
Picea sitchensis (Sitka spruce)	D	0.35	0.35–0.36	3
	C	0.37	0.34–0.39	3

TABLE 2.—*Charcoal Bulk Density Values Determined by Maximum Moisture Content Technique (continued).*

Species	Source	Mean D_b (g/cm^3)	Range (g/cm^3)	n
Pinus ponderosa (ponderosa pine)	A	0.23	0.22–0.24	3
	D	0.41	0.36–0.45	3
	C	0.48	0.45–0.50	3
Pseudotsuga menziesii (Douglas fir)	D	0.44	0.41–0.46	2
Purshia tridentata (antelope-brush)	A	0.44	0.38–0.49	3
	B	0.80	0.59–1.05	3
	C	0.31	0.28–0.37	3
Quercus garryana (Oregon white oak)	A	0.40	0.40	2
	D	0.56	0.53–0.60	3
Ribes sanguineum (red currant)	A	0.43	0.42–0.45	3
	C	0.41	0.37–0.43	3
Rubus spectabilis (salmonberry)	A	0.36	0.35–0.37	3
	B	0.30	0.27–0.31	3
	C	0.35	0.34–0.37	3
Sorbus scopulina (Cascade mountain-ash)	A	0.25	0.19–0.29	3
	B	0.27	0.25–0.32	3
	C	0.12	0.11–0.12	3
Thuja plicata (western redcedar)	D	0.29	0.20–0.34	3
	C	0.33	0.30–0.35	3
Tsuga heterophylla (western hemlock)	D	0.17	0.15–0.18	3
	C	0.64	0.51–0.83	3
Vaccinium parvifolium (red huckleberry)	A	0.40	0.35–0.44	3
	B	0.36	0.29–0.42	3
	C	0.35	0.30–0.39	3

Note: Source of wood samples: A, base of dominant stem; B, midlength of dominant stem; C, new distal stem growth; D, midlength of lateral branch. Wood samples were derived from a single individual for each species, with the exception of ponderosa pine, in which case the wood from source A was obtained from one tree, and the samples from sources D and C were collected from a second tree. D_b is bulk density, and n is the number of fragments analyzed.

