Articles

Dating Methods of Pleistocene Deposits and Their Problems: V. Tephrochronology and Fission-Track Dating

John A. Westgate
Department of Geology
University of Toronto,
Toronto, Ontario M5S 1A1

Nancy D. Briggs*
Physical Sciences Group
Scarborough College
University of Toronto
West Hill, Ontario M1C 1A4

*Present Address:
United States Geological Survey
Federal Center
Denver, Colorado 80225

Summary

Much interest and activity is presently centred on the stratigraphic use of tephra. Distinctive tephra layers constitute important time-parallel markers, which if widespread, offer the potential for reliable correlation over long distances. Furthermore, they provide valuable geochronological control for their age can be determined by several radiometric methods. Confident correlations require a multiple criteria approach to tephra characterisation; samples should only be considered equivalent if their stratigraphic, palaeontologic, palaeomagnetic, and radiometric age relations are compatible and the physico-chemical properties of their glass shards and phenocrysts agree. Special attention should be given to the possibility of resedimentation into a younger stratigraphic position. Because grain-discrete methods of analysis are sensitive to contamination effects, they are to be preferred over those methods that require use of bulk separates.

Coarse, proximal tephra can be reliably dated by the K-Ar method as pure mineral separates can be readily isolated, but distal ash-grade tephra is better dated by the fission-track method in which ages are based on tracks counted in individual grains so that detrital contaminants can be easily recognised and avoided. The recent successful application of the fission-track method to distal tephra has resulted in a greatly improved understanding of the late Cenozoic geochronology of areas remote from volcanic centres.

Tephrochronology is a useful tool in many areas of Quaternary research; in particular, it will undoubtedly continue to play an important role in the connection of marine and continental sequences, refinement of the palaeomagnetic chronology, calibration of hominid evolution in eastern Africa and other areas, and age-definition of Antarctic and Greenland ice cores.

Introduction

A wide range of studies are currently focused on tephra. Insights into the character, magnitude, explosivity, and duration of past volcanic eruptions are being sought through analysis of the physical properties of tephra, especially granulometry, shard morphology, and size and shape of the dispersal fan (Walker, 1971, 1973; Heiken, 1972; Huang and Watkins, 1976; Ledbetter and Sparks, 1979). Mineralogical and geochemical gradients in tephra piles monitor compositional stratification of the parent magma body and so constitute a valuable source of information pertinent to differentiation mechanisms (Lipman, 1971; Hildreth, 1976; Shaw *et al.*, 1976). Distinctive and widespread tephra layers have much stratigraphic value for they represent time-parallel markers that permit reliable correlation over long distances (Wilcox, 1965; Vucetich and Pullar, 1969; Machida, 1976). For example, tephra has been recognised in deep-sea sediments at distances as great as 3000 km from its source (Huang *et al.*, 1973), and even on the continents, where preservation potential is not as good, discrete beds discontinuously persist to distances exceeding 1500 km (Figure 1 and Table I). Moreover, because the age of tephra beds can be determined by several radiometric techniques, they provide important geochronological control.

This review is concerned with the latter aspect of tephra studies, a field commonly referred to as "tephrochronology" (Thorarinsson, 1974), and the prominence given to the fission-track dating method is in recognition of recent significant advances in Quaternary stratigraphy that have resulted from the application of this method to tephra, especially distal units.

The pioneering work in tephrochronology was done by Thorarinsson (1944) in Iceland and by Sahlstein (1932) and Auer (1950) in South America. These efforts were soon followed by comparable studies in Japan, New Zealand, and Europe (see Westgate and Gold, 1974). Interest in the subject developed more slowly in North America. It was not long ago that Wilcox (1965, p. 807) noted in his review of the status of Quaternary tephrochronology in the United States: "... one is impressed with the potential offered for solutions to problems in Quaternary geology, archaeology, paleopedology, and palynology. The presence of ash layers has been noted in many studies in these fields, but for only a few layers has the requisite work been done to enable their full use as stratigraphic tools." Even less work had been done in western Canada at this time – a surprising fact given the large number of Quaternary vents and proximity of others in southeastern Alaska, the Pacific Northwest, and the Yellowstone region (Fig. 2). Today, on the other hand, there is much interest and activity in the Quaternary tephrochronology of western North America. Thus, most of the tephra units listed in Table I were defined during the last decade. This

