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Chapter 5

Quaternary tephrochronology

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INTRODUCTION

Tephrochronology as used here is the study of tephra layers—volcanic ash beds and tuffs—for purposes of correlation and dating of sediments, rocks, and structures. Tephrochronology is used to provide stratigraphic and age control for such studies as regional stratigraphic and tectonic synthesis; determinations of ages, rates, and directions of crustal motions; calibration and evaluation of provincial and regional faunal, magnetostratigraphic, isotopic, and chemical age dating methods; and correlation of continental and marine faunal and isotopic stages (Sarna-Wojcicki and others, this volume). Tephrochronology is also the study of tephra layers for their own sake: to determine the manner of their eruption and emplacement, their areal distributions; and to infer from their physical, mineralogical, and chemical characteristics the evolution of their parent magmas. Tephrochronology can also be used to determine the eruptive sources of tephra and to determine the frequency of eruptions from specific areas or vents—information necessary for assessments of regional volcanic hazards (Crandall and Mullineaux, 1978; Miller, 1989). Lastly, tephrochronology is important in providing critical age and correlation control in studies of human history—anthropology and archeology (Davis, 1982; Mehringer and Foit, 1990).

Terminology

In this chapter and in Sarna-Wojcicki and others (this volume), we use the term tephra in its larger meaning as defined by Thorarinsson (*in* Westgate and Gold, 1974, p. xvii-xviii): ". . . A collective term for all the clastic volcanic material which during an eruption is transported from the crater through the air . . ., including both air-fall and flow pyroclastic material." However, in this chapter we qualify the term when necessary to indicate the flow origin of pyroclastic units.

We recommend that the term tephra layer or tephra bed be used rather than ash bed, because the term ash has a size connotation that can be confusing (Thorarinson, 1974). We also recommend that the term tephra not be used synonymously with a tephra bed, tephra layer, or tephra deposit. The term tephra, in our understanding of the term, refers to the pyroclastic material erupted from a volcanic vent, to the material of which a tephra layer or bed is composed, and to the physical and chemical characteristics of this material. Despite our preferences, we follow previous usage in this chapter in instances where confusion or misunderstanding might otherwise result.

Thorarinsson (1974 *in* Westgate and Gold, p. xviii) defined *tephrochronology* ("volcanic ash chronology" of Wilcox, 1965, and other pioneer American workers) as ". . . A chronology based on measurement, connection and dating of tephra layers. In particular, tephrochronology is concerned with the establishment of a chronosequence of geologic events based on the unique characteristics of tephra layers." Thus, the basic premise of tephrochronology is that tephra layers have unique characteristics, physical or chemical, by which they can be distinguished one from another, and by which they can be consistently and correctly identified. Only if this basic premise is fulfilled can tephrochronology be applied successfully as a stratigraphic and geochronologic tool.

Characteristics

The characteristic properties of tephra layers, such as the morphology of glass shards, the presence of mineral species and their abundances, and the chemical composition of the volcanic glass and minerals do not vary randomly; groups of tephra layers related genetically to the same volcanic source area tend to have similar properties (Sarna-Wojcicki, 1971, 1976; Sarna-Wojcicki and others, 1984; Davis, 1978; Izett, 1981). The chemical compositions of tephra, both glass and minerals, are probably related to three main variables: the tectonic setting of the volcanic field from which the tephras were erupted, the composition of the rocks from which their parent magmas were derived, and the differentiation history of these magmas (Sarna-Wojcicki and others, 1984; see below). These three variables obviously are related to each other.

Large volumes of silicic tephra that are capable of producing a large eruption are usually produced along the margins of, or

*Deceased.

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within, sialic continental crust. Tephra produced from magma chambers situated above subduction zones (e.g., the Cascade Range of the Pacific Northwest of the United States) differ in chemical composition and mineralogy from that produced along margins of spreading continental areas (e.g., the Long Valley caldera of east-central California, and the Jemez Mountains area of northwestern New Mexico). These also differ from tephra produced from magmas within continental crust, rising above mantle hot spots (e.g., tephra erupted from the calderas of the Yellowstone National Park area). Furthermore, tephra produced within similar plate-tectonic settings but in different areas, are chemically different from each other (e.g., tephra of the Cascade Range compared to those of the Alaskan Peninsula). Smaller compositional differences generally are observed among tephra erupted from the same volcanic province or field, and still smaller differences usually are found among tephra erupted from the same volcano or vent. Smallest chemical differences are usually observed among replicate samples of the same tephra layer (Sarna-Wojcicki, 1976). It is these systematic orders of variability that make it possible to identify the tectonic setting, specific geographic region, volcanic field, and (for young tephra layers) vent, from which the tephra of a particular layer was erupted, as well as individual units of a particular eruption.

For further discussion of the composition of tephra and pyroclastic rocks in general, and of the processes that control the formation of tephra and pyroclastic rocks, see Fisher and Schmincke (1984) and Heiken and Wohletz (1985).

Subdisciplines

Tephrochronology includes two subdisciplines: tephrostratigraphy and tephrochronometry. Tephrostratigraphy is the correlation of tephra layers by their distinguishing physical and chemical characteristics, and by the characteristic stratigraphic sequences. Tephrostratigraphy by itself provides temporal stratigraphic correlation and relative age control in a manner similar to biostratigraphy or other relative-age dating methods. Tephrochronometry, a term proposed by J. A. Westgate (written communication, 1990) is the numerical age determination of tephra layers, either directly from the tephra itself (e.g., by potassium-argon or fission-track analyses of specific comagmatic phenocrysts or glass shards in a tephra layer), or indirectly from ages of strata stratigraphically above and below a tephra layer (Rosholt and others, this volume).

Tephrochronology in its broader meaning, the combination of both tephrostratigraphy and tephrochronometry, is a powerful chronostratigraphic tool that applies to geologic, anthropologic, archeologic, and even historic studies. Tephra from an explosive volcanic eruption can be injected high into the atmosphere and carried over a large area within several hours or days (Royal Society of London, Krakatau Commission, 1888; McCormick, 1981; Sarna-Wojcicki and others, 1981b). The layer at the surface of the earth that results from tephra fallout after such an eruption provides a virtually instantaneous time datum that is more than sufficiently precise for most geologic, and even for some historic, studies.

After a large tephra eruption, tephra are rapidly eroded from uplands and redeposited in lowlands, such as terrestrial low-energy fluvial environments and lakes and depositional basins of seas and oceans. Because tephra have low density compared to other sediments, fluvial and subaqueous reworking after an eruption will initially transport only tephra, producing first a reworked layer, then progressively less pure tephra containing greater percentages of "normal" sediment. This is why many tephra layers, whether airfall or reworked, typically have a sharp basal contact and are fairly pure at the base, but usually have a transitional upper contact (Fig. 1).

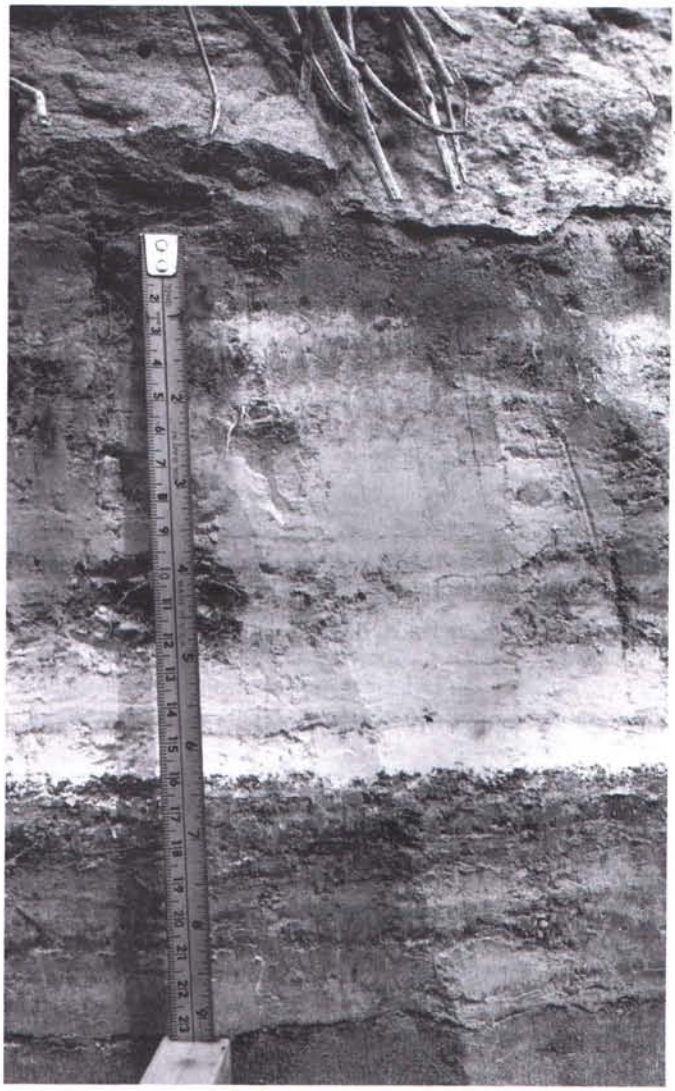


Figure 1. Photograph of tephra layer exposed in fine-grained, upper Pliocene and Pleistocene fluvial sediments, Beaver basin, south-central Utah. Measuring tape in photo is graded in centimeters (left side) and inches (right side). Note sharp basal contact with underlying sedimens and gradational upper contact. This tephra layer underlies the Huckleberry Ridge ash bed with small stratigraphic separation. It correlates with the tuff of Taylor Canyon, near Glass Mountain, California, the eruptive center of this tephra. The age of the layer is about 2.0 to 2.1 Ma.

Where a tephra has been reworked shortly after eruption, the layer can be identified by its physical and chemical characteristics. Time spans between eruption and redeposition are usually short, a few months to a few years, so that even the time-transgressiveness of reworked tephra layers is short compared to the analytical errors of most geochronological methods (Shipley, 1983).

When erosion and reworking occur long after the deposition and burial of a tephra layer, the tephra usually becomes mixed in the much more voluminous local clastic load, so that there is no longer a recognizable tephra layer in the enclosing sediments. A small percentage of volcanic glass shards is common in many sedimentary layers. These shards are products of volcanic events that occurred prior to or during the depositional cycle that formed a given stratum, and provide a maximum age for the enclosing sedimentary layers.

Reworking can cause serious problems in identifying tephra layers close to eruptive sources, where tephra layers are commonly thick or numerous. In such situations, the stratigraphic context of each tephra layer and its homogeneity must be examined to determine if multiple compositional modes of more than one tephra are present.

A major shortcoming of tephrochronology is that macroscopic tephra layers have limited areal distribution. Even though unusual wind patterns and counterwinds at higher altitudes can carry tephra in several directions (Sarna-Wojcicki and others, 1981b), tephra is usually carried from volcanic vents by prevailing winds within a limited geographic sector. Thus, to develop reliable regional Quaternary chronostratigraphic frameworks, tephrochronologic information is obtained in areas downwind from volcanic sources, and integrated with other chronostratigraphic data.

Another limitation of tephrochronology is that the physical, mineralogic, and chemical characteristics of tephra layers can change with (1) distance from volcanic source, (2) depositional environment, and (3) age (see Methods, below).

PLINIAN ERUPTIONS AND THEIR PRODUCTS[1]

Eruptions from Quaternary volcanoes in the United States have varied greatly in magnitude, in terms of the volume of material erupted, in explosiveness (as measured by the thermal and kinetic energy released per unit time), and in the type of material erupted. Here, we are concerned only with explosive volcanic eruptions that have introduced large amounts of volcanic ejecta into the atmosphere. Such eruptions—termed Plinian (for the Roman, Pliny the Younger, who described this type of eruption from Mount Vesuvius in 79 A.D.)—are produced by the sudden release of confining pressure in magma reservoirs situated at shallow depths (about 5 to 10 km) in the Earth's crust. Typically, such eruptions are produced from viscous, silicic magmas (SiO_2 content from about 64 to 74 percent), containing high concentrations of volcanic gases. The silica polymerizes the magma, increasing its viscosity relative to low-silica magmas, such as basalt or andesite, which enables high concentrations of volcanic gases (including H_2O, CO_2, H_2, Cl_2, H_2S, SO_2, and CO) to accumulate and remain in solution. When pressure on the magma reservoir is suddenly released by failure of the confining solid rock crust above the magma reservoir, gases are emitted rapidly from the magma, transforming it into a liquid-gas froth. The resultant rapid increase in volume of the magma is explosive, propelling it in the direction of low pressure—generally upward and into the atmosphere. Sometimes, as at Mount St. Helens, the blast is directed laterally, with devastating results. Because basaltic and andesitic magmas are usually less viscous than silicic magmas, volatile pressures within them are lower and produce less explosive and less widespread tephra layers.

A Plinian eruption can introduce large volumes of volcanic ejecta into the atmosphere and lower stratosphere (altitudes above about 11 km) in a relatively short time (Fig. 2). During the May 18, 1980, eruption of Mount St. Helens, 1 to 2 km^3 of tephra were erupted within about ten hours, and some material went as high as 27 km (Sarna-Wojcicki and others, 1981b). Although this was a rather small eruption, ash as thick as 5 cm accumulated on the ground within 300 km downwind from the volcano, and lesser amounts extended 600 km from the volcano, covering an area of about 200,000 km^2. Fine ash and dust from this eruption encircled the Northern Hemisphere within about two weeks (McCormick, 1981).

Ash clouds may also form above ash-flow sheets (ignimbrites) by rapid, turbulent, convective rise of hot air and other gases from the flows. According to some workers, such clouds may produce widespread fine ash layers that are termed coignimbritic (Sparks and Walker, 1977).