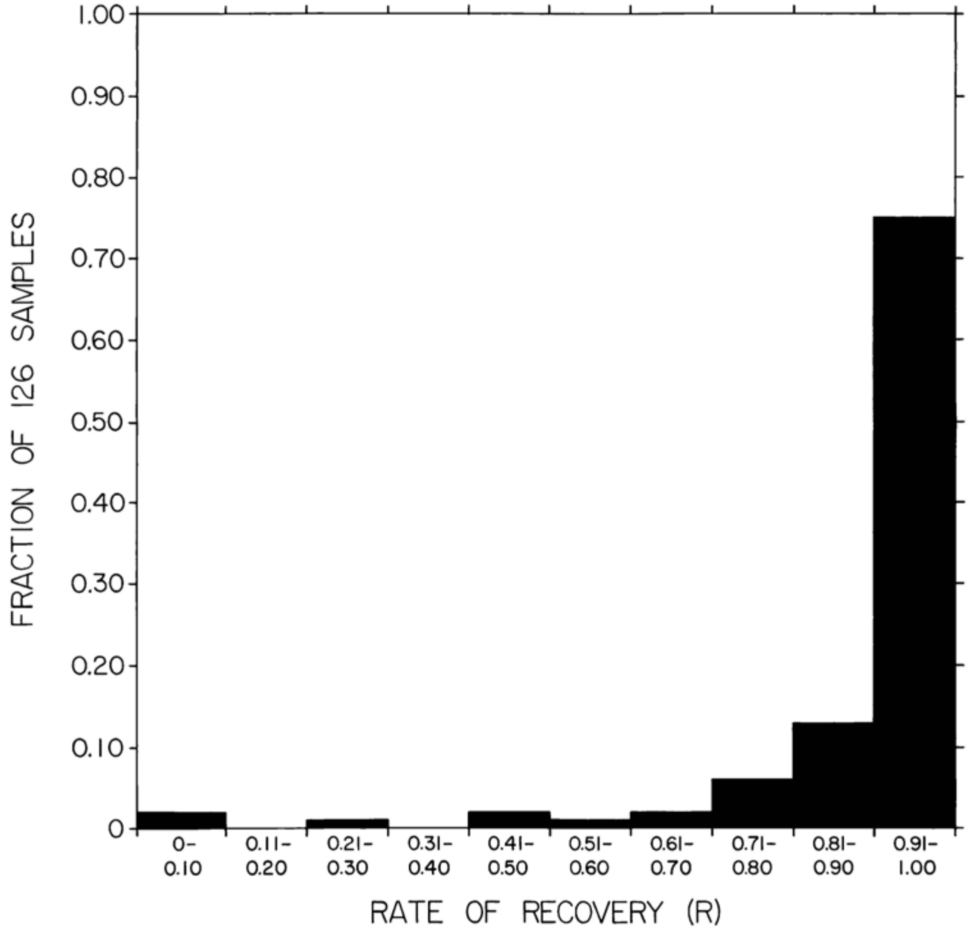

FIG. 2.—Histogram showing the distribution of 126 charcoal fragment samples among 10 classes representing recovery rate (R) intervals. Note that three-fourths of the samples are associated with recovery rates in excess of 90%.

Before discarding the general model presented above (equation 4), the *ceteris paribus* assumption, which is a necessary specification for the testing of any model, must be scrutinized. The *ceteris paribus* assumption associated with this study embodies the following components: (1) The maximum moisture content technique is a valid means of measuring the bulk density of charcoal, (2) bulk density is the sole determinant of the rate of recovery of charred wood submitted to flotation, and (3) the stresses imposed by flotation are of sufficient magnitude to produce observable differences, on the basis of bulk density, in the recovery rates of charcoal samples.