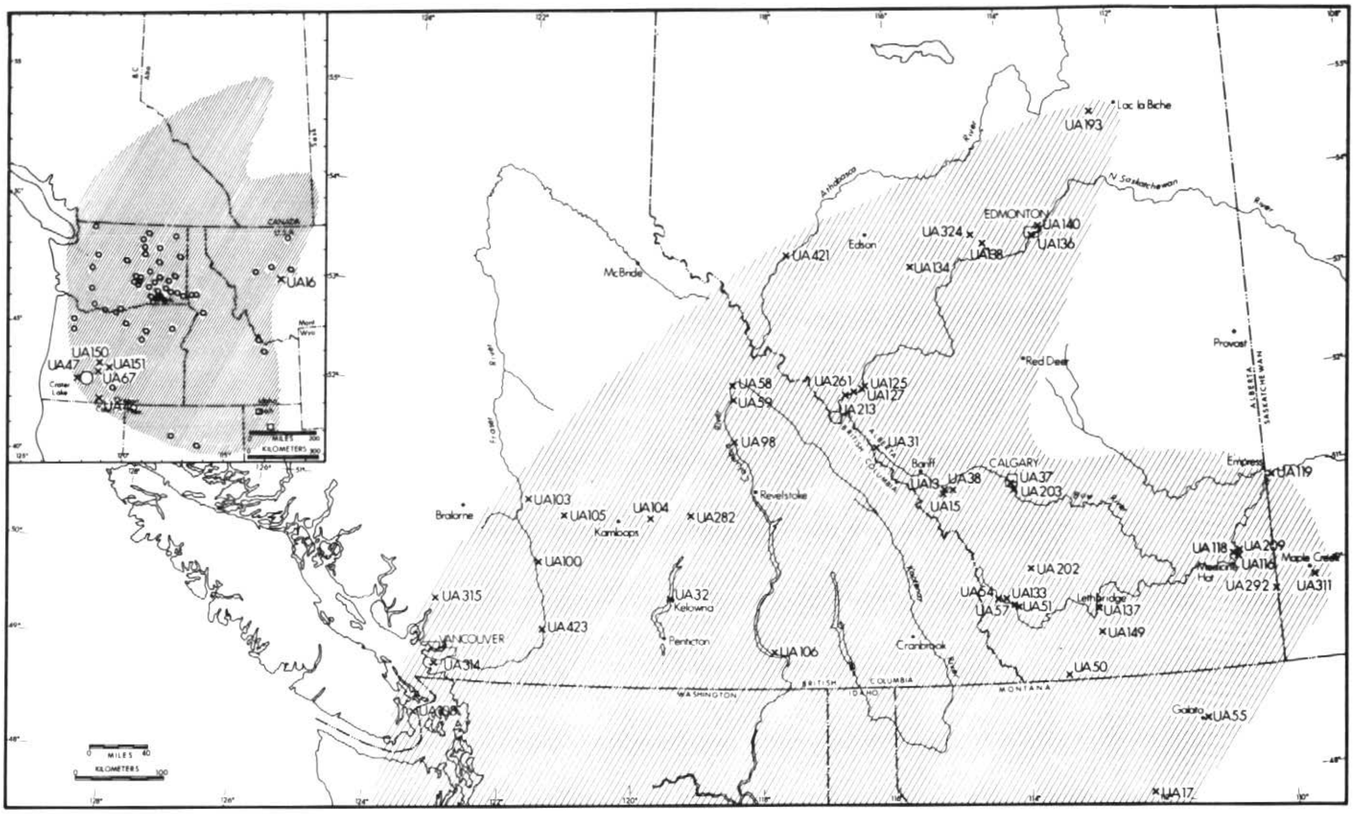

Figure 1
Distribution of Mazama tephra in western North America. The source vent is located at Crater Lake (inset map), which formed after the collapse of Mount Mazama about 6600 years ago. The aggregate volume of liquid magma, entrained crystals, and lithic fragments blasted from the top of Mount Mazama during its climactic outburst was approximately 40 km^3 (Williams and Goles, 1968). The most distant locality, where tephra occurs as a discrete bed, is Lac la Biche, Alberta, about 1550 km northeast of Crater Lake, Oregon. Crosses and circles represent sample localities of Westgate and other workers, respectively.

Table I. Some widespread and well-documented tephra marker beds of Quaternary age in North America

Stratigraphic Unit	**Source‡**	**Geographic Extent†**	**Age* (k.y.)**	**References**
White River Ash, eastern lobe	Mt. Bona, Alaska (1)	Fort Wrigley, N.W.T.; 950 km	1.25	Lerbekmo *et al.*, 1975
Bridge River tephra	Meager Mountain, B.C. (2)	Nordegg, Alberta; 550 km	2.60	Westgate, 1977
Mount St. Helens, an older member of set Y tephra	Mount St. Helens, Washington (4)	Baptiste Lake, Alberta; 1150 km	4.30	Mullineaux, 1974; Westgate, 1977
Mazama tephra	Crater Lake, Oregon (5)	Lac la Biche, Alberta; 1550 km	6.60	Powers and Wilcox, 1964; Fryxell, 1965
Glacier Peak tephra, southeastern lobe	Glacier Peak, Washington (3)	Yellowstone National Park; 950 km	11.20	Porter, 1978; Westgate and Evans, 1978
Pearlette "O" tephra	Yellowstone National Park (6)	Cudahy Ash Mine, Kansas; 1200 km	600	Izett *et al.*, 1970; Naeser *et al.*, 1973
Bishop Tuff	Long Valley, California (7)	Nuckolls County, Nebraska; 1850 km	700	Izett *et al.*, 1970; Izett and Naeser, 1976
Pearlette "S" tephra	Yellowstone National Park (6)	Cedar County, Nebraska; 1200 km	1200	Izett *et al.*, 1970; Boellstorff, 1976
Pearlette "B" tephra	Yellowstone National Park (6)	Meade County, Kansas; 1200 km	2000	Naeser *et al.*, 1973; Boellstorff, 1976

Notes
†Identity and distance of farthermost locality from vent is indicated.
*Age of the Bishop Tuff and Pearlette tephra layers determined by the fission-track method; age of other units is in ^{14}C years.
‡Locations of source vents are shown on Figure 2, where each is identified by the number shown here in parentheses.

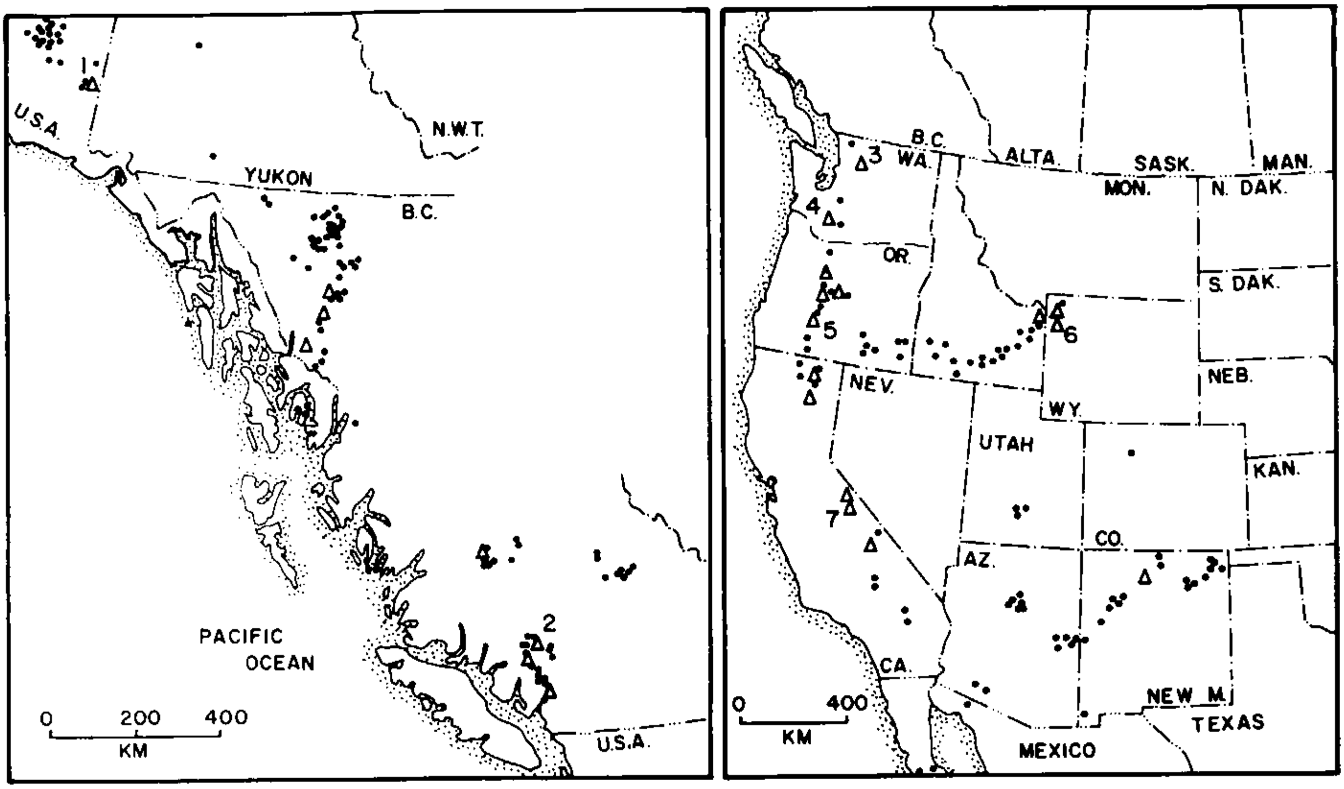

Figure 2
Distribution of Quaternary vents in western North America based on maps by Wilcox (1965) and Souther (1976). Open triangles represent vents that have erupted large volumes of silica-rich tephra; the numbers are identified in Table 1. Filled circles represent vents that have furnished silica-poor tephra; resultant tephra layers are restricted in extent because they are generally associated with relatively weak eruptions.

vitality clearly has its roots in Wilcox's (1965) excellent summary of the method and its potentialities.