The nature and composition of tephra layers

Tephra consists of several major components. All large Plinian eruptions contain material, termed juvenile, that is molten at the time of the eruption. This material cools from rapid expansion and from contact with the air, producing particles of ash and coarser ejecta that are usually solid by the time they fall to the ground. Preexisting rocks can also be incorporated into the erupting material, particularly in the early, more explosive phases of an eruption. In addition, tephra usually contains a smaller percentage of crystals or crystal fragments of minerals that crystallized from the magma before eruption. The main components of tephra are discussed below.

Pumice. Pumice is a solidified rock froth of volcanic glass, including crystals of one or more kinds of minerals and voids formed by gas bubbles (vesicles). The glass is a supercooled, natural liquid. Crystals and crystal fragments within the glass formed from the magma prior to eruption. The abundant vesicles are formed by outgassing of dissolved gases caused by a decrease in pressure of the magma during eruption. By the time the pumice

[1]Much of the description of Plinian eruptions and their products and of the nature and composition of tephra is taken, with some modification, from Shipley and Sarna-Wojcicki (1983).

Figure 2. Plinian eruption column rising from the crater of Mount St. Helens on May 18, 1980. View to the northeast. Photo from Austin Post (1980).

fragments fall to the ground, or shortly thereafter, the original gases that formed these bubbles have escaped or are highly diluted by infiltrating air; air-fall pumice fragments diminish in size downwind from their source vent. Because of the large number of voids, pumice has low density, generally between 0.7 and 1.2 g/cm^3. If large amounts of pumice are erupted, it may accumulate as floating mats on the surface of water bodies lying downwind. If many of the vesicles are connected, as they often are in tubular pumice, the voids may fill with water and the pumice may sink. If the voids are not connected, the pumice may continue to float indefinitely. Such pumice clasts may be transported over long distances by ocean currents, far beyond the limits of air transport of such coarse particles.

Glass shards. At distal locations, tephra generally consist of very small pumice shards and glass shards derived from the bubble walls and bubble-wall junctions of exploded rock froth. The latter two are essentially pure glass, but may contain some vesicles and small crystals or crystal fragments. Silicic glass shards commonly have densities of 2.35 to 2.45 g/cm^3. Basaltic glass is denser. Glass shards have various morphologies, depending on the temperature of eruption, composition of the parent magma, the geometry of the volcanic vents, depth of the magma chamber, and other factors.

Crystalline minerals and crystal fragments. This component of tephra can be minerals that crystallized from magma before eruption and either were incorporated into pumice or glass shards or were erupted as discrete particles. Crystalline material also may be from the wall rock of the vent and volcanic edifice during an explosive event. Magmatic crystals formed from a magma before eruption are variously called pyrogenic, cogenetic, or comagmatic. We prefer the term comagmatic with reference to minerals that have formed from the same magma as the coexisting glass shards. Commonly, comagmatic crystals have a coating of volcanic glass, whereas accidental crystals of older rock do not,

unless the older rock is also tephra. Such distinctions are important in identification and separation of minerals from tephra for numerical dating, and for evaluation of the results. Densities of minerals vary widely, generally from 2.6 to 5.2 g/cm^3.

Lithic fragments. The force of a volcanic eruption is commonly great enough to disintegrate much of the solid roof of the magma reservoir. This material, commonly ejected simultaneously with the juvenile components, may range from blocks more than a meter in diameter near the volcanic vent, to composite particles a fraction of a millimeter in diameter deposited at greater distances. Lithic fragments usually consist of intergrowths of one or more kinds of minerals. Densities of these particles generally range from 2.7 to 3.2 g/cm^3. Obsidian fragments are common, especially in proximal areas, where the fragments are coarse and black; in distal areas, obsidian fragments are difficult to distinguish from blocky glass shards. Most obsidian fragments are probably at least slightly older than the associated tephra, because obsidian is formed by slow extrusion from a vent, not by a Plinian eruption.

Other materials. Many tephra layers contain some material that has been incorporated into the tephra during transport, deposition, or after deposition. Such material may include clastic, bioclastic, and organic sediment, and chemical precipitates. Tephra layers commonly become cemented and indurated with age and are called tuffs. Common cementing materials are calcite, silica, limonite/goethite, pyrite, and gypsum. Cementation can also be due to devitrification, alteration and authogenesis of primary components, and to compaction by burial.

NOMENCLATURE OF TEPHRA LAYERS

Tephrochronologic nomenclature in the United States follows at least three different schemes. This probably is due to the random manner in which large areas have been mapped, to the patchy distribution of widespread tephra layers, and to the personal preferences of individual workers.

When the sources of tephra layers are unknown, the layers are often assigned local names or arbitrary letters or numbers (e.g., in the Cascade Range, Crandell and others, 1962; also see Allison, 1945; Davis, 1985; Lajoie, 1968). Tephra layers named in this way may consist of a name of the section or area, plus a letter or number that designates the stratigraphic position of the layer (e.g., Wilson Creek #15). This is a workable system, but the designations tend to be uninformative, and are difficult to keep in sequence when new layers are found.

Another system of nomenclature names tephra layers after correlative units present near the source from which the tephra was erupted. For example, the distal correlative tephra layer of the proximal Huckleberry Ridge Tuff in the Yellowstone National Park area (Christiansen and Blank, 1972) is named the Huckleberry Ridge ash bed (Naeser and others, 1973; Izett and Wilcox, 1982). The source of many tephra layers, however, is unknown and correlative proximal tephra may be unnamed. Names must be changed when the source and the proximal correlative units are identified.

Yet another scheme is to name tephra layers as lithostratigraphic units, according to the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 1983). Tephra layers are readily subsumed under the rubic of key, or marker beds (Article 26, p. 858). When a tephra layer is found to be correlative with a previously named layer, the previous name takes precedence; otherwise, names do not change. This system does not generally name the source; however, it requires no additional nomenclatorial rules beyond those used in lithostratigraphy. The Quaternary tephra layers of northwestern Nevada were named in this way by Davis (1978).

METHODS OF CORRELATION

Field Criteria

Field characteristics are the simplest but often most effective criteria for identification and correlation of tephra layers. They generally work best over short distances of up to several tens of kilometers. They are often not sufficient for correlations over long distances, for multiple sets of tephra layers, or for tephra layers deposited in different sedimentary environments. Tephra layers may often be traceable laterally; indeed, there is no better criterion for correlation of a tephra layer than its continuity. Multiple samples taken laterally and vertically within a continuously exposed unit define the statistical range of variability of a tephra layer with respect to various physical and chemical correlation criteria. This range can then be compared to the statistical range of variability observed between sites apparently lacking continuity (Sarna-Wojcicki, 1971, 1976); the former range then becomes a guide for acceptance or rejection of correlation between the latter sites.

Other field characteristics such as thickness, color, texture, and bedding may distinguish layers from each other and be useful for local correlation. These criteria work best for airfall tephra layers over distances of tens to 100 to 200 km from their source.

A tephra layer can have a distinctive color that is relatively constant over short to intermediate distances (as much as 100 to 200 km). Over longer distances, the color of a tephra layer becomes lighter away from the eruptive source, because grain size diminishes with distance owing to settling-out of coarser particles. Tephra layers are commonly white, light gray, or tan in color, making them relatively easy to distinguish from enclosing darker sediments. Light tephra layers are sometimes discolored to various shades of pink, reddish-brown, and brown on weathered surfaces. In sections containing fine-grained clastic sediments, where the tephra layers are more permeable than the enclosing sediments, they often have a dark orange-brown, cemented layer of limonite or goethite at the base of the layer and, less frequently, at the top.

Petrography

Microscopic petrographic examination of tephra has been widely used in tephra correlation. The most common objects of these studies are glass shards and mineral grains. Glass shards are

examined for their morphology, degree of hydration and superhydration (Roedder and Smith, 1965; Steen-McIntyre, 1975, 1981; Izett, 1981), and indices of refraction (Wilcox, 1962, 1965); mineral grains are examined for the species present, their abundance, habit, size, and refractive indices of the principal optic directions (Wilcox, 1959a, 1965; Izett and others, 1970; Sarna-Wojcicki, 1971; Davis, 1978; Juvigne, 1983).

Glass shards in tephra layers. Izett (1981), in an important general summary of upper Cenozoic silicic tephra layers in the western United States, has divided silicic tephra layers into three major types: W (white), G (gray), and dacitic types, primarily on the basis of iron and calcium content of the volcanic glass. Tephra layers of each of these three types have a number of characteristics in common, including glass-shard morphology, mineralogy, and chemical composition. Type G tephra layers are usually light gray in color, contain mostly bubble-wall shards with a large radius of curvature (Fig. 3a), and bubble-wall-junction shards (Fig. 3b). The type W tephra layers are usually white in color, and are composed dominantly of pumiceous shards (Figs. 3c, 4a, b). The dacitic type of tephra layers, generally less silicic in composition than the other two types, ranges more widely in color, from white to gray and various shades of tan or light brown, and generally consist of dominantly pumiceous shards, often with bubble-wall and bubble-wall junction shards as well. The dacitic type of tephra may also contain blocky, poorly vesiculated or solid-glass shards. As a broad generalization for Quaternary tephra in the western conterminous United States, the major source for type G tephra are the volcanic calderas in the vicinity of Yellowstone National Park, Wyoming and east-central Idaho; for the type W tephra, the Long Valley caldera of east-central California and the Jemez Mountains of northwestern New Mexico; and for the dacitic type, the Cascade Range of the Pacific Northwest. Most of the different shard shapes, however, can be found within each major Quaternary source area in the United States, and in some of the minor source areas as well (see Leudke and Smith, this volume; and Sarna-Wojcicki and others, this volume).

Pumiceous shards are of two main types: grains with irregular or equant outlines, containing spherical or oval vesicles (Fig. 4a), and elongated grains, with spindle-shaped, capsule-shaped, or tubular vesicles (Fig. 4b), the latter sometimes drawn out into very thin, long capillaries. The shape of the former type appears to be due to isotropic expansion, while the shape of the latter, to expansion within a laterally constrained space, such as a vent or conduit, where the pumice expanded anisotropically, or where turbulence resulted in anisotropic pressure distribution during movement of magma (for further or alternative interpretations see Fischer and Schmincke, 1984; Heiken and Wohletz, 1985; Rose and Chesner, 1987). Gradations between the two pumice types exist, and the degree of vesiculation between pumiceous shards also varies considerably.

The finest shards of tephra layers that are made up mostly of pumiceous shards are bubble-wall and bubble-wall-junction shards. Also, when pumiceous shards are crushed down to dis-

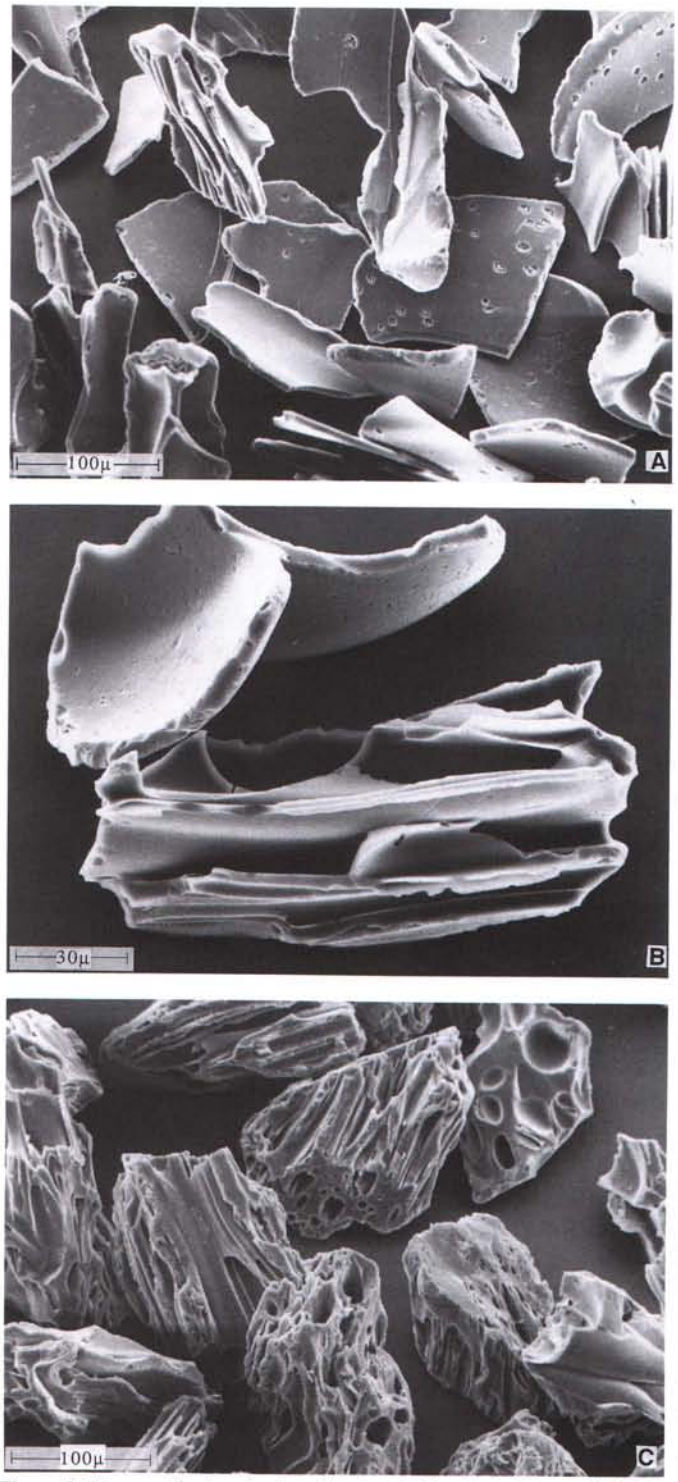


Figure 3. Shapes of volcanic glass shards: A. Mostly bubble-wall shards with large radius of curvature, and a few straight-ribbed bubble-wall-junction shards. Lava Creek B ash bed. Scanning electron microscope (SEM) microphotograph by Robert Oscarson, U.S.G.S. B. Bubble-wall-junction shards: cuspate bubble-wall-junction shard (above), straight-ribbed bubble-wall-junction shard (below). SEM microphotograph by Robert Oscarson, U.S.G.S. C. Pumiceous shards, moderately to poorly vesiculated. Glass Mountain G ash bed. SEM microphotograph by Robert Oscarson, U.S.G.S.