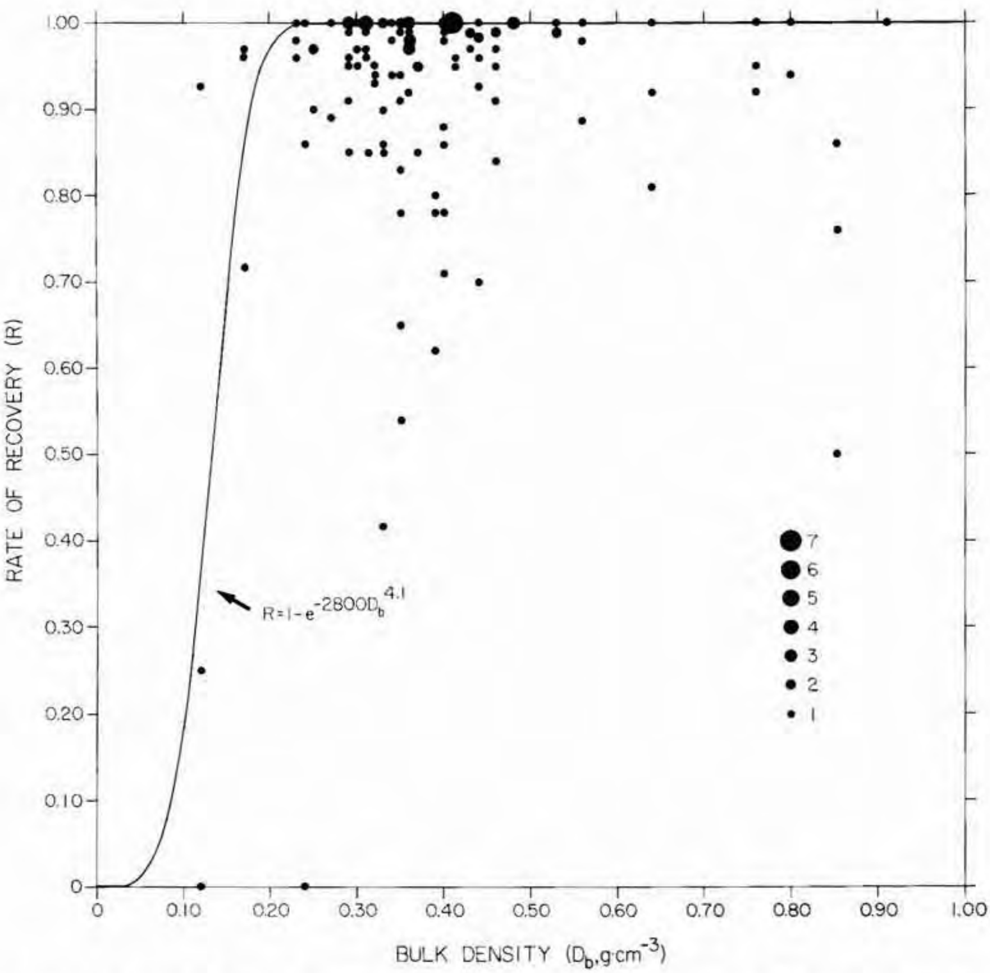

FIG. 3.—A plot of bulk density (D_b) versus rate of recovery (R) for 126 charcoal fragment samples submitted to flotation. The number of data points occurring at a particular location on the graph is proportional to the size of the dot (a legend is given in the lower right-hand portion of the figure). The curve and associated equation were obtained by fitting a model of the form given in equation (4) in the text to the data.

Validity of maximum moisture content technique.—Smith (1954) listed several assumptions implicit in the use of the maximum moisture content technique for determining the bulk density of wood specimens: (1) the wood is absolutely saturated when m_{sat} is measured, (2) m_{sat} can be obtained validly in air, (3) the density of cell wall substance is constant for all wood samples, and (4) the cell lumina contain no extraneous materials. The same assumptions apply in the case of charred wood fragments.

Smith reported that wood samples apparently were saturated after having been placed under vacuum conditions for seven days, since, after that point, the sample masses stabilized. To insure complete saturation, the charcoal used in the present study was held under vacuum for 28 days. Secondly, all excess surface water presumably was removed from each fragment before being weighed. Smith found that, for wood, the magnitude of D_b was exaggerated by only 0.0001 g per square centimeter of surface area when a piece of damp muslin was used to remove excess moisture. As regards the true density constant, Smith demonstrated in a later paper (1955) that, in actuality, a small error in the true density constant produces an even smaller error in the calculated bulk density value. The influence of extraneous materials on the measured bulk density values was assessed neither by Smith for wood, nor by the present author for charcoal. Despite its limitations, the maximum moisture content technique probably represents a fairly accurate means of determining the bulk density of porous, irregularly-shaped charcoal fragments, especially in comparison to techniques requiring the measurement of volume (e.g., the volumetric, pycnometric, and gasometric schemes described by Tayor [1967]).

Visual examination of the charcoal used for the density determinations reveals that the measurements produced a ranking of the fragments that roughly coincides with that which would be created intuitively. That is, fragments assigned high bulk density values possess compact xylary structures, while those given low density values are characterized by a high proportion of parenchymatous pith. Furthermore, the small ranges that characterize, in most cases, the density determinations support the assumption that, for a given charcoal specimen, the average density obtained for several fragments using the maximum moisture content technique is representative of that of each fragment used in the mock flotation samples. Hence, the data, themselves, offer no cause for concern as regards the validity of the density determinations.

Alternative factors affecting the recovery of charcoal.—The ability of bulk density to reflect the strength properties of wood (and, presumably, charcoal) may be subordinated to factors including the presence of cross-grain, knots, splits, gums, resins, and certain cell wall components such as lignin and extractives (Forest Products Laboratory 1974, Panshin and de Zeeuw 1980:223-226). Anatomical factors, as well, sometimes compromise the predictive value of density. For example, the presence of large rays amid thin-walled longitudinal cells often restrains radial shrinkage, thereby altering the stress regime within drying wood (Panshin and de Zeeuw 1980:211). Such factors, the taxonomic distributions of which usually are limited and known, might result in the degradation of charcoal by flotation stresses in some pattern other than that expected on the basis of bulk density values. However, perusal of these data fails to reveal any indication of correlation between rate of recovery and the taxonomic affinity of charcoal samples.

Insufficient magnitude of flotation stresses.—The lack of correlation between D_b and R, along with the high rate of recovery of most samples, would seem to point to a violation of the third element of the *ceteris paribus* assumption. That is, the actual magnitudes of stresses generated by the flotation process are so small, relative to the strength of the charcoal used in the present experiments, as to produce little variation in the rate of recovery among fragments, despite differences in bulk density. Intuitively, this conclusion is not surprising, since the charcoal used in this study appears, in general, to be quite robust. In fact, the modern charcoal employed here is less brash and friable than charcoal fragments routinely encountered in archaeological deposits.