Characterisation of Tephra
Although efforts have been made to find a rapid, single-parameter method for tephra identificaiton (Czamanske and Porter, 1965; Smith and Westgate, 1969) most workers now acknowledge that reliable correlation requires a multiple criteria approach to tephra characterisation. Equivalence of samples should only be considered firmly established if: 1) their stratigraphic, palaeontologic, palaeomagnetic, and radiometric age relations are compatible, 2) properties of the glass shards and phenocrysts agree, and 3) the combination of these characteristics is distinctive from that of other tephra beds in the area (Wilcox and Izett, 1973). The last requirement presupposes a comprehensive knowledge of the geologic record, which is still unattained for many areas, so that although it is generally agreed that tephra beds provide one of the most useful and precise means for time-correlation, one must still accept Weller's (1960, p. 565) comment that "very rarely or never is the evidence absolutely conclusive".

Field criteria that should be documented include colouration, degree of weathering, granulometry, sedimentary structures, distribution, thickness, and stratigraphic position. These attributes may provide sufficient control for identification in regions close to source vents (Topping, 1973) but detailed petrographic and petrochemical studies are usually required to identify distal tephra units (Izett *et al.*, 1970; Westgate and Fulton, 1975). In the latter context, desirable parameters are those that do not change over the fall-out zone - namely, the physico-chemical properties of the glass shards and primary phenocrysts. Bulk tephra analyses do not satisfy this condition because the tephra has been subjected to sedimentary differentiation. However, such information is of local value, provides data pertinent to location of the source vent (Lerbekmo and Campbell, 1969), and, in some cases, has been used sucessfully to correlate tephra beds over large distances (Bowles *et al.*, 1973).

Felsic tephra beds are commonly distinguished from one another on the basis of the properties of their volcanic glass. The popularity of glass in this respect lies in its abundance, ease of concentration, and homogeneous composition or narrow compositional range within a single eruptive unit. However, proneness to alteration limits or prevents its use for older beds and in those areas where chemical weathering is vigorous. Some workers have stressed the physical properties of glass shards in their studies, documenting morphology, transparency, vesicularity, microphenocryst content, hydration, and refractive index (Steen-McIntyre, 1977), whereas others have concentrated on chemical characteristics.

Much attention has been given to use of the range and modal value of the refractive index of volcanic glass, as measured with refractive index oils, but these efforts have met with mixed success. Silicic volcanic glasses do not vary greatly in their major element composition so that differences in their refractive indices are small, and, in some cases, insufficient to permit distinction between separate eruptive units (Ninkovich, 1968; Kohn 1970). Further difficulties arise from differential hydration, which increases the dispersion of such data (Wilcox, 1965). Correlations based on refractive index histograms (Steen-McIntyre, 1977) defined by several hundred measurements are obviously more securely based but the time-consuming nature of the method has discouraged its use. However, the recent demonstration by Hodder (1978) that refractive index determination by the thermal immersion method offers improved precision over the usual method with oils should stimulate the continued use of refractive index data.

Bulk glass analyses suffer from the inevitable presence of inclusions and microlites, the possible occurrence of foreign particles and weathering products on the surface of shards and pumice fragments, and more rarely, the occurrence of detrital glass reworked from older tephra – a phenomenon observed in the Wellsch Valley tephra where less than one per cent of the shards show anomalously high fossil fission track densities (Westgate *et al.*, 1978). Nevertheless, minor and trace element compositions of bulk glass separates, as determined by x-ray fluorescence spectrometric analysis (Sarna-Wojcicki, 1976), atomic absorption (Izett *et al.*, 1970), and instrumental neutron activation analysis (Borchardt *et al.*, 1972), are one of the best means of discriminating between tephra layers for they can differ between one another by a large factor (Jack and Carmichael, 1969; Bowles *et al.*, 1973). The major element composition of volcanic glass is more accurately determined by the electron microprobe technique (Smith and Westgate, 1969), which is a grain-discrete method that avoids the problems associated with analysis of bulk separates (Westgate and Fulton, 1975) and so permits distinction of minor variation in the chemistry of glasses (Fig. 3).

Most workers identify the phenocryst suite and some place emphasis on the types of ferromagnesian silicates present together with their respective refractive indices and optical properties (Wilcox, 1965; Mullineaux, 1974). Iron-titanium oxides, however, are the most used minerals in chemical characterisation studies. They are very sensitive to the environmental conditions of initial crystallisation and bulk rock chemistry (Haggerty, 1979) and so exhibit a considerable range in compositions and modal abundances in igneous rocks. Other factors that have encouraged their use include ubiquitous occurrence in volcanic rocks, relative stability during weathering, and ease of extraction by magnetic methods. Grain-discrete methods of analysis are to be preferred over the use of bulk separates because they permit detection of post-depositional changes, contamination effects, and the presence of more than one indigenous phase of a given mineral (Lerbekmo *et al.*, 1975; Westgate *et al.*, 1970). For example, in seeking possible correlatives of a thin tephra layer in South Island, New Zealand, Kohn (1979) found that bulk titanomagnetite analyses could not be used because of the presence of detrital titanomagnetite derived from the enclosing loess. However, electron microprobe analyses of a few homogeneous titanomagnetite grains soon suggested a correlative. Similarly, bulk titanomagnetite analyses of the Pearlette "O" layer (Table I) would have given meaningless information because of the presence of five distinct, primary species (Westgate *et al.*, 1977). Identification of tephra by thermomagnetic properties (Momose *et al.*, 1968) suffers for the same reasons.