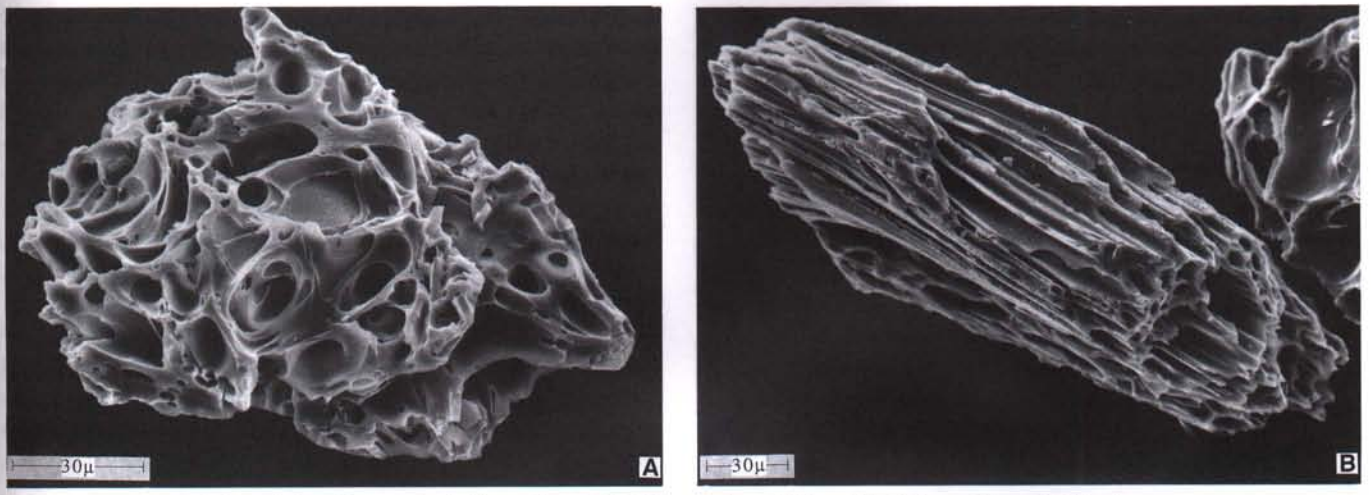


Figure 4. Pumiceous shards from May 18, 1980, eruption of Mount St. Helens, Wash. SEM microphotographs by Robert Oscarson, U.S.G.S. A. Irregularly shaped pumiceous shard with spherical to oval vesicles. B. Tubular pumiceous shard with elongated, tubular vesicles or "capillaries." This type of shard can have drawn-out, spindle-shaped vesicles or long, cylindrical vesicles.

crete, unvesiculated shards, the latter generally consist of bubble-wall and bubble-wall-junction shards. Thus, bubble-wall and bubble-wall-junction shards are the pieces of exploded or broken pumice clasts. The difference in the type G and type W shards is that in the case of the former, the bubbles probably grew larger, and their walls thinner, during eruption, ultimately exploding the pumice to form discrete, mostly unvesiculated shards; whereas in the case of the latter, the bubbles were smaller, and discrete small pumice shards were better preserved as individual grains. In the G-type shards, gas pressure within the vesicles must have been greater than the combination of viscosity and/or surface tension of the growing bubbles, but in the W-type shards, the pressure must have been less (Verhoogen, 1951; Fischer and Schmincke, 1984). At the most distal localities of type W ash beds, the particles are also largely bubble-wall and bubble-wall-junction shards, although they are generally smaller than corresponding particles in type G ash beds. The difference in shard types of the G, W, and dacitic tephra types is probably largely a result of differences in viscosity of the parent magmas, which in turn is probably a consequence of differences in the compositions of the magmas, including volatile content, and in the temperatures and pressures of eruption (see discussion in Izett, 1981; Fisher and Schmincke, 1984; Heiken and Wohletz, 1985).

Blocky shards are believed to be products of phreatoplinian eruptions, a consequence of the explosive interaction of magma and water (Heiken and Wohletz, 1985). Rarer are spherical bubbles (Fig. 5) completely enclosed in glass. Some of these, like highly vesiculated pumice containing sealed vesicles, float and are carried long distances by streams and ocean currents.

Characteristics of glass shards can divide tephra layers into several broad categories, but they will not allow identification to unit level. Shard morphology can be useful as a way of reducing the number of possibilities in considering the correlation of an unknown layer, but caution needs to be exercised before groups containing other shard morphologies are rejected as candidates for correlation. Wind and water transport may winnow shards so that only certain shard types predominate at a given locality.

Indices of refraction of glass shards have also been used by some workers to help characterize tephra layers (Wilcox, 1965). Indices of refraction of glass shards of a single tephra layer compose a range, rather than a single index. Previously, careful and rather painstaking work was required to determine this range accurately by using the Becke line method (Sarna-Wojcicki, 1971), resulting in considerable eyestrain because of the need to focus in and out of individual grain margins. The focal-masking technique of Cherkasov (Wilcox, 1962) is a more rapid and easy but equally accurate method for determining the range of refractive indices of glass shards. Many physical properties of volcanic glasses are related to their major-element compositions. Because of the narrow major-element compositional range of most silicic volcanic glasses, physical properties such as density and index of refraction also tend to be narrow; consequently, there is considerable overlap in the ranges of refractive indices between tephra layers. Again, though indices of refraction may suggest correlations, by themselves they will usually not provide definitive matches.

Mineralogy of tephra layers. Mineral characteristics have been used successfully to identify tephra layers and suites of tephra layers over distances of several hundred kilometers (Wilcox, 1965; Sarna-Wojcicki, 1971, 1976; Mullineaux and Crandell, 1986; Smith and others, 1977a, b), and over distances of as much as 1,000 km (Izett, 1981). Minerals commonly found in silicic tephra layers are feldspar (plagioclase and sanidine), quartz, biotite, hornblende, orthopyroxene (hypersthene), clinopyroxene (augite), ilmenite and magnetite, apatite, and zircon. Rarer minerals are allanite, chevkinite, and sphene. Anorthoclase, leucite,

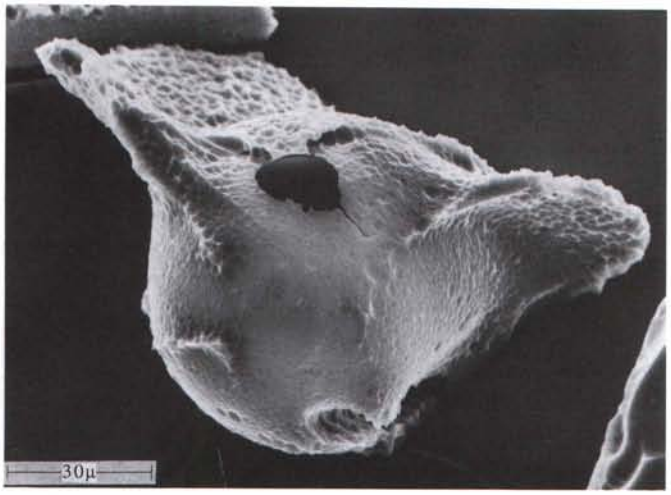


Figure 5. Droplet-shaped shard. Spherical shard enclosing a large vesicle that formed at the bubble-wall junction of several larger vesicles (now broken away). SEM microphotograph by Robert Oscarson, U.S.G.S.

and nepheline are also present in alkalic tephra, but to our knowledge not in Quaternary tephra of the United States. The type G and W tephra layers often contain plagioclase feldspar and sanidine, quartz, orthopyroxene, and hornblende, and sparser accessory minerals. Type G tephra layers also may contain rare chevkinite and fayalite (Izett and others, 1970). Type W layers may contain, in addition to the above, biotite and, rarely, allanite. Dacitic tephra layers usually contain plagioclase feldspar but no comagmatic quartz or sanidine. In addition, they may contain hornblende, orthopyroxene, clinopyroxene, and rarely, cummingtonite and biotite. Magnetite, ilmenite, apatite, and zircon may be present in all three types of tephra. Sphene, to our knowledge, has been described only in older, Tertiary tephra layers of the United States, such as the Peach Springs Tuff of Young and Anderson (1974; Gusa and others, 1987).

Comagmatic mineral grains usually make up a small fraction of the total volume of a tephra layer. Consequently, thin sections of tephra layers are not very useful for determining the presence and relative abundance of mineral species in a tephra sample because they do not contain a sufficiently representative number of mineral grains. We find it more effective to concentrate the mineral grains from the bulk sample, and examine them under a binocular or petrographic microscope—preferably the latter because more diagnostic properties can be determined. The usual procedure is to disaggregate and sieve the tephra layer to a convenient grain size that will allow separation of discrete mineral grains without crushing them. Because most mineral grains are heavier than glass shards, the mineral grains can be separated using mixtures of heavy and light liquids, such as methylene-iodide and acetone. The mineral grains can then be mounted in optic oils and examined under a microscope.

The presence and relative abundance of comagmatic minerals in tephra layers, especially the heavier ferromagnesian minerals, have been used with considerable success in identifying and mapping distributions of tephra layers from volcanic vents in the Cascade Range of the Pacific Northwest for distances of as much as 100 to 200 km downwind (Mullineaux, 1974; Mullineaux and others, 1978; Crandell and Mullineaux, 1978; Mullineaux and Crandell, 1981, 1986). These workers have been eminently successful in unravelling the complex late Quaternary tephrostratigraphy of Mount St. Helens and Mount Rainier, Washington, by employing a combination of field methods (lateral continuity, field characteristics, and stratigraphy), and mineralogy of the tephra layers, combined with tree-ring and radiocarbon dating.

The abundance of comagmatic mineral grains in tephra layers is unreliable for correlation over distances longer than about 10 to 50 km because mineral grains are sorted during transport by wind or water. At distal sites, most of the heavier mineral grains are absent or too small for convenient study, especially if tephra is contaminated with detrital minerals. Because of differences in density, grain size, and cleavage of comagmatic mineral grains, the relative abundances of minerals change with distance from source (Fig. 6; Sarna-Wojcicki and others, 1985a). Close to source, generally within several kilometers to several tens of kilometers, most airfall tephra layers are composed chiefly of pumice clasts, and the mineral species and their relative abundances are usually consistent from site to site for individual units. Farther away, at some critical distance from the source for each tephra layer[1], the layers consist mostly of small pumice lapilli or shards, together with a relatively high concentration of discrete mineral and lithic tephra grains that are smaller and denser than the pumice particles; the latter grains have settled from the air at about the same rate as the associated larger pumice clasts. Beyond this zone, tephra layers generally become progressively depleted in mineral and lithic grains, and the concentration of fine pumice and glass shards increases. This variation is also reflected in chemical analyses that have been made of bulk tephra samples at increasing distances from eruptive sources (Lerbekmo and Campbell, 1969; Sarna-Wojcicki and others, 1981a; see Fig. 7).

Indices of refraction of the principal optic directions of minerals have also been employed to characterize tephra layers (Wilcox, 1965; Izett and others, 1970; Mullineaux and others, 1978). Wilcox (1959a) recommends using the spindle stage for such determinations. This method is useful to distinguish between tephra layers that contain the same mineral suite but are suspected of being different in age or source.

Chemical techniques

As a consequence of new or more precise methods of chemical analysis, and the availability and improvement of analytical instrumentation, chemical methods of identifying tephra layers have become common. Precise chemical analyses of glass shards and/or mineral grains of tephra can provide virtual "fingerprints" by which tephra layers can be identified (Powers and Wilcox,

[1]For small eruptions, the critical distance will be short; for larger eruptions, longer.

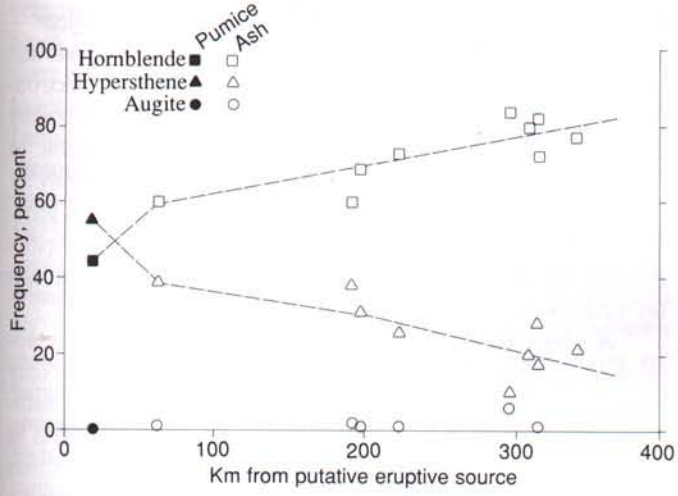


Figure 6. Downwind variation in relative amounts of hornblende, hypersthene, and augite in the Rockland ash bed. Distances are measured from Brokeoff Mountain near Lassen Peak, California, near the eruption source of the tephra. Sample at 295 km probably contains both detrital and comagmatic augite. Note that the abundance of hypersthene is greater than that of hornblende in the pumice clasts, but that the reverse is true in the ash. Hornblende becomes relatively enriched with distance from the source. From Sarna-Wojcicki and others (1985a).