The recovery of 24% of the fragment samples, having various bulk densities, was considerably less than complete. Many of the samples associated with low recovery rates are particularly small, i.e., they are characterized as having rather small masses prior to flotation (m_{before}). To test for a positive correlation between R and m_{before}, the data summarized in Table 1 were analyzed using the program RANKTEST. Spearman's rank correlation coefficient (r_S), incorporating modifications proposed by Siegel (1956:206-210) to account for a large number of ties in rank order, was determined. The associated t-statistic was calculated as well, in accordance with Siegel (1956:212), who suggested its use when $n \geq 10$. The analysis returned a correlation coefficient of 0.29. For a one-tailed test ($t = 3.42$, $p < 0.05$, $n = 126$), one concludes that, in fact, a statistically significant positive correlation exists between sample mass prior to flotation and the rate of recovery following the operation. The fact that a particularly small coefficient is found to be statistically significant may seem alarming. Because of the large sample size involved, the correlation coefficient must fall below a very low value ($0.14 < r_S < 0.15$) before one fails to reject the null hypothesis for a one-tailed test and $p < 0.05$. Fifty-seven percent of the samples associated with low recovery rates ($<$90%) are derived from young stem wood obtained near branch tips (source C in Table 1). These samples are characterized by exceptionally low values of m_{before} ($\leq$0.41 g), and are composed of segments of narrow twigs. The positive correlation between R and m_{before} is not particularly surprising, since the destruction of even a single fragment in a sample composed of minute pieces of charcoal clearly will result in a considerable decline in the rate of recovery.

Implications for palaeoethnobotanical research.—This investigation has demonstrated that the recovery of modern, nonarchaeological charcoal from a clean sand matrix using the flotation system described here is not biased as a result of differences in bulk density among the charcoal fragments. The charcoal apparently possesses sufficient strength that significant variation in recovery rates was not observed. In fact, the flotation procedure produced recovery rates generally in excess of 90%.

Due to failure of the *ceteris paribus* assumption, the results of the present study do not provide a basis for rejecting the assumption that charcoal samples retrieved by flotation are representative of the remains contained in the sediment matrix. However, two important factors preclude the projection of these seemingly optimistic results onto archaeological situations. Firstly, the rate of recovery of plant remains is influenced by the specific procedures followed, and equipment used, in flotation (Pendleton 1983, Wagner 1982, Watson 1976), as well as by the characteristics of the matrix in which they are embedded (Wagner 1982).

Hence, nearly complete recovery may be restricted to situations in which charcoal is retrieved from a clean sand matrix using a flotation system identical to that described above. The relationship between R and D_b embodied in equation (4) may be manifested when charcoal fragment samples are processed using harsher flotation operations. Secondly, archaeological charcoal fragments may be less dense, structurally weaker, and consequently, more readily degraded during flotation than the modern charcoal used in the present investigation. This may result from (1) differences in the temperature regime of the pyrolytic process (see Baileys and Blankenhorn 1982, Sandberg *et al.* 1979), (2) pre- and post-depositional mechanical stresses (e.g., those stemming from repeated wet/dry episodes, trampling, and vertical transport within the sediment), (3) chemically-mediated deterioration (e.g., partial oxidation subsequent to charring), and (4) biologically-mediated deterioration of wood prior to charring (e.g., decay resulting from fungal infection). Without doubt, the recovery rates calculated by reference to modern charcoal overestimate the recovery probabilities of actual archaeological remains.

Future inquiries aimed at elucidating the influence of flotation on the rate of recovery of archaeological charcoal clearly should entail experiments similar to that reported here, but using various flotation systems, sediment matrices, and actual or simulated fossil remains. Although logistical constraints probably preclude the use of actual archaeological charcoal, modern charred wood that has been weakened structurally by exposure to mechanical stresses similar to those expected in an archaeological setting might be used profitably to appraise the effects of possible biasing mechanisms, including bulk density.

Beyond the issue of the degree to which charcoal retrieved by flotation is representative of that *in situ*, two basic assumptions remain to be examined critically before attempting to formulate cultural or environmental interpretations on the basis of the results of charcoal analysis. These assumptions, which were put forth in the introductory section of this paper, may be restated as follows: (1) The wood charred and deposited at a site is representative of its role in the prehistoric cultural system or environment, and (2) the charcoal preserved and present *in situ* is representative of that deposited. Until the validity of each of the assumptions associated with charcoal analysis is substantiated, the information generated by the identification of charred wood is doubtless best used in a nominal manner.

NOTE

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