The stratigraphic value of a tephra layer is greatly enhanced if its age and palaeomagnetic properties are known. The K-Ar, fission-track, ^{40}Ar–^{39}Ar, and ionium (Kigoshi, 1967) dating techniques, along with the more qualitative hydration method (Steen-McIntyre, 1975), can be applied to Quaternary tephra, but all are too imprecise to be used alone for identification purposes. The radiocarbon age of associated organic matter is likewise only suggestive of the identity of a tephra layer. Palaeomagnetic characteristics facilitate correlation but in themselves do not date tephra beds. The magnetic polarity, however, does provide a means of assessing the reliability of radiometric age data in that the chronology of polarity reversals for the Quaternary Epoch is reasonably well-established (Mankinen and Dalrymple, 1979). Caution is necessary at present for our understanding of the polarity sequence is still evolving (Mankinen *et al.*, 1978; Cooke *et al.*, 1979). The pattern of secular variation of the earth's magnetic field, as recorded in the tephra-bearing sediments, is another useful signature for correlation on a local and regional scale (Creer *et al.*, 1976; Westgate and Evans, 1978).

Significant advances in Quaternary geochronology have been made recently as a result of successful application of the fission-track dating method to fine-grained, distal tephra. Earlier attempts at age definition of ash-grade tephra by other methods seldom produced reliable results. For example, the K-Ar method gives valuable information for near-source volcanic rocks but does not produce reliable ages for the distal air-fall equivalents because: 1) glass shards are particularly susceptible to incorporation of excess Ar or may lose Ar during hydration (Naeser *et al.*, 1973), and 2) detrital contaminants are nearly ubiquitous and are difficult to separate completely from the bulk samples used for dating. Fission-track dates, on the other hand, are based on tracks counted in individual grains so that detrital fragments can be readily recognised and avoided. This success justifies a more detailed statement on the technique and some of its attendant problems.

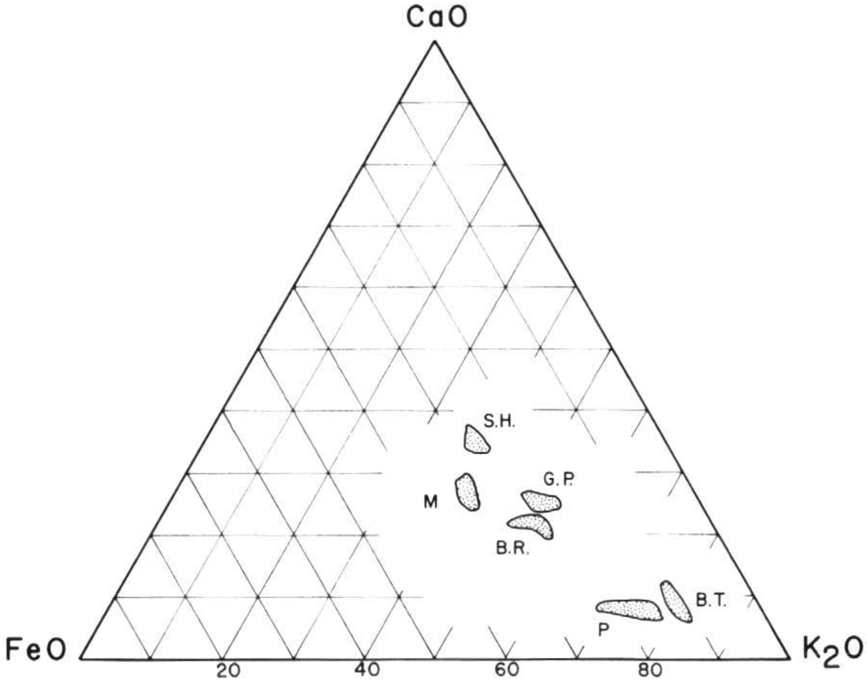

Figure 3
Relative abundance of FeO, CaO, and K_2O in glass of some widespread Quaternary tephra layers in western North America. All determinations were done on an electron microprobe. Compositional range is based on 43 samples in the case of Mazama (M) tephra, 21 for Bridge River (B.R.) tephra, 15 for St. Helens (S.H.) set Y tephra, 16 for Pearlette (P) tephra, and 18 samples for the Bishop Tuff (B.T.). The Bishop Tuff data and some of that for Pearlette tephra come from Izett et al. (1970); the remainder is the work of Westgate (1977). Table 1 contains further details on these eruptive units.

Fission-Track Dating

Fission tracks are the zones of intense damage resulting from the fission of heavy elements. Several naturally occurring isotopes undergo spontaneous fission, but only ^{238}U has a fission half-life which produces a significant number of tracks over geologic time. ^{238}U occurs in trace amounts in glasses and many minerals and undergoes spontaneous fission at a constant rate so that fission tracks form the basis of a valuable dating method, conceived by Fleischer, Price, and Walker in the early 1960s. The age of a mineral or glass can be calculated by determining the amount of uranium and the number of spontaneous tracks which it contains. For details of the method see Fleischer *et al.* (1975) and Naeser (1976).

Several factors determine if a sample can be successfully dated by the fission-track method. Firstly, the sample must contain a glass or mineral of appropriate uranium content. Young samples should be relatively high in uranium so that a statistically significant number of tracks can be counted in a reasonable time. Secondly, tracks should be retained once they are formed. Heat is by far the most significant environmental factor which causes partial or complete fading of spontaneous tracks. Critical temperatures at which track fading or "annealing" occurs have been determined by: 1) extrapolating laboratory heating experiments to geologic time (Naeser and Faul, 1969), and 2) measuring age-decrease with increasing depth and temperature in deep drillholes (Naeser and Forbes, 1976). Such studies have shown that annealing temperatures are a function of the mineral species or glass involved and the period of heating. Although annealing can cause problems in determining the primary age of samples, it offers great potential for studies of their thermal history (Naeser, 1979).

Etching studies have shown that tracks can be revealed in more than 150 minerals and glasses (Fleischer *et al.*, 1975) but the combination of such factors as typical uranium content, annealing characteristics, and relative abundance results in very few minerals being routinely used for dating. Zircon and glass are the only phases in Quaternary tehpra that are dated on a routine basis.

Natural glasses present special problems. They lose spontaneous tracks by thermal annealing at temperatures lower than any of the minerals commonly used in fission-track dating (Fleischer *et al.*, 1975, table 2-4). For example, recent work by Naeser *et al.* (1980) has shown that both hydrated and non-hydrated glasses can anneal at ambient temperatures over geologic time. Therefore, great care must be used in the interpretation of glass ages. If glass is the only phase available for dating, then it should be checked for annealing by either the plateau-annealing method (Storzer *et al.*, 1973) or the track diameter measurement method (Storzer and Wagner, 1969). However, an age corrected by either of these methods is occasionally lower than the geologic age and should still be quoted as a minimum age (Gentner *et al.*, 1969; Macdougall, 1976; Naeser *et al.*, 1980). Glasses with abundant microlites may be difficult or impossible to date because of the close resemblance of the etched microlites to fission tracks; this is a problem common to dating obsidians but it is rarely encountered in glass shards. Another limitation relates to grain-size and vesicularity. It is difficult to count tracks and determine glass area by the conventional method of a grid in the eyepiece of the microscope when the shards are very fine-grained or pumiceous (Fig. 4). The problem of determining area can be overcome for many samples by use of a point-counting technique analogous to that used in petrographic modal analysis (Seward, 1974; Briggs and Westgate, 1978). Even so, dating such glass is very time-consuming. Despite these problems glass is frequently used because it is the only datable phase present in some tephra units, and, in some situations, even minimum dates provide useful information.