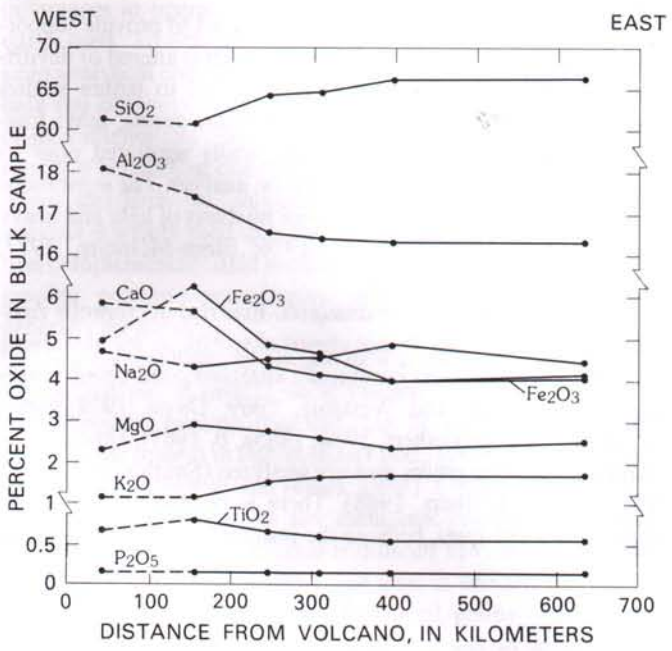


Figure 7. Downwind variation in composition of bulk samples of air-fall ash from the May 18, 1980 eruption of Mount St. Helens, Washington. The apparent increase in iron, magnesium, and titanium at about 160 km from the volcano probably corresponds to enrichment of the airfall ash with discrete grains of ferromagnesian minerals (hornblende, hypersthene, augite, magnetite, and ilmenite) at this distance. Wavelength-dispersive X-ray fluorescence analysis by V. G. Mossotti, Chris Heropolos, and J. F. Carr, U.S.G.S., Menlo Park. From Sarna-Wojcicki and others (1981a).

1964; Czamanske and Porter, 1965; Jack and Carmichael, 1969; Smith and Westgate, 1969; Izett and others, 1970, 1972, 1988; Westgate and others, 1970; Sarna-Wojcicki, 1971, 1976; Randle and others, 1971; Mehringer and others, 1977, 1984; Smith and others, 1977a, b; Davis, 1978, 1985; Izett, 1981; Smith and Leeman, 1982; Sarna-Wojcicki and others, 1979, 1983, 1984, 1985b, 1987). Chemical methods of tephra identification have become popular because a large number of chemical elements can be analyzed with high precision, results expressed in quantitative terms, and correlations expressed in probabilistic terms. However, application of chemical techniques alone to identify tephra layers is not entirely desirable because many correlation problems can be resolved by simpler and less expensive methods.

Analytical methods now commonly employed are electron microprobe, wavelength-dispersive and energy-dispersive x-ray fluorescence, and instrumental neutron-activation analyses; less used are atomic absorption and direct-current arc emission spectrography. Inductively coupled plasma atomic-emission spectrometry has good potential because of its high precision for many elements and small sample size requirements.

Although several workers have attempted to correlate tephra layers by chemical analysis of bulk tephra samples, and some have claimed success using this approach (Hahn and others, 1979), we advise caution here because of the selective effects of aeolian and hydraulic sorting of tephra components during transport, variations in purity of tephra layers (due to introduction of extraneous detritus) at different sites, and differences in preservation (degrees of hydration, devitrification, alteration, and cementation) from site to site. All of these could cause differences in chemical composition in the same tephra layer. A safer approach is to analyze one or more components (glass, minerals) of a tephra layer that are likely to have a relatively constant composition regardless of depositional environment or distance transported, or that may provide a systematic or characteristic trend, laterally or vertically, within a tephra layer.

Analysis of bulk samples may provide adequate data for correlation if: (1) widespread tephra layers have uniform proportions of the major constituents (glass, minerals, lithic fragments), or (2) if they are or were composed of essentially pure glass shards; and (3) if they are unaltered or have been altered or divitrified isochemically and to the same extent at all sites where they were studied. In our experience, these conditions seldom are met, and it is difficult to evaluate them before a study is undertaken. For modern and older eruptions that have been well documented, bulk tephra vary considerably in chemical character with distance from a source (Fig. 7; Sarna-Wojcicki and others, 1981a; Lerbekmo and Campbell, 1969). When separated components such as volcanic glass are analyzed, data scatter is reduced and resolution increased (Fig. 8; Sarna-Wojcicki, 1971).

Components used for chemical analyses of tephra are volcanic glass and comagmatic mineral grains. Because volcanic glass is usually ubiquitous and abundant at proximal, intermediate, and distal sites, and usually is the most chemically homogeneous phase, it is most often chosen for chemical analysis.

Comagmatic mineral grains may be analyzed to provide supportive data, or to supplant glass when the latter is altered or devitrified. Techniques of chemical analysis suited to tephra studies require that the components (glass, mineral grains, lithic fragments, and organic material) be physically separated prior to analysis, except for electron-microprobe analysis. The separations are usually done magnetically or with mixtures of light and heavy liquids (Sarna-Wojcicki, 1971, 1976; Steen-McIntyre, 1977; Froggatt and Gosson, 1982).

Electron-microprobe analysis. Electron-microprobe analysis is a rapid and easy-to-use chemical technique for identifying tephra layers. The most commonly analyzed component is volcanic glass (Smith and Westgate, 1969; Davis, 1978, 1985; Sarna-Wojcicki and others, 1984, 1985a, b, 1987), although comagmatic mineral grains also are analyzed (Smith and Leeman, 1982; Izett and others, 1988). There is no need for elaborate separation techniques, because the instrument can analyze small areas of the specimen—as small as one micrometer in diameter—although some workers sieve the samples and concentrate the glass to facilitate analysis. A further advantage of electron-microprobe analysis is that the grain-to-grain chemical variability of the glass shards can be determined. Thus, it is possible to determine whether a sample is homogeneous or randomly or systematically heterogeneous (whether shard compositions show a "shotgun" scatter or definite compositional trends) and whether discrete, multiple-compositional modes are present (see section on methods of data evaluation below).

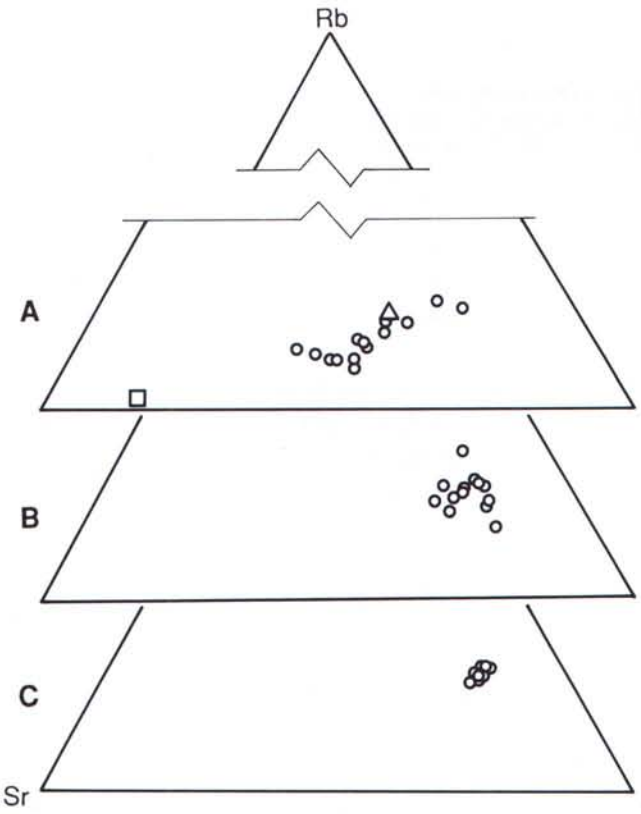


Figure 8. Decrease in compositional scatter (Rb, Sr, and Zr) of a tephra layer as a consequence of chemical treatment and physical separation of volcanic glass from other components of the layer. The water-deposited Lawlor Tuff (see Sarna-Wojcicki and others, this volume); data by wavelength-dispersive x-ray fluorescence. A, (circles) untreated whole-rock samples and untreated light fraction; (square) composition of plagioclase grains separated from tuff (plagioclase grains probably contain some zircon inclusions); (triangle) composition of sediments underlying tuff. B, whole-rock samples and light fraction treated with 10 percent HCl to remove soluble, ground-water-precipitated carbonate; C, magnetically and gravimetrically separated volcanic glass, treated with 10 percent HCl. After Sarna-Wojcicki, 1971.

A disadvantage of the electron-microprobe technique applied to analysis of silicic volcanic glass or minerals is that only major and a few minor elements can be determined with sufficient precision for chemical characterization. Major elements in silicic glasses that are commonly determined using the electron microprobe are Si, Al, Fe, Ca, K, and Na; the minor elements are Mg, Mn, Ti, Cl, P, and Ba. Of these elements, only about six to eight are usually in sufficient concentration in any particular glass to be useful in distinguishing tephra layers from each other. In rhyolitic glasses, the most useful are the major elements, and occasionally chlorine and barium. In dacitic to andesitic glasses, magnesium, titanium, and, occasionally, manganese are present in useful concentrations. For suites of chemically similar tephra layers erupted from the same volcanic field or vent, electron-microprobe analysis may not be adequate to distinguish among the layers. This limitation, however, varies with the specific volcanic field or vent under investigation. Successive eruptions from small magma chambers, such as those in the Cascade Range of the Pacific Northwest, result in greater compositional contrasts among successively erupted tephra layers, than eruptions from large magma systems. Large systems such as the Yellowstone National Park volcanic field and the Long Valley caldera have produced large magma bodies that have persisted for long periods of time (on the order of 10^5 to 10^6 yrs), and have been tapped repeatedly by successive eruptions. Chemical techniques sensitive for minor and trace elements are often required to distinguish among tephra layers from large magma systems.

Presence of water and other fluids such as carbon dioxide in the glass complicates electron-microprobe analyses of volcanic glasses. Such fluids generally cannot be analyzed by electron-microprobe, because they are composed of light elements that are not measurable with most standard electron microprobes. Electron-microprobe analyses for cations are usually recorded and reported as the weight-percent of their respective oxides. The latter, together with the anions, are summed, and should total close to 100 percent for accurately analyzed samples. Most natural glasses, particularly those older than historic, however, usually total somewhat less than 100 percent, from about 98 to as low as about 85 percent. This deficit is due largely to the presence of water in the glass. Natural glasses generally contain little water (0 to 3 percent) shortly after eruption (Sarna-Wojcicki and others, 1981b), but soon begin to hydrate with exposure to water or water vapor. Glass shards may become completely hydrated within 10,000 years after eruption, acquiring as much as 5 per-

cent water (Ross and Smith, 1955; Friedman and Smith, 1960; Steen and Fryxell, 1965). Also, finer glass shards appear to hydrate more rapidly, as do more deeply buried shards. Subsequent to total hydration of the glass, more water may be absorbed into pumiceous shards by gradual filling of their vesicles. This phenomenon, "superhydration," has been used as a semiquantitative method of determining ages of tephra layers (Steen-McIntyre, 1975), with mixed success, perhaps because hydration is not solely a function of age. Nevertheless, cation-oxide values obtained from electron microprobe analysis can be normalized to 100 percent, on a fluid-free basis, so that differences between more and less hydrated samples of the same tephra layer are minimized. Oxide totals of volcanic glasses that are lower than about 95 percent appear to result from cation exchange, where hydronium ions have replaced the more mobile elements in volcanic glass, particularly the alkalies (Cerling and others, 1985; Sarna-Wojcicki and others, 1985b). Such replacement is most common in arid or semiarid regions, where isotropic glasses with totals as low as 85 percent have been sampled. Ionic replacement under these conditions may be facilitated by advancing and retreating hydration fronts in the glass shards, corresponding to alternately wet and dry periods. Recalculations of oxide concentrations of such tephra layers are probably not valid, unless a concomitant correction for alkali loss can be made. Recalculated totals of samples with large deficits in their totals result in silica values that are uncharacteristically high compared to those of chemically similar, younger tephra erupted from the same volcanic provinces (F. H. Brown, personal communication, 1989).

Because of alkali mobility, the alkali concentrations in volcanic glasses older than several thousand years may be considerably different than what they were at the time of deposition. Alkali concentrations may differ from site to site for the same layer, depending on environment of deposition (Cerling and others, 1985). For Quaternary tephra layers within the conterminous United States, it has been our experience that the following ranges in alkali concentrations are common for tephra in rhyolitic to dacitic glasses (SiO_2 about 78 to 65 percent): sodium, 3 to 5 percent, and potassium, 2 to 5 percent. Severe leaching or enrichment of alkalies should be suspected where the alkalies fall below or above these limits for these types of glasses. For upper Cenozoic silicic tephra within the western conterminous United States, alteration from the original composition of volcanic glasses is likely where the recalculated silica values are above 78 percent, and definitely when the glass is anisotropic.

Electron-microprobe analysis of sodium in volcanic glass is complicated because sodium becomes mobile under the electron beam and tends to migrate away from the focal zone, resulting in lower values than those determined by other methods. Means of compensating for this effect are to defocus the beam and move the sample mount continually beneath the beam (Smith and Westgate, 1969), or to scan the focused beam over the sample mount (Sarna-Wojcicki and others, 1984; C. E. Meyer, personal communication, 1983).