Obsidian fragments in air-fall tephra less than 40,000 years old have been dated (Sato *et al.*, 1972) as have zircons from tephra beds as young as 100,000 years (Herd and Naeser, 1974; Nishimura and Yokoyama, 1973). Archaeological materials have also been dated by fission tracks. For example, Bigazzi and Bonadonna (1973) and Suzuki (1973, 1974) dated obsidian artifacts and Watanabe and Suzuki (1969) dated a glass glaze on a bowl fragment that was only 500 years old. One of the youngest materials to be dated by the fission-track method is man-made uranium glass that was manufactured within the last 140 years (Wagner, 1978).

The Problem of Reworking

A variety of mixing processes act on tephra once it is deposited unless it is rapidly buried by younger sediment. Disturbances by soil-forming processes, creep, frost activity, bioturbation, uprooting of trees, and reworking by wind and running water are important in subaerial regions whereas bioturbation and resedimentation by slumping and associated turbidity flows occur in subaqueous depositional environments. Proximal tephra beds may escape full reworking because of their thickness but thin distal beds can be lost as discrete units by these mixing processes. The original stratigraphic position of the dispersed tephra is then best estimated by the level of maximum concentration of glass shards (Persson, 1966, 1967; Huang *et al.*, 1973; Ruddiman and Glover, 1972). Tephrostratigraphic investigations are especially difficult where mixing processes have worked on several thin, superimposed tephra beds, although careful application of grain-discrete methods of analysis can

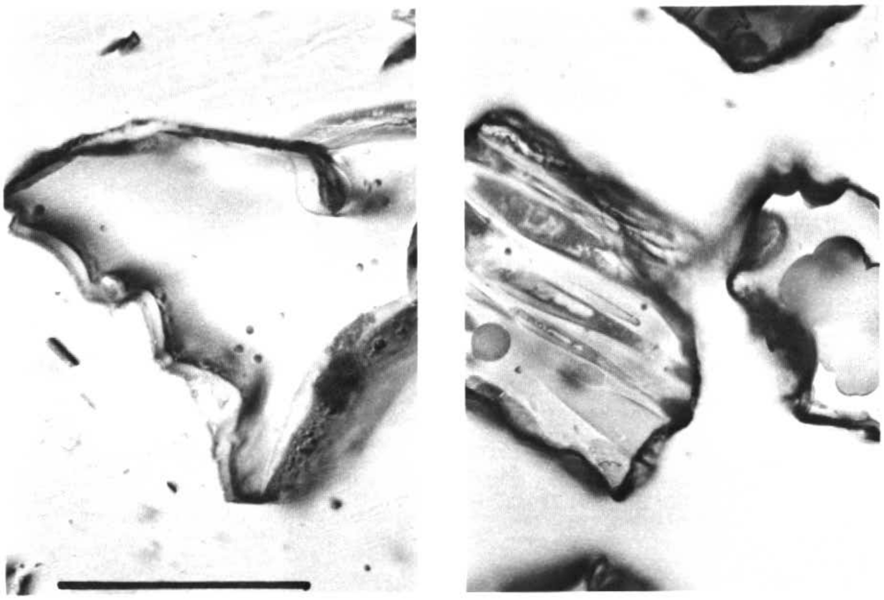

Figure 4
Induced fission tracks in glass shards. The track density of the clear, chunky shard on the left can be determined by the grid method, but the pumiceous shards on the right can only be dated by use of the point-counting technique (see text). Scale bar is 0.1 mm long.

produce useful results, as has recently been demonstrated by A.G. Hogg's work on late Quaternary tephra of the Coromandel Peninsula, New Zealand (unpublished data, University of Waikato). The same mixing processes permit only crude estimates of tephra volumes.

Identification of tephra layers is hindered by reworking, which can be detected by: 1) presence of non-volcanic sediment, 2) separation of phenocrysts from the vitric component, 3) abnormal thickness or grain size, given the distance from the source, and 4) diffuse boundaries to the bed. But perhaps a more serious hazard is resedimentation into a stratigraphic position that is much younger than the intrinsic age of the tephra. Thus, careful examination for reworking and consideration of other local stratigraphic controls are necessary in order to safeguard against gross errors. For example, the stratigraphic position in deep-sea sediments of a tephra-rich horizon derived immediately from ablating icebergs does not equate with the time that that material was erupted. Hence, the age of that stratigraphic level can not be defined by radiometric methods applied to the tephra, which would probably be of mixed origin anyway. Ruddiman and Glover (1972) have shown that much of the tephra in the North Atlantic deep-sea sediments is of this origin, and the same is probably true of tephra in the upper Quaternary sediments of Baffin Bay, where its occurrence most likely monitors those times when icebergs could drift northwards into the Bay (Aksu and Piper, 1979). Similarly, it is not surprising that the pumice fragments concentrated on a 5000-year old strandline at Cape Storm, southern Ellesmere Island, are definitely greater than 5000 years old and may be as much as several hundred thousand years old on the basis of the uranium content and the spontaneous fission tracks they contain (J. Boellstorff, in Blake, 1975, p. 13).

Applications

Tephrochronology can be very useful in unravelling the eruptive histories of some volcanoes (Topping, 1973; Machida, 1976); indeed, the prolific record of tephra layers in deep-sea sediments adjacent to volcanic arcs offers the best means of definition of the timing of large-scale eruptions during the late Cenozoic (Ninkovich and Donn, 1976). Tephrochronology is a valuable tool in geomorphological, palaeoclimatological, and palaeoecological studies in that some tephra beds span several climatic zones (Wilcox, 1965). Temporal control on the important hominid fossils from Plio-Pleistocene sediments in eastern Africa is largely based on tephra beds. Furthermore, the geological record of diverse sedimentary environments in the oceans and on the continents and ice sheets can be effectively linked by extensive tephra beds. The Pearlette "O" bed (Table I) illustrates this well; it is the product of a catastrophic eruption of more than 900 km^3 of rhyolitic tephra that issued from vents in Yellowstone National Park some 600,000 years ago (Eaton *et al.*, 1975). Remnants of this bed, which have been found over large parts of the midwestern United States (Naeser *et al.*, 1973; Boellstorff, 1976) and occur as far north as the southern Canadian plains (Westgate *et al.*, 1977), facilitate correlation between Laurentide and Cordilleran glacial sequences, which, in turn, can be related to the sedimentary record of the Colorado Piedmont and intermontane basins of California, Nevada, and Utah (Izett *et al.*, 1970). Work on the abundant tephra layers in Quaternary deep-sea sediments will undoubtedly produce numerous firmly-based marine-continental correlations in the future, but at present few such linkages have been established.