Variations in electron-microprobe analysis may be due to differences in operator technique, instrumentation, or the standards used. To achieve maximum precision, it is preferable to keep analytical conditions as uniform as possible. Inferences from data sets obtained by different analysts using different standards or instrumentation may be suspect. However, factors can be derived for converting one data set to another from mutually analyzed standards or samples. Although electron-microprobe analysis is widely used in tephrochronology, most workers agree that complementary data such as comprehensive studies of stratigraphic position, petrography, and trace-element chemistry generally are needed.

Concentrations of minor and trace elements in glass. Precise analysis of natural silicic volcanic glasses for minor and trace elements requires that the glass be separated from other components present in tephra (Eastwood, 1969; Sarna-Wojcicki, 1971; Sarna-Wojcicki and others, 1984). Large phenocrysts and lithic fragments as well as any authigenic cements must be removed before analysis. It often is difficult to remove all phenocrysts from glass, particularly if the glass is vesiculated, because pumiceous glass shards buoy up mineral grains embedded in them, and such particles can float, hover, or sink in heavy liquids, depending on the degree of vesiculation of the pumice and the size and density of the embedded mineral grains. Using finer size fractions to separate fine phenocrysts from glass shards may work, but in the case of microphenocrysts or microlites it may be impossible to remove the crystalline material completely. In such instances, it is important that the degree of separation is consistent for samples of putative correlative tephra layers collected from different sites. Care must also be taken to avoid the introduction of artifacts into the sample separate, for example, by contamination with foreign materials during disaggregation or other processing (as, e.g., by use of metal crushers or metal screens), or by use of techniques that would change the composition of the glass by selectively removing or concentrating part of the normal compositional spectrum of the glass shards.

X-ray fluorescence analysis. X-ray fluorescence (XRF) analysis has been applied to studies of Quaternary tephra layers in the United States by Jack and Carmichael (1968), Sarna-Wojcicki (1971), and Sarna-Wojcicki and others (1979), among others. Both wavelength-dispersive (Taggart and others, 1987) and energy-dispersive (Johnson and King, 1987) methods can be used.

Volcanic glass is favored for this type of analysis because pure crystalline material is much more difficult to separate in tephra samples. A major disadvantage of XRF analysis is that about 0.5 to 3 g of pure glass must be obtained from tephra samples. Elements in volcanic glass that are commonly analyzed by XRF for purposes of correlation are potassium, calcium, titanium, manganese, iron, rubidium, strontium, yttrium, zirconium, and niobium. Occasionally barium, lanthanum, and cerium are also determined in silicic tephra, and chromium, cobalt, nickel, copper, and zinc in more mafic tephra. Potassium, calcium, titanium, manganese, and iron are also determined in electron-microprobe analysis, but titanium and manganese are determined

with higher precision by XRF. The major- and minor-element concentrations determined by electron microprobe are not strictly comparable to those obtained by XRF because the former are spot samples, usually on clear, isotropic, internal surfaces of single glass shards. By contrast, XRF analyses are made on a glass separate consisting of many shards, which may also contain some microphenocrysts and microlites as well as secondary filling in vesicles of pumiceous shards (e.g., calcite or gypsum) that cannot be removed during sample preparation.

Instrumental neutron activation analysis. Instrumental neutron activation (INA) analysis is the most sensitive and precise chemical technique for the characterization of tephra currently in use, particularly for chemical "fingerprinting" of volcanic glass. About 40 major, minor, and trace elements can be determined by this method, of which about 20 are useful in correlation of silicic volcanic glasses. These elements are particularly useful in INA because of three factors, all of which are related: the elements are present in sufficient concentrations in volcanic glass to be detected, their detection limits are sufficiently low relative to their concentration in the glass so that good precisions can be obtained, and the sensitivity for them by INA is high. These elements are (in order of increasing atomic number) scandium, manganese, iron, zinc, rubidium, cesium, and barium; the rare-earth elements lanthanum, cerium, neodymium, samarium, europium, terbium, dysprosium, ytterbium, and lutecium; and the heavy trace metals hafnium, tantalum, thorium, and uranium. Elements that are also routinely determined by this technique with relatively high precision are sodium, aluminum, and potassium. Zirconium, molybdenum, antimony, and tungsten are marginally useful. In glasses of the more basic tephra layers, vanadium, chromium, and cobalt may be used. Also, cross checks on many of the elements used in EMA and XRF can be made by this technique.

Analysis of volcanic glass by INA usually provides unique fingerprints for tephra layers. For example, the Lava Creek B ash bed (0.62 Ma; correlative of the Lava Creek Tuff) and the Huckleberry ridge ash bed (about 2.0 Ma; correlative of the Huckleberry Ridge Tuff) are chemically very similar, and are distinguished with difficulty and only marginal confidence by EMA, XRF, and petrography. Analysis of their volcanic glasses by INA, however, reveals some large differences in several elements (Fig. 9). For scandium, the means of the averages of the two tephra layers are separated by ten standard deviations, significantly different at a high level of confidence.

The disadvantages of INA analysis for tephra are: (1) as with XRF, the volcanic glass must be carefully separated from the rest of the sample before analysis; about 0.2 to 1 g of pure glass are required; (2) the sample must be irradiated in a nuclear reactor, and consequently handled with considerable care; (3) time for completion of analysis is long (three to four months) because certain radioactive isotopes must decay before others can be measured; (4) there is considerable demand for this technique, resulting in sample backlogs at the few laboratories where this type of analysis is conducted; and (5) the analyses are expensive.

Most tephra correlation problems can be resolved by some combination of other techniques, without resorting to INA. The few percent that cannot, can almost surely be resolved by INA. Inductively coupled plasma spetrographic analysis holds considerable promise for chemical characterization of tephra, and may eventually complement or even supplant INA.

A considerable amount of information can be obtained by analyzing volcanic glass by EMA, XRF, and INA, even when the same elements are analyzed. Differences in composition provide us with information regarding crystallization and depositional histories of tephra and, most importantly, allow us to evaluate the different elements with respect to reliability as criteria for correlation.

Chemical techniques such as EMA, XRF, and INA are particularly appropriate for large data bases used in the development of regional chronostratigraphic frameworks. The quantitative results of these techniques lend themselves readily to computer data storage and manipulation.

The use of chemical characterization for identification and correlation of tephra layers can result in misidentification because the compositional range of silicic tephra is rather narrow, because differences among tephra layers erupted from the same volcanic field or vent may be small, or because the parent magma of individual eruptions may be compositionally zoned, resulting in compositional overlap between successive tephra layers. Nevertheless, when the entire battery of techniques available to the tephrochronologist is used, we find that miscorrelations are avoided.

Factors controlling the chemical characteristics of volcanic glasses

Volcanic glasses represent the rapidly quenched liquidus of magmas—that part of the magma that was fluid before eruption—minus the volatile gases that escaped during eruption. Consequently, the chemical compositions of volcanic glasses and the differences among them are of interest to us not only because they can provide correlation and age control, but also because they may tell us something about the origin of the magmas and the source rocks from which they were formed.

Differences in chemical compositions of volcanic glasses appear to be controlled by several factors. The largest differences observed in chemical compositions of tephra layers are between silicic and basaltic glasses, even for tephra derived from the same volcanic province or field (Sarna-Wojcicki, 1976). Thus, differences in the parent materials of which magmas are formed, or long-term, fundamental magmatic differentiation processes, appear to play a dominant role in determining the chemical composition of volcanic glasses.

Among silicic glasses (SiO_2 contents of about 64 to 78 percent), greatest differences are observed among tephra layers derived from different tectonic provinces. Thus, the plate-tectonic setting of the volcanic source area, and the related factors of source-rock composition, depth and temperature of magma formation and crystallization, the composition of the rocks hosting

the magma bodies, and the history of magma differentiation and crystallization, all probably play a role in determining the composition of the erupted volcanic glass.

A detailed discussion of the similarities and differences among silicic tephra erupted from the major Neogene source areas in the western United States, and the reasons for these differences, is beyond the scope of this report. In brief, tephra erupted from the Cascade Range is primitive in composition, being depleted in lithophile elements (Fig. 9). Magmas formed within this province are derived by differentiation of basaltic oceanic crust or poly-cyclic basaltic to intermediate volcanic and sedimentary rocks within a convergent plate margin, above a subduction zone. A crude north-to-south enrichment of lithophile elements is observed within this province (Fig. 9). The Long Valley–Mono Glass Mountain volcanic province of east-central California and the Jemez Mountains volcanic province of northwestern New Mexico are situated within zones of crustal spreading adjacent to cratonic rocks of intermediate and silicic compositions, where upward intrusion of basaltic magmas from the mantle interacts with the more silicic cratonic rocks, forming long-lived, large-volume silicic magma bodies at shallow depth in the upper crust. Tephra from these sources is enriched in lithophile elements relative to that of the Cascade Range (Fig. 9). Equally enriched in lithophile elements is silicic tephra derived from the Yellowstone National Park area of northwest Wyoming and east-central Idaho. Large magma bodies were formed within this area as a result of the passage of the North American continental plate over a mantle hot spot, causing upward intrusion of basaltic rocks from the mantle into intermediate and silicic cratonic rocks at moderate to high levels in the continental crust. Differences in concentrations of the major, minor, and trace elements among silicic glasses from these latter three provinces are nevertheless apparent, as are the similarities among tephra layers within the provinces.

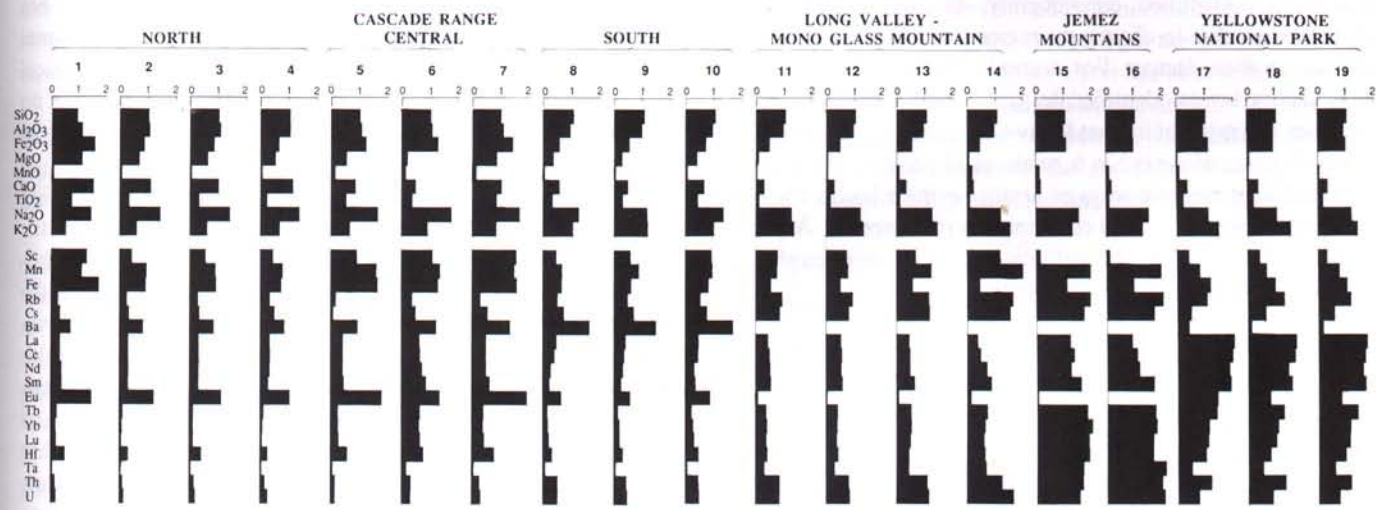


Figure 9. Histograms comparing the chemical compositions of volcanic glasses of tephra layers from the four major late Pliocene and Quaternary source areas in the conterminous United States. Values plotted are concentrations of oxides and elements determined by electron-microprobe (EMA) and neutron activation (INA) analysis, as a ratio to the concentration of the same oxides and elements in an artificial numerical standard that represents the approximate median of the range for each oxide or element. For discussion of ages of tephra layers, see text and Sarna-Wojcicki and others, Chapter 6, this volume.

Cascade Range (Washington, Oregon, and northeast California; north to south)

1. Mount St. Helens, May 18, 1980, layer, Washington.
2. Mount St. Helens Ye layer, Washington; about 3,400 B.P.
3. Mount St. Helens Sg Layer, Washington; about 13,000 B.P.
4. Mount St. Helens Cw layer, Washington; about 35,000 B.P.
5. Rio Dell ash bed of Sarna-Wojcicki and others (1982), specific source unknown; about 1.45 Ma.
6. Loleta ash bed of Sarna-Wojcicki and others (1982) (= Bend Pumice of Taylor, 1981; Bend, Oregon); Humboldt County, California; about 0.3 to 0.4 Ma.
7. Mazama ash bed, Crater Lake, Oregon, about 6,850 B.P.
8. Rockland ash bed, Lassen Peak area, California; about 0.4 Ma.
9. Ishi Tuff Member (of the Tuscan Formation), southern Cascade Range, California; about 2.5 Ma.
10. Nomlaki Tuff Member (of the Tehama and Tuscan Formations), southern Cascade Range, California; about 3.4 Ma.

Long Valley—Mono Glass Mountain area (east-central California)

11. Bishop ash bed; about 0.74 Ma.
12. Glass Mountain D ash bed; about 0.9 Ma.
13. Bailey ash bed of Izett (1981); about 1.2 Ma.
14. Tuff of Taylor Canyon; about 2.0 to 2.1 Ma.