Application of the fission-track dating method to distal tephra has resulted in a greatly improved understanding of the late Cenozoic geochronology of areas remote from volcanic centres. These new data are exposing major stratigraphic errors in some areas. Thus, the well-known Pearlette tephra was formerly believed to be a single unit (Frye *et al.*, 1948) but recent fission-track and geochemical studies have shown that at least three beds are involved (Table I), ranging in age from about 2.0 m.y. to 0.6 m.y. (Naeser *et al.*, 1973; Boellstorff, 1976). It follows, therefore, that gross miscorrelations must have been made in a region which serves as the type area for many of the North American Pleistocene stages. This has led to the call for a new or revised time-stratigraphic classification (Boellstorff, 1978).

Tephra layers in Pleistocene marine sediments provide an independent means of age assessment for boundaries of biostratigraphic (e.g., Seward 1974, 1979; Maenaka *et al.*, 1977) and $\delta\,^{18}O$ stages (Shackleton and Opdyke, 1973; Ninkovich *et al.*, 1978), which are more commonly estimated on the basis of assumed uniform sedimentation rate, calibrated by the pattern of magnetic polarity change. The palaeomagnetic chronology, however, is itself in need of improvement, as has recently been stated by Kukla and Nakagawa (1977, p. 288), who believe that the most promising approach to this problem is multiple K-Ar and fission-track analyses of well-defined tephra layers embedded in continuous sedimentary sequences, such as those in Japan and New Zealand. Similarly, tephra beds offer the hope of an improved chronology for the Antarctic (Gow and Williamson, 1971) and Greenland (Herron and Langway, 1978) ice cores.

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References

Auer, V., 1950, Las capas volcánicas como base de la cronología postglacial de Fuegopatagonia: Revista de Investigaciones Agricolas, v. 3, p. 49-208.

Aksu, A. E., and D. J. W. Piper, 1979, Baffin Bay in the past 100,000 yr.: Geology, v. 7, p. 245-248.

Bigazzi, G., and F. Bonadonna, 1973, Fission track dating of the obsidian of Lipari Island (Italy): Nature, v. 242, p. 322-323.

Blake, W., Jr., 1975, Radiocarbon age determinations and postglacial emergence at Cape Storm, southern Ellesmere Island, Arctic Canada: Geografiska Annaler, v. 57, p. 1-71.

Boellstorff, J. D., 1976, The succession of late Cenozoic volcanic ashes in the Great Plains: a progress report: in C. K. Bayne, ed., Guidebook, 24th Annual Meeting of the Midwestern Friends of the Pleistocene: Kansas Geological Survey, p. 37-71.

Boellstorff, J. D., 1978, North American Pleistocene stages reconsidered in light of probable Pliocene-Pleistocene continental glaciation: Science, v. 202, p. 305-307.

Borchardt, G. A., P. J. Aruscavage, and H. T. Millard, Jr., 1972, Correlation of the Bishop ash, a Pleistocene marker bed, using instrumental activation analysis: Jour. Sed. Petrol., v. 42, p. 301-306.

Bowles, F. A., R. N. Jack, and I. S. E. Carmichael, 1973, Investigation of deep-sea volcanic ash layers from equatorial Pacific cores: Geol. Soc. Amer. Bull., v. 84, p. 2371-2388.

Briggs, N. D., and J. A. Westgate, 1978, A contribution to the Pleistocene geochronology of Alaska and the Yukon Territory: fission-track age of distal tephra unit: in R. E. Zartman, ed., Short papers of the Fourth International Conference, Geochronology, Cosmochronology, Isotope Geology: United States Geol. Survey, Open-File Report 78-701, p. 49-52.

Cooke, H. B. S., J. M. Hall, and A. Ronai, 1979, Palaeomagnetic, sedimentary and climatic records from boreholes at Dévaványa and Vésztö, Hungary: Proceedings of the IGCP Project 128, Budapest, Hungary, August 1979, 28 p.

Creer, K. M., D. L. Gross, and J. A. Lineback, 1976, Origin of regional geomagnetic variations recorded by Wisconsinan and Holocene sediments from Lake Michigan, U.S.A., and Lake Windermere, England: Geol. Soc. Amer. Bull., v. 87, p. 531-540.

Czamanske, G. K., and S. C. Porter, 1965, Titanium dioxide in pyroclastic layers from volcanoes in the Cascade Range: Science, v. 150, p. 1022-1025.

Eaton, G. P., R. L. Christiansen, H. M. Iyer, A. M. Pitt, D. R. Mabey, H. R. Blank, Jr., I. Zietz, and M. E. Gettings, 1975, Magma beneath Yellowstone National Park: Science, v. 188, p. 787-796.

Fleischer, R. L., P. B. Price, and R. M. Walker, 1975, Nuclear tracks in solids: principles and applications: Berkeley, University of California Press, 605 p.

Fyre, J. C., A. Swineford, and A. B. Leonard, 1948, Correlation of the Pearlette volcanic ash from the glaciated region into the Southern High Plains: Geol. Soc. Amer. Bull., v. 58, p. 1182.

Fryxell, R., 1965, Mazama and Glacier Peak volcanic ash layers: relative ages: Science, v. 147, p. 1288-1290.

Gentner, W., D. Storzer, and G. A. Wagner, 1969, New fission track ages of tektites and related glasses: Geochim. Cosmochim. Acta, v. 33, p. 1075-1081.

Gow, A. J., and T. Williamson, 1971, Volcanic ash in the Antarctic ice sheet and its possible climatic implications: Earth and Planetary Sci. Letters, v. 13, p. 210-218.

Haggerty, S. E., 1979, The aeromagnetic mineralogy of igneous rocks: Canadian Jour. Earth Sci., v. 16, p. 1281-1293.

Heiken, G., 1972, Morphology and petrography of volcanic ashes: Geol. Soc. Amer. Bull., v. 83, p. 1961-1988.

Herd, D. G., and C. W. Naeser, 1974, Radiometric evidence for pre-Wisconsin glaciation in the northern Andes: Geology, v. 2, p. 603-604.

Herron, M. M., and C. C. Langway, Jr., 1978, Impact of volcanic eruptions on atmospheric composition as revealed in Greenland ice sheet strata: Geol. Soc. Amer., Abst. with Programs, v. 10, p. 420.

Hildreth, W., 1976, The Bishop Tuff: compositional zonation in a silicic magma chamber without crystal settling: Geol. Soc. America, Abst. with Programs, v. 8, p. 918.

Hodder, A. P. W., 1978, Refractive index and hydration of rhyolitic glass from Holocene tephras, North Island, New Zealand: New Zealand Jour. Geol. and Geophys., v. 21, p. 155-166.