Jemez Mountains (New Mexico)

15. Tsankawi pumice bed; about 1.12 Ma.
16. Guaje pumice bed; about 1.45 Ma.

Yellowstone National Park area (Wyoming and Idaho)

17. Huckleberry Ridge ash bed, about 1.98 Ma.
18. Mesa Falls ash bed, about 1.27 Ma.
19. Lava Creek B ash bed, about 0.62 Ma.

Stratigraphic sequence

An important criterion for increasing confidence in correlations of sets of tephra layers is their relative position within stratigraphic sequences. This criterion must be combined with one or more criteria used in identification of tephra layers (e.g., field, petrographic, or chemical characteristics). The basic idea is that if the same stratigraphic sequence of tephra layers, as defined by physical or chemical criteria, is found at two or more localities, then the probability is greater than the respective tephra layers of the sequence correlate among these localities. This is true only if it can be shown that such sequences did not form by chance or by cyclic differentiation processes at different times in the past.

Considering chance, the number of possible combinations of a sequence increases with the number of layers in the sequence, the number of locations where the sequence is found, and the number of independent variables by which the members of the sequence are identified; consequently, the probability that such sequences are due to chance decreases correspondingly with the increase in these factors. For example, if the same sequence of three tephra layers, identified by one variable, is found at two localities, the probability that the two sequences are the same as a result of chance alone is 1 in 6, or about 17 percent, because there are 6 different possible ways of arranging these layers when the sequence at one site is held constant as a reference set. A general relation describing the probability that such stratigraphic sequences result from chance is given by:

$$p = \frac{1}{(n!)^{sf-1}}$$

where p = the probability that sequence results from chance; n = number of tephra layers in sequence, s = number of localities at which sequence is found, and f = the number of independent variables, or factors, that discriminate among the tephra layers in the sequence. Thus, if three tephra layers are found at three localities in the same sequence, and each is identified by three independent variables, each of which distinguishes all three, the probability that such a situation resulted from chance alone is about 1.68×10^{-6}, or one in 1,680,000.

The other possibility, that a sequence of tephra layers with the same set of characteristics can be duplicated at different times by a cyclic process, can be eliminated on the basis of historical observations of the eruptive behavior of volcanoes, and a survey of sequences of tephra layers whose age ranges are known. Although there is evidence for some gross cyclicity in the chemical composition of tephra layers in some tephra sequences erupted from large magma chambers, such as those from the Valles and Toledo calderas of the Jemez Mountains, New Mexico, and the Long Valley caldera of east-central California (Smith, 1979), the cycles are never ideally replicated in tephra sequences. If there is some degree of cyclicity in the eruptive products of magmatic systems, there also appears to be an even larger measure of randomness in the timing between successive eruptions from the same source, and in the composition of the products erupted—and even more so when several different sources are considered together. Lastly, of all the tephra sequences that we have studied to date for which there are independent, reliable ages, we have not seen eruptive sequences, as determined by the glass composition of tephra layers, replicated through time.

Because chance and cyclicity are virtually eliminated as probable causes of the repetition of tephra sequences at different localities, identification of characteristic sequences becomes strong evidence supporting correlation of the tephra layers in these sequences.

Methods of data evaluation

Methods of evaluating tephrochronological data and documenting correlations have ranged in the scientific literature from blunt assertions that tephra layers correlate, without presentation of convincing supporting data, to sophisticated quantitative statistical analysis of tephra characteristics. The former approach has been inadvertently encouraged by the practice of some journal editors of discouraging inclusion of basic numerical analytical data in order to save space. In such instances, the reader has no way of evaluating the validity of the data or the appropriateness of conclusions regarding correlation.

Three major points need to be addressed in the presentation and evaluation of quantitative tephrochronological data for the purpose of correlation of a tephra layer: (1) the internal variability of the layer needs to be defined with respect to each of the parameters used in characterization; (2) the match between correlated tephra samples needs to be compared with respect to this internal variability and with respect to the analytical error determined for each of the parameters used in characterization; and (3) the differences between the tephra layer and other tephra layers (i.e., those that are known to be of different age on the basis of stratigraphic or other data) need to be evaluated with respect to the internal variabilities of each tephra layer and the analytical errors of each of the characterizing parameters. In other words, it is not sufficient to say that several samples of a tephra layer are the same within the error of analysis of the variables used in characterization, and are thus correlative. It must also be shown that these samples are significantly different from other tephra layers of demonstrably different age.

The most effective test of correlation data is obtained from the combination of stratigraphic continuity and superposition. From stratigraphic continuity of a tephra layer we can determine its internal variability, and select those characterizing parameters that appear to be the most precise for the tephra layer. From a sequence of superposed tephra layers, we can determine which measured parameters show the most contrast and differentiate most systematically between the layers, and determine if differences are statistically significant at the level of confidence that we seek to achieve. Failure to address these points often leaves the basic question of correlation unresolved. Correlation can also be documented by other criteria, such as other age-dating techniques (isotopic, biostratigraphic, magnetostratigraphic), but this dimin-

ishes the usefulness of a tephra layer as an independent and precise test of other dating techniques.

Evaluation of data often is aided by graphic plots, such as binary and ternary diagrams, and histograms of the characterizing parameters. These also are effective in visual presentation of the data. We have found it convenient to show histograms as ratios to an analyzed standard of a silicic rock, such as U.S.G.S. G-1 (Fig. 10), or an artificial numerical standard that represents the approximate midpoint of the range of concentrations for each element used in a comparison (Fig. 9). Such plots make is possible to present differences and similarities among samples within a range that can be shown effectively on a histogram.

For a more quantitative comparison of the compositions of volcanic glasses, a mathematical comparison procedure that we have found useful is the similarity coefficient (Borchardt and others, 1972; Borchardt, 1974; Sarna-Wojcicki, 1976; Sarna-Wojcicki and others, 1984, 1985a, 1987; Davis, 1985). This comparison adapts readily to a computer program, but a shortcoming is that it cannot be used to predict probabilities of correlations, because it does not have a normal distribution. A variation of the similarity coefficient, termed RATIONAL (Sarna-Wojcicki and others, 1984), however, does have a normal distribution, and the standard deviation of RATIONAL can be used for a probabilistic assessment of correlations.

For suites of tephra layers that are similar in physical and chemical characteristics, multivariate statistical analysis may be necessary to determine whether samples are significantly different or not. Many of the physical and chemical parameters used in characterizing tephra layers are mutually dependent. For example, iron, magnesium, calcium, titanium, scandium, and europium, and the refractive indices of glass, are often positively correlated in genetically related suites of tephra. The above parameters generally correlate negatively with silica, the alkalies, and many of the lithophile trace elements, such as the rare-earth elements (except europium), and with hafnium, tantalum, thorium, and uranium. Consequently, it may be important to perform a factor analysis on the data set to determine the codependence of these parameters on each other, and to derive a set of independent (orthogonal) variables that can be used in statistical analysis. One such statistical approach is the cluster analysis of Parks (1970; see Sarna-Wojcicki, 1976; and Sarna-Wojcicki and others, 1984). Like the similarity coefficient, this technique can be readily adapted to a computer program that allows rapid comparison of a large data base.

An important adjunct to both the similarity coefficient and cluster analysis programs is the dendrogram, which shows the degrees of similarity among samples using the particular mathematical or statistical measure of similarity used in the program (similarity coefficient, distance function, correlation coefficient, etc.; Fig. 11a, b). A dendrogram provides in two dimensions a visual representation of the multivariate relations of a sample population. In addition to supporting specific correlations, such diagrams can provide information on genetic relations and provenance of tephra layers. For other statistical techniques that can be employed in the evaluation of tephrochronological data, see Davis (1973).

NUMERICAL AGE CONTROL

The age of tephra layers may be determined directly, by analysis of their primary, comagmatic components, or indirectly, by age determinations of underlying and overlying levels, or by foreign material (e.g., carbon, or fossil) incorporated into the tephra layer during deposition. A wide spectrum of dating methods is available to those studying Quaternary deposits, and most of these are applicable to the dating of tephra layers (see Rosholt and others, this volume).

Conventional potassium-argon dating

Potassium-argon (K-Ar) analysis of Quaternary tephra layers works if detrital or accidental contamination can be avoided, or if such contamination is removed from the phases to be analyzed, and if sufficient radiogenic argon has accumulated in such phases that a precise determination can be made.

Because widespread tephra layers, be they airfall or flow, are products of explosive eruptions, the possibility of entraining "accidental" older rock or mineral grains from the roof or wall rock

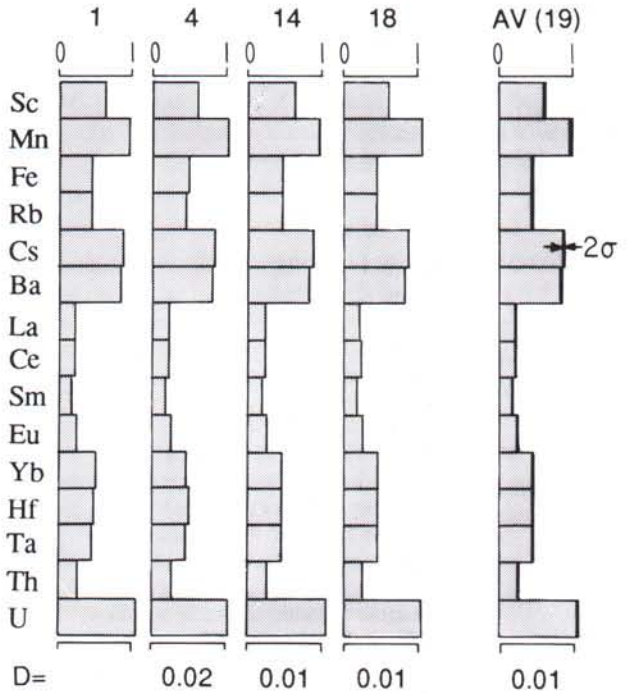


Figure 10. Histograms from instrumental neutron activation analysis showing abundances of major, minor, and trace elements in volcanic glass of the 0.4-Ma Rockland ash bed. Values shown are ratios of concentrations of elements in glass of tephra layers to concentrations of same elements in U.S. Geological Survey rock standard G-1. First four samples from the left (1, 4, 14, and 18) are of the Rockland tephra layer. AV(19) is an average of 19 analyses of samples of this layer; the bold vertical line at the right end of each bar in this histogram represents a range of two standard deviations from the average of 19 analyses.

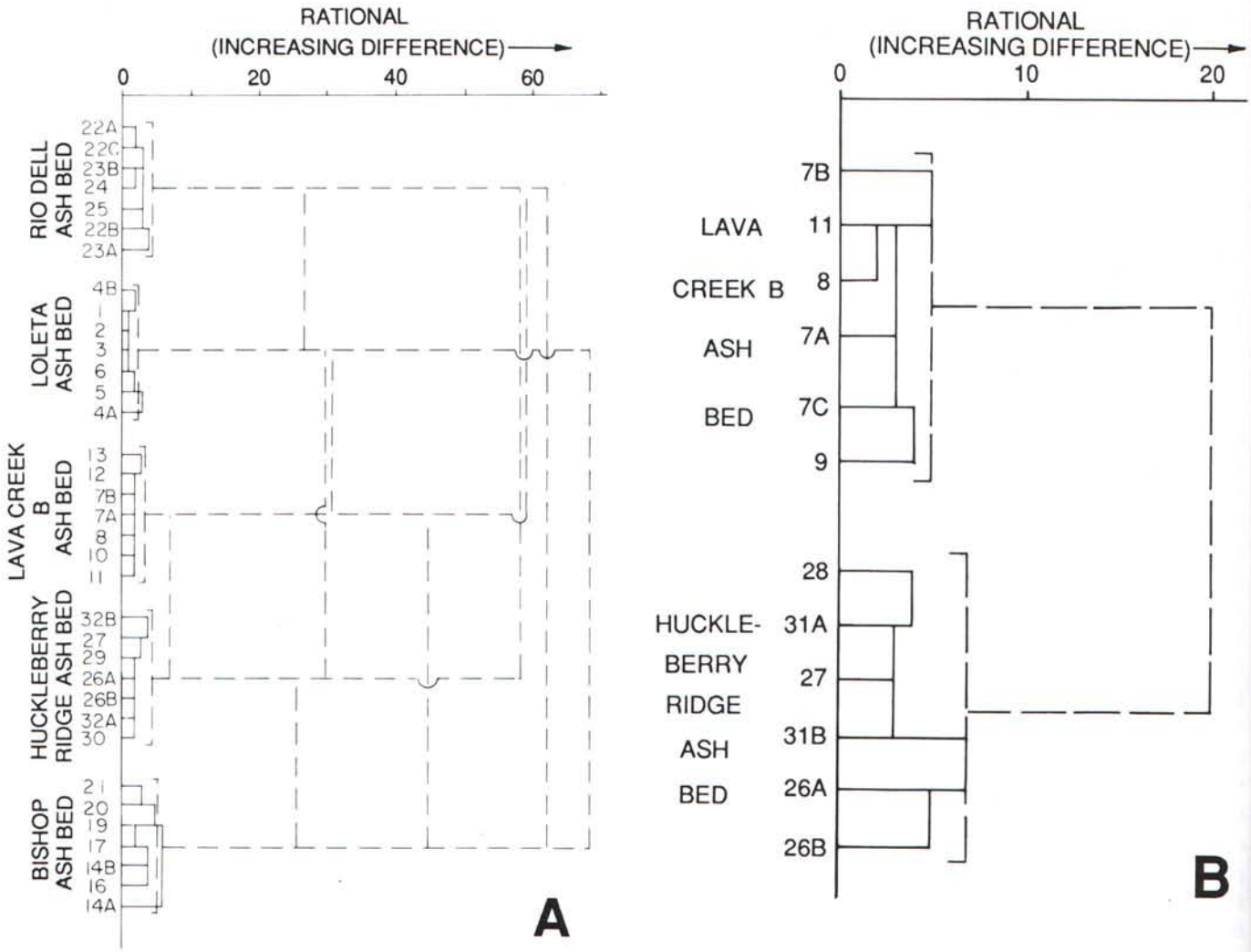


Figure 11. A. Dendrogram showing relation between compositions of sample pairs and sample groups of volcanic glasses, based on electron microprobe analyses, using the average of the standard deviations of ratios of element concentrations (RATIONAL; Sarna-Wojcicki and others, 1987). RATIONAL values are measures of dispersion from the limiting value of zero, which represents a perfect match. Samples are linked at lowest RATIONAL (×100) values for individual sample pairs (solid lines) and at average values for sample groups (dashed lines). The linkages are drawn at the appropriate RATIONAL values as indicated by the scale at the top of the figure. For instance, samples 22A and 22C of the Rio Dell ash bed are linked at a value of 2. The average of the Rio Dell ash bed samples is linked with the average of the Loleta ash bed samples at a value of about 26, the average intergroup value for the Rio Dell and Loleta ash beds. The Rio Dell ash bed differs much more from the other ash beds, and its similarity to the Loleta ash bed reflects their common provenance from the same volcanic province, the central Cascade Range. Also note the low RATIONAL value linking the Lava Creek B and Huckleberry Ridge ash beds, which reflects their similarity and common provenance from the same volcanic source in the Yellowstone National Park area. After Sarna-Wojcicki and others, 1987. B. Dendrogram showing relation between sample pairs of the Lava Creek B and Huckleberry Ridge ash beds, and between the two groups of samples, based on instrumental neutron activation analyses, using the average of the standard derivations of ratios of element concentrations (RATIONAL). Explanation of symbols same as for A. After Sarna-Wojcicki and others, 1987.

of the magma chamber, from conduit walls, or from rocks overlying the vent is very real. Also, tephra becomes contaminated by older detrital sediment during transport and deposition in air or water. For this reason, conventional K-Ar analysis of bulk tephra samples is not recommended. Furthermore, we recommend against conventional K-Ar analysis of mineral separates from fine-grained, distal airfall or reworked tephra layers. Because conventional K-Ar requires analysis of a sample composed of many grains, the possibility of some of these being detrital or accidental is high. Conventional K-Ar analysis of tephra layers works best on minerals separated from coarse pumice clasts, which occur only close to the eruptive source.

For Quaternary tephra layers, there is also the analytical problem of precision in both conventional and other types of K-Ar analyses. For young tephra layers, the amount of radiogenic argon accumulated in minerals and glass is small relative to the amount of atmospheric argon present during analysis (Dalrymple and Lanphere, 1969). Thus, the signal-to-noise ratio is small compared to that obtained in older rocks. To provide an adequate signal-to-noise ratio, a larger separate is commonly required compared to that for older tephra—statistically increasing the chance of contamination because of the larger number of particles required for analysis.

The best phases for dating of Quaternary rocks are usually those that contain the highest concentrations of potassium, to provide a correspondingly high concentration of radiogenic argon that is derived from the potassium. For tephra of Quaternary age in the United States, sanidine is commonly the best mineral for analysis; biotite, hornblende, and plagioclase feldspar have also been used successfully. Outside of the United States, Quaternary tephra layers erupted from alkalic provinces may contain leucite, nepheline, or anorthoclase, minerals that have high concentrations of potassium, and are thus excellent material for dating. K-Ar analyses of volcanic glass shards have generally proved unreliable for tephra layers—being either too young or too old—when tested against K-Ar ages of mineral phases from the same units, or when compared against other reliable numerical or stratigraphic age control. Glass shards may retain excess radiogenic argon, or they may lose radiogenic argon during hydration or alteration. Post-depositional loss or gain of potassium in glass shards also introduces an error into the K-Ar age calculations, for which an initial potassium content is assumed based on measurements of the concentration present in the glass. K-Ar analyses of obsidian fragments present in tephra layers, however, have often provided ages that are roughly consistent with other independent age evidence. Although obsidian fragments in Plinian tephra layers are probably most xenolithic, and consequently older than the associated tephra layers, the age differences between the obsidians and tephra layers that contain them may often be small.

Because of the analytical limitations of precision, compounded by problems of contamination, conventional K-Ar analysis under the best conditions is usually limited to units older than about several tens of thousands of years, and commonly to units older than about several hundred thousand years. Because of these limitations, there has been until lately a virtual "gap" in adequate numerical age control for Upper Pleistocene sediments and rocks in the age range from about 40 ka, roughly the practical maximum-age limit of conventional radiocarbon dating, to about 500 ka, roughly the practical age limit of the conventional K-Ar method. Within about the last 20 yrs, however, new or experimental dating techniques such as amino-acid racemization, uranium-series and uranium-trend, thermoluminescence, and electron-spin resonance analyses have been developed that are beginning to bridge this age gap (see Rosholt and others, this volume). Moreover, new improvements in established isotopic techniques, such as mass-accelerator radiocarbon analysis and single-grain laser-fusion $^{40}Ar/^{39}Ar$ K-Ar analysis, are providing new age calibration in this previously poorly controlled time interval.

Laser-fusion $^{40}Ar/^{39}Ar$ potassium-argon analysis

Laser-fusion potassium-argon analysis is a relatively new development in K-Ar dating (York and others, 1981; Dalrymple, 1989). Mineral grains to be dated are irradiated in a nuclear reactor, as in $^{40}Ar/^{39}Ar$ K-Ar dating of bulk separates (Lanphere and Dalrymple, 1971). Mineral grains or sets of a few grains are then fused with a continuous monochromatic laser under a microscope, in a sealed vessel, and the extracted gas is analyzed in a mass spectrometer. The advantage of this method is that ages of individual grains or sets of a few grains can be obtained fairly rapidly, and the dispersion of values examined to determine whether detrital or accidental contamination is present in the mineral separate.

Although the limits of this technique are not yet defined, many of the initial results on early to middle Quaternary tephra samples are in good agreement with ages determined by other techniques (Sarna-Wojcicki and Meyer, unpublished data, 1989). The laser-fusion K-Ar technique promises to provide a quantum leap to geochronologic studies of Quaternary deposits. Tephrostratigraphy, however, will always remain an important control to this and other Quaternary chronostratigraphic techniques, and will remain essential to studies of provenance and correlation of tephra layers, eruption frequencies, and evolution of silicic magmas.

Fission-track dating of zircons and glass shards of tephra layers

Besides K-Ar analysis, the only other direct-dating technique that is commonly used for dating of tephra layers is fission-track analysis (see Rosholt and others, Chapter 3, this volume). The advantage of this technique, as in laser-fusion K-Ar analysis, is that individual grains can be dated, so that the possibility of xenocrystic or detrital contamination can be evaluated and results from contaminated phases can often be eliminated. The most common phases in tephra dated by this method are zircon and

glass shards. Fission-track ages of glass shards are often younger than ages determined on coexisting zircons or ages determined by the K-Ar technique, due to fading or appealing of fossil tracks with time or at elevated temperatures (Naeser and others, 1980). Application of the plateau annealing technique to fission-track dating of glass shards, however, makes it possible to correct for track fading (Storzer and Poupeau, 1973; Naeser and others, 1980; Westgate, 1989).

Other direct and indirect dating methods

Other direct dating methods currently employed in dating Quaternary tephra are hydration, thermoluminescence, and magnetostratigraphy (if the last can be considered by itself to be a dating method). Use of thermoluminescence to date sediments has increased in recent years, but application to tephra (Berger, 1986; Wintle and Westgate, 1986) has lagged behind. Indirect age dating techniques that are used in dating tephra are radiocarbon, electron-spin resonance, amino-acid racemization, uranium series and uranium-trend dating, ice-core stratigraphy (a specialized application of tephrochronology and tephrostratigraphy), dendrochronology, and written and oral history.

SOURCES, AGES, AND AREAL DISTRIBUTIONS OF WIDESPREAD TEPHRA LAYERS IN THE UNITED STATES

All sources of Quaternary tephra in the conterminous United States are in the west because here volcanism has accompanied subduction, transform faulting, extension, and hotspot activity. The central and eastern parts of the United States are a relatively stable craton. The main sources of major Quaternary volcanism and the major tephra sources in the western conterminous United States are discussed in Leudke and others, and Sarna-Wojcicki and others (this volume). Although Alaska has many sources of Quaternary tephra, little work was done on their identification, correlation, and dating until recently (Wilcox, 1959b; Péwé, 1975a, b; Porter, 1981; Naeser and others, 1982; Westgate and others, 1983, 1985; Riehle, 1985; Riehle and others, 1990).

Sarna-Wojcicki and others (this volume) provide information on the ages and areal distribution of widespread upper Ceno-

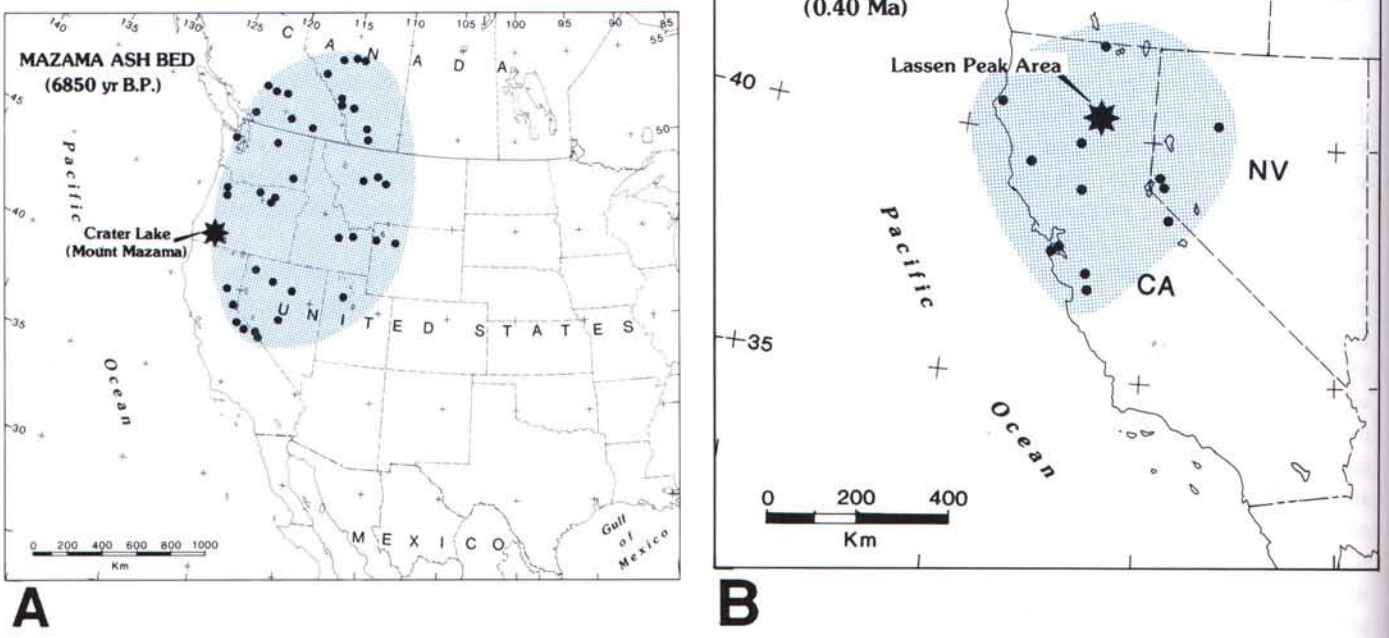
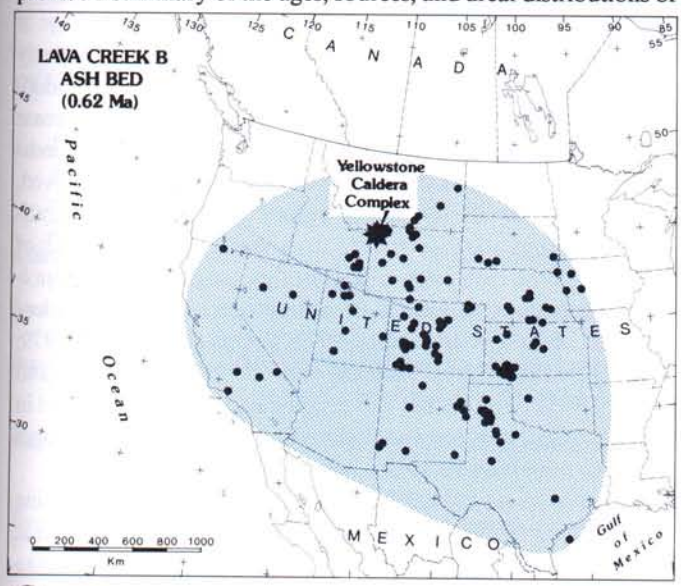


Figure 12. Areal distributions of some widespread tephra layers within the western conterminous United States. Solid circles on each map represent sites at which tephra layers are found. Not all sites at which these tephra layers have been identified are shown. The colored shaded patterns represent the minimum areas covered by each tephra layer. There may be areas within the shaded patterns, however, where ash from a particular eruption did not fall. For example, we know that the Mazama ash bed may have consisted of as many as five lobes (Mullineaux and Wilcox, 1980; Young, 1989), each of which had a more or less restricted area of fallout. The shaded area in the map for the Mazama ash bed is an envelope enclosing all the eruptive lobes. On the other hand, it is more than likely that new localities will be found in the future outside the shaded area, judging from the history of investigations of these tephra layers. A, expanded and modified from Mullineaux, 1974, and Sarna-Wojcicki and others, 1983; B, from Sarna Wojcicki and others, 1985a; C and E, expanded and modified from Izett and Wilcox (1982); D, expanded and modified from Izett and others (1988); F, from unpublished data of A. M. Sarna-Wojcicki.