Huang, T. C., and N. D. Watkins, 1976, Volcanic dust in deep-sea sediments: relationship of microfeatures to explosivity estimates: Science, v. 193, p. 576-579.

Huang, T. C., N. D. Watkins, D. M. Shaw, and J. P. Kennett, 1973, Atmospherically transported volcanic dust in south Pacific deep sea sedimentary cores at distances over 3000km from the eruptive source: Earth and Planet. Sci. Letters, v. 20, p. 119-124.

Izett, G. A., and C. W. Naeser, 1976, Age of the Bishop Tuff of eastern California as determined by the fission-track method: Geology, v. 4, p. 587-590.

Izett, G. A., R. E. Wilcox, H. A. Powers, and G. A. Desborough, 1970, The Bishop ash bed, a Pleistocene marker bed in the western United States: Quaternary Research, v. 1, p. 121-132.

Jack, R. N., and I. S. E. Carmichael, 1969, The chemical "fingerprinting" of acid volcanic rocks: California Division of Mines and Geology, Special Report 100, p. 17-32.

Kigoshi, K., 1967, Ionium dating of igneous rocks: Science, v. 156, p. 932-934.

Kohn, B. P., 1970, Identification of New Zealand tephra-layers by emission spectrographic analysis of their titanomagnetites: Lithos, v. 3, p. 361-368.

Kohn, B. P., 1979, Identification and significance of a late Pleistocene tephra in Canterbury district, South Island, New Zealand: Quaternary Research, v. 11, p. 78-92.

Kukla, G., and H. Nakagawa, 1977, Late Cenozoic magnetostratigraphy. Comparisons with bio-, climato-, and lithozones: Quaternary Research, v. 7, p. 283-293.

Ledbetter, M. T., and R. S. J. Sparks, 1979, Duration of large-magnitude explosive eruptions deduced from graded bedding in deep-sea ash layers: Geology, v. 7, p. 240-244.

Lerbekmo, J. F., and F. A. Campbell, 1969, Distribution, composition and source of the White River ash, Yukon Territory: Canadian Jour. Earth Sci., v. 6, p. 109-116.

Lerbekmo, J. F., J. A. Westgate, D. G. W. Smith, and G. H. Denton, 1975, New data on the character and history of the White River volcanic eruption, Alaska: in R. P. Suggate and M. M. Cresswell, eds., Quaternary Studies: Royal Society of New Zealand, Bull. 13, p. 203-209.

Lipman, P. W., 1971, Iron-titanium oxide phenocrysts in compositionally zoned ash-flow sheets from southern Nevada: Jour. Geol., v. 79, p. 438-456.

Macdougall, J. D., 1976, Fission-track annealing and correction procedures for oceanic basalt glasses: Earth and Planet. Sci. Letters, v. 30, p. 19-26.

Machida, H., 1976, Stratigraphy and chronology of late Quaternary marker-tephras in Japan: Geographical Reports of Tokyo Metropolitan University, no. 11, p. 109-132.

Maenaka, K., T. Yokoyama, and S. Ishida, 1977, Paleomagnetic stratigraphy and biostratigraphy of the Plio-Pleistocene in the Kinki district, Japan: Quaternary Research, v. 7, p. 341-362.

Mankinen, E. A., and G. B. Dalrymple, 1979, Revised geomagnetic polarity time scale for the interval 0 - 5 m.y. B.P.: Jour. Geophys. Res., v. 84, p. 615-626.

Mankinen, E. A., J. M. Donnelly, and C. S. Grommé, 1978, Geomagnetic polarity event recorded at 1.1 m.y. B.P. on Cobb Mountain, Clear Lake volcanic field, California: Geology, v. 6, p. 653-656.

Momose, K., K. Kobayashi, K. Minagawa, and M. Machida, 1968, Identification of tephra by means of ferromagnetic minerals in pumice: Earthquake Research Institute Bull., v. 46, p. 1275-1292.

Mullineaux, D. R., 1974, Pumice and other pyroclastic deposits in Mount Rainier National Park, Washington: United States Geol. Survey Bull. 1326, 83 p.

Naesar, C. W., 1976, Fission-track dating: United States Geol. Survey, Open-File Report 76-190.

Naeser, C. W., 1979, Fission-track dating and geologic annealing of fission tracks: in E. Jäger and J. C. Hunziker, eds., Lectures in Isotope Geology: Springer-Verlag, Berlin, p. 154-169.

Naeser, C. W., and H. Faul, 1969, Fission track annealing in apatite and sphene: Jour. Geophys. Research, v. 74, p. 705-710.

Naeser, C. W., and R. B. Forbes, 1976, Variation of fission-track ages with depth in two deep drill holes: EOS, Trans. American Geophys. Union, v. 57, p. 353.

Naeser, C. W., G. A. Izett, and J. D. Obradovich, 1980, Fission-track and K-Ar ages of natural glasses: United States Geol. Survey Bull. 1489, in press.

Naeser, C. W., G. A. Izett, and R. E. Wilcox, 1973, Zircon fission-track ages of Pearlette family ash beds in Meade County, Kansas: Geology, v. 1, p. 187-189.

Ninkovich, D., 1968, Pleistocene volcanic eruptions in New Zealand recorded in deep-sea sediments: Earth and Planet. Sci. Letters, v. 4, p. 89-102.

Ninkovich, D., and W. L. Donn, 1976, Explosive Cenozoic volcanism and climatic implications: Science, v. 194, p. 899-906.

Ninkovich, D., N. J. Shackleton, A. A. Abdel-Monem, J. D. Obradovich, and G. A. Izett, 1978, K-Ar age of the late Pleistocene eruption of Toba, north Sumatra: Nature, v. 276, p. 574-577.

Nishimura, S., and T. Yokoyama, 1973, Fission-track ages of volcanic ashes in 200m core sample of Lake Biwa, Japan: Proceedings Japan Academy, v. 49, p. 615-618.

Persson, C., 1966, Försök till tefrokronologisk datering av några svenska torvmossar: Geol. Föreningens i Stockholm Förhandlingar, v. 88, p. 361-394.

Persson, C., 1967, Försök till tefrokronologisk datering i tre norska myrar: Geol. Förenings i Stockholm Förhandlingar, v. 89, p. 181-197.

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

Powers, H. A., and R. E. Wilcox, 1964, Volcanic ash from Mount Mazama (Crater Lake) and from Glacier Peak: Science, v. 144, p. 1334-1336.

Ruddiman, W. F., and L. K. Glover, 1972, Vertical mixing of ice-rafted volcanic ash in North Atlantic sediments: Geol. Soc. Amer. Bull., v. 83, p. 2817-2836.