zoic tephra layers in the Pacific borderland of the United States and the western part of the conterminous United States. Izett (1981) presents information on the ages, areal distributions, and characteristics of upper Cenozoic tephra layers in the western United States, with emphasis on the central Great Plains and Midwest. Porter (1981) discusses the use of tephrochronology and the areal distribution of Quaternary tephra layers in the United States, summarizing work in Alaska, Hawaii, and the conterminous United States. Izett and Wilcox (1982) provide information on the areal distribution of the Pearlette family of ash beds (the Huckleberry Ridge ash bed, Mesa Falls ash bed—correlative of the Mesa Falls Tuff—and Lava Creek ash bed, and some of their predecessors). Sarna-Wojcicki and others (1983) provide a summary of the ages, sources, and areal distributions of Holocene volcanic rocks and upper Pleistocene and Holocene tephra layers in the conterminous United States (see Fig. 6 and Table 1 of Sarna-Wojcicki and others, this volume; Plate 1). Izett and others (1988) provide information on the age, petrographic characteristics, chemistry, and areal distribution of the widespread Bishop ash bed—correlative of the Bishop tuff—and older, genetically related tephra layers. Sarna-Wojcicki and others (1987; and this volume), present information on correlation of tephra layers between the western conterminous United States and the adjoining areas of the Pacific Ocean. Self and Sparks (1981) and Heiken and Wohletz (1985) present an extensive



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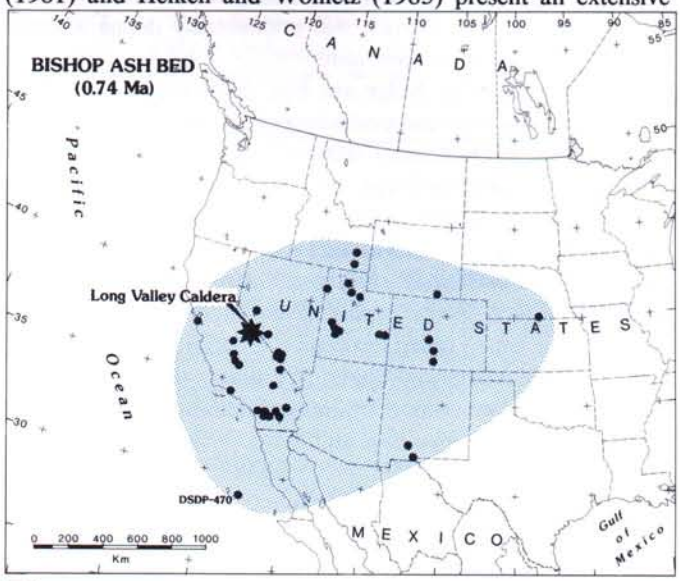

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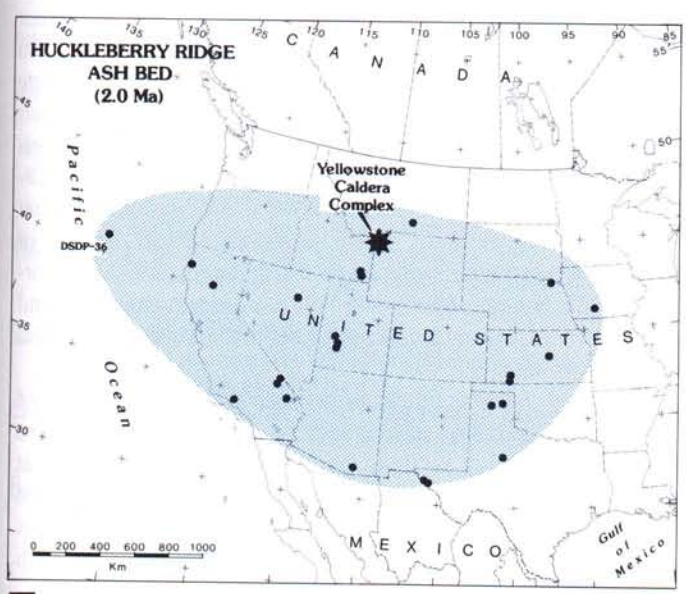

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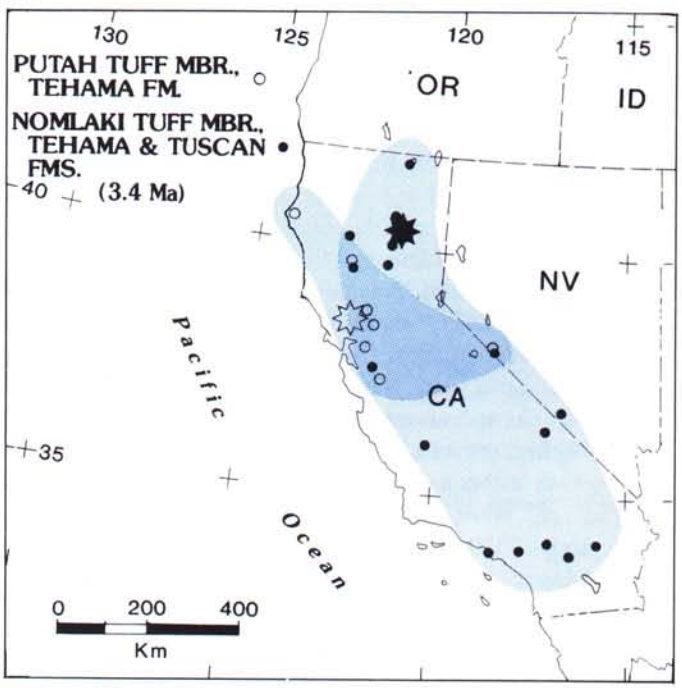

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compilation of information on tephra layers worldwide, including known dispersal patterns and areal distributions of historic and prehistoric tephra layers.

Among the most widespread and generally most useful tephra layers for studies of uppermost Pliocene and Quaternary stratigraphy in the western conterminous United States are the Huckleberry Ridge, Bishop, and Lava Creek B ash beds (Fig. 12e, d, and c). In addition to being found at numerous sites within the conterminous U.S., these three ash beds have also been found in marine deposits of the Pacific Ocean, and one (the Lava Creek B) in the Gulf of Mexico as well (C. L. Ostergren, written communication, 1990). Further work will undoubtedly define a much broader distribution for these units.

The Huckleberry Ridge ash bed, dated at about 2.0 Ma, provides an important chronostratigraphic marker for upper Pliocene and lower Quaternary sections in the United States that often lack other diagnostic age control. This tephra layer, incidentally, was previously referred to as the Pearlette type B ash bed—the name derived from the Pearlette Ash Member of former usage (of the Sappa Formation)—before its source was determined. As a matter of fact, several tephra layers of different ages were thought to be one so-called Pearlette ash, and were used to correlate glacial and interglacial Quaternary units in the central United States. This resulted in considerable confusion until the units were eventually correctly identified and dated (Wilcox, 1965; Naeser and others, 1973; Izett, 1981; Izett and Wilcox, 1982). Thus, in addition to providing precise age control, tephrochronology also offers great potential for confusion if correlations are not well documented. The Pearlette ash bed was subsequently subdivided into types B, S, and O, which now correspond to the Huckleberry Ridge (1.97 Ma; J. D. Obradovich, written communication, 1987), the Mesa Falls (1.27 Ma; Izett and Wilcox, 1982), and the Lava Creek A and B ash beds (0.62 Ma; Izett and Wilcox, 1982), respectively.

The Bishop and Lava Creek B ash beds (0.74 and 0.62 Ma, respectively) provide key time-stratigraphic datums for middle Quaternary continental and marine sequences. The Bishop ash bed, together with the slightly older Brunhes Normal Polarity/Matuyama Reversed Polarity Chron boundary (see Sarna-Wojcicki, this volume), provide convenient datum planes for division of Quaternary sequences in the conterminous United States into lower and upper Quaternary (Fig. 12d).

In California and Nevada, the Rockland ash bed of Sarna-Wojcicki and others (1985a; see also Meyer and others, 1991; 0.40 Ma) provides an important datum for upper Quaternary deposits within an otherwise poorly constrained time interval (Fig. 12b), while the Mazama ash bed of Lemke and others (1975; about 6850 yr B.P.) provides an important marker for lower Holocene deposits in the northwestern United States (Fig. 12a). Older tephra layers, such as the Nomlaki and Putah Tuff Members of the Tehama Formation (3.4 Ma; Fig. 12f), provide age control for the upper Pliocene stratigraphic and structural framework of Quaternary deposits in the western United States (see Sarna-Wojcicki and others, this volume).

CONCLUDING REMARKS

Perhaps one of the most important chronostratigraphic uses of Quaternary tephra layers is to provide precise correlations between deep-ocean, uplifted onshore marine, and continental stratigraphic sequences (Sarna-Wojcicki and others, 1985b, 1987). Such correlations are difficult to make by other techniques because they require correlation between sediments of different facies, deposited at different rates under diverse depositional environments, and in diverse tectonic settings. A widespread tephra layer may be dated at several sites by several methods. A tephra layer, if confidently identified, provides a precise relative time datum against which ages can be tested for concordance, regardless of the actual age of the layer. Once the correlation and age of a tephra layer are well established, they allow us to quantitatively evaluate other types of chronostratigraphic data that are associated stratigraphically with the layer. Concordant ages increase confidence in the results and in techniques; discordant ages indicate problems in methods or techniques that need to be resolved.

Because tephra layers are virtual time datums in stratigraphic sections, they allow us to study specific, short intervals of time in the past, over large areas. For this reason, tephrochronology is important to studies of paleoenvironments and paleoclimates (Mehringer and others, 1977; Blinman and others, 1979; Mehringer, 1985; Sarna-Wojcicki and others, 1985b; Adam and others, 1990). Such studies will become increasingly important in light of current concern about climatic and other global changes that have been induced by the activity of humans.

Within about the last 2 m.y., a period of time encompassing somewhat more than the Quaternary period, there have been at least eight great volcanic eruptions that have produced more than 100 km^3 of tephra (Table 1) and formed widespread tephra layers that are important time and stratigraphic horizons for the study of Quaternary deposits. Tephrochronologic and other studies of these layers are important not only because they can provide age and correlation data, but also because they contribute to an understanding of the climatic and ecological effects that such large eruptions may have (Pollack and others, 1976; Axelrod, 1981; Self and others, 1981; Rose and Chesner, 1987). Explosive volcanic eruptions produce a veil of dust and aerosols that are hemispheric or even global in extent (Royal Society of London, Krakatau Commmission, 1888; Lamb, 1970; McCormick, 1981; Scuderi, 1990), and thus have at least transient, and perhaps more profound and lasting, effects on climate and the earth's ecosystem.

Because volcanic eruptions produce such extensive veils of dust, disseminated fine tephra particles in stratigraphic sections provide a possibility for long-distance correlations. Though at present we do not have the ability to separate, analyze, and identify this very fine material in sediments, the potential exists for developing hemispheric or even global correlations with tephra, and this potential should be exploited.

TABLE 1. TEPHRA LAYERS OF EIGHT GREAT ERUPTIONS THAT HAVE OCCURRED IN THE CONTERMINOUS UNITED STATES DURING LATEST PLIOCENE AND QUATERNARY TIME*

Name of Tephra layer	Vent Locality	Age (Ma)	Volume (km^3)	Reference
Mazama ash bed	Crater Lake, Oregon	0.007	~120	Bacon, 1983
Rockland ash bed	Lassen Peak area, California	0.40	~120	Sarna-Wojcicki and others, 1985a
Lava Creek ash bed	Yellowstone, Wyoming, Idaho	0.62	1,000	Christiansen, 1979
Bishop ash bed	Long Valley, California	0.74	500	Bailey and others, 1976
Tshirege Member of Bandelier Tuff	Valles Caldera, New Mexico	1.15	300	Smith, 1979
Mesa Falls ash bed	Yellowstone, Wyoming, Idaho	1.27	280	Christiansen, 1979
Otowi Member of Bandelier Tuff	Valles Caldera, New Mexico	1.47	300	Smith, 1979
Huckleberry Ridge ash bed	Yellowstone, Wyoming, Idaho	1.97	2,500	Christiansen, 1979

*Eruptive volumes of about 100 km^3 or more.

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This chapter on Quaternary Tephrochronology is dedicated to the memory of Jonathan O. Davis, who died on December 15, 1990, shortly after the chapter was completed, from injuries suffered in an auto accident caused by an intoxicated driver. Jonathan's premature, tragic, and senseless death is a great loss to all of us who have known him, and to geologists, archeologists, and other earth scientists who have worked in the Great Basin.

Jonathan was both an archeologist and geologist, and has made important contributions to both fields. His most significant contribution was to the chronostratigraphy of the Great Basin, and in particular to that of the Lahontan Basin. By means of careful, methodical, and insightful field and laboratory research conducted over the last 15 years, Jonathan developed a tephrochronologic space-time framework for late Quaternary deposits of this region that precisely correlates and dates processes and events such as the timing of pluvial lake expansion and contraction, of early human occupation in this region, and of the climatic changes that were in large measure responsible for these phenomena. His work is, and will remain, an invaluable reference to earth scientists studying the natural history of this region and elsewhere.

Because of his talents, abilities, and knowledge, there was much demand on Jonathan's expertise and time. However, one of Jonathan's secret ambitions, and one that he at times achieved, was to be a scholarly desert vagabond. He loved the beauty, solitude, and cleanness of the desert country where he worked and loved to wander in the secret places of the Great Basin.

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