Sahlstein, T. G., 1932, Petrologie der postglazialen vulkanischen Aschen Feuerlands: Acta Geographica, v. 5, p. 1-35.

Sarna-Wojciki, A. M., 1976, Correlation of late Cenozoic tuffs in the central Coast Ranges of California by means of trace- and minor-element chemistry: United States Geol. Survey Prof. Paper 972, 30 p.

Sato, K., S. Aramaki, and J. Sato, 1972, Discrepant results of C-14 and fission track datings for some volcanic products in southern Kyushu: Geochemical Jour., v. 6, p. 11-16.

Seward, D., 1974, Age of New Zealand Pleistocene substages by fission-track dating of glass shards from tephra horizons: Earth and Planet. Sci. Letters, v. 24, p. 242-248.

Seward, D., 1979, Comparison of zircon and glass fission-track ages from tephra horizons: Geology, v. 7, p. 479-482.

Shackleton, N. J., and N. D. Opdyke, 1973, Oxygen isotope and palaeomagnetic stratigraphy of equatorial Pacific core V28-238: oxygen isotope termperatures and ice volumes on a 10^5 and 10^6 year scale: Quaternary Research, v. 3, p. 39-55.

Shaw, H. R., R. L. Smith, and W. Hildreth, 1976, Thermogravitational mechanisms for chemical variations in zoned magma chambers: Geol Soc. America, Abst. with Programs, v. 8, p. 1102.

Smith, D. G. W., and J. A. Westgate, 1969, An electron probe technique for characterising pyroclastic deposits: Earth and Planet. Sci Letters, v. 5, p. 313-319.

Souther, J. G., 1976, Geothermal power, the Canadian potential: Geosci. Canada, v. 3, p. 14-20.

Steen-McIntyre, V., 1975, Hydration and superhydration of tephra glass – a potential tool for estimating age of Holocene and Pleistocene ash beds: in R P. Suggate and M. M. Cresswell, eds., Quaternary studies: Royal Society of New Zealand, Bulletin 13, p. 271-278.

Steen-McIntyre, V., 1977, A manual for tephrochronology: Ph.D. dissertation, University of Idaho, Moscow, published by the author, Idaho Springs, Colorado, 167 p.

Storzer, D., G. Poupeau, and M. J Orcel, 1973, Ages-plateaux de mineraux et verres par la methode des traces de fission: Compt. rend . Paris, v 276, p. 137-139.

Storzer, D., and G. A. Wagner, 1969, Correction of thermally lowered fission track ages of tektites: Earth and Planet. Sci. Letters, v. 5, p. 463-468.

Suzuki, M., 1973, Chronology of prehistoric human activity in Kanto, Japan. Part I: Journal of Science, University of Tokyo, sec. V, v IV, p. 241-318.

Suzuki, M., 1974, Chronology of prehistoric human activity in Kanto, Japan. Part II: Journal Faculty of Science, University of Tokyo, sec V, v IV, p. 395-469.

Thorarinsson, S., 1944, Tefrokronologiska studier på Island, (English summary: Tephrochronological studies in Iceland): Geografiska Annaler, v. 26, p. 1-217.

Thorarinsson, S., 1974, The terms "tephra" and "tephrochronology": in J. A. Westgate and C. M. Gold, eds., World Bibliography and Index of Quaternary Tephrochronology, Printing Services Department, The University of Alberta, Edmonton, P. xvii-xviii.

Topping, W. W., 1973, Tephrostratigraphy and chronology of late Quaternary eruptives from the Tongariro volcanic centre, New Zealand: New Zealand Jour. Geol. and Geophys., v. 16, p. 397-423.

Vucetich, C. G., and W. A. Pullar, 1969, Stratigraphy and chronology of late Pleistocene volcanic ash beds in central North Island, New Zealand: New Zealand Jour. Geol. and Geophys., v. 12, p. 784-837.

Wagner, G. A., 1978, Archaeological applications of fission-track dating: Nuclear Track Detection, v. 2, p. 51-64.

Walker, G. P. L., 1971, Grain-size characteristics of pyroclastic deposits: Journal of Geology, v. 79, p. 696-714.

Walker, G. P. L., 1973, Explosive volcanic eruptions – a new classification scheme; Geologischen Rundschau, v. 62, p. 431-446.

Watanabe, N., and M. Suzuki, 1969, Fission track dating of archaeological glass materials from Japan: Nature, v. 222, p. 1057-1058.

Weller, J. M. 1960, Stratigraphic principles and practice: Harper and Row, Publishers, New York, 725 p.

Westgate, J. A., 1977, Identification and significance of late Holocene tephra from Otter Creek, southern British Columbia, and localities in west-central Alberta: Canadian Jour. Earth Sci., v. 14, p. 2593-2600.

Westgate, J. A., N. D. Briggs, A. MacS. Stalker, and C. S. Churcher, 1978, Fission-track age of glass from tephra beds associated with Quaternary vertebrate assemblages in the southern Canadian plains: Geol. Soc. Amer. Abst. with Programs, v. 10, p. 514-515.

Westgate, J. A., E. A Christiansen, and J. D. Boellstorff, 1977, Wascana Creek Ash (Middle Pleistocene) in southern Saskatchewan: characterisation, source, fission track age, palaeomagnetism and stratigraphic significance: Canadian Jour. Earth Sci., v. 14, p. 357-374

Westgate, J. A. and M. E. Evans, 1978, Compositional variability of Glacier Peak tephra and its stratigraphic significance: Canadian Jour. Earth Sci., v. 15, p. 1554-1567.

Westgate, J. A. and R. J. Fulton, 1975, Tephrostratigraphy of Olympia interglacial sediments in south-central British Columbia, Canada: Canadian Jour. Earth Sci., v 12, p. 489-502.

Westgate, J. A., and C. M. Gold, eds., 1974, World bibliography and index of Quaternary tephrochronology: Printing Services Department, The University of Alberta, Edmonton, 528 p.

Westgate, J. A., D. G. W. Smith, and M. Tomlinson, 1970, Late Quaternary tephra layers in southwestern Canada: in R. A. Smith and J. W. Smith, eds., Early man and environments in northwestern North America. University of Calgary Archaeological Association, The Students' Press, Calgary, p. 13-34.

Wilcox, R E., 1965, Volcanic-ash chronology: in H. E. Wright, Jr. and D G. Frey, eds., The Quaternary of the United States: Princeton University Press, p. 807-816.

Wilcox, R. E. and G. A. Izett, 1973, Criteria for the use of volcanic ash beds as time-stratigraphic markers: Geol. Soc. America, Abst. with Programs, v. 5, p. 863.

Williams, H. and G. Goles, 1968, Volume of the Mazama ash-fall and the origin of Crater Lake caldera: in H. M. Dole, ed., Andesite Conference Guidebook: Department of Geology and Mineral Industries, Oregon, Bull. 62, p. 37-41.

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