URANIUM FISSION-TRACK DATING OF GLASS SHARDS FROM SELECTED VOLCANIC ASH DEPOSITS IN THE SOUTHERN HIGH PLAINS BORDER REGION

BY

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PREFACE

A desire to obtain a better understanding of the Pleistocene geomorphic evolution of and soil development in western and central Oklahoma, south central Kansas, and the eastern part of the Texas Panhandle was the primary motivation for this research. A major lithologic discontinuity occurs between the Permian bedrock and the unconsolidated sediments which rest upon it over much of the area. Volcanic ash deposits are included in the alluvial and eolian deposits. Ash deposits are potential time marker beds for reference in soil and landscape development interpretations because it is possible to date them. The upland terraces of the major rivers were of particular interest because they are important to the agriculture of the area, are a major water source for many parts of the area, and the soils described on them are well developed.

The initial proposal for this project was the dating of the ash deposits and a detailed study of soils associated with some of the ashes. A year into the project it became apparent that the soils part had to be dropped. Dating of 35 ash deposits proved to be time consuming and provided enough valuable information to make this thesis.

The results of the dating are fairly consistent with results reported by other researchers involved in the dating of volcanic ash deposits. Continued characterization and correlation research on the ashes dated in this study should make them unique and valuable time markers for use in interpreting the Pleistocene geomorphic evolution of

a large and important region. A better understanding of the soil development in the unconsolidated deposits of the region should also be accomplished by using the dated ash deposits as time marker beds.

The years I have spent working on this project have been some of the best I have known. I need to thank Dr. John Boellstorff for his assistance and encouragement. The suggestions of Dr. Arthur Hounslow and Dr. Jack Vitek made this work much more readable and understandable and their help was greatly appreciated. I would like to thank my parents, Phil and Kitty Ward, Jr. of Tushka, Oklahoma for their never ending support and much needed advice. I would also like to thank all the people I have worked with in the lab namely Troy Collier, Dhivy Sathianathan, Mary Mckinzie, Judy Birch, Alfredia White, Jennifer Martin, Vicki Jacobsen, Steve Alspach, and all the others for putting up with me and making being in the lab a lot of fun. I also need to thank the Agronomy Department and the University Center for Water Research for their financial support. My sincerest thanks go to Dr. Brian Carter. His guidance, encouragement, and support were the best of help. I do not believe I could have learned as much and still had as much fun with anyone else. I will never forget the field trips to the ash deposits. The beauty of the ashes and associated landscapes is forever entrenched in my mind.

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INTRODUCTION

Introduction

Time is a key factor in the development of landscapes and soils. Present day landscapes and soils are the result of geologic and geomorphic processes operating for billions of years. Erosion, deposition, tectonics, volcanism, climatic change, and biotic activity are some of the processes that continually shape and reshape the surface of the earth.

Time passes, continuing on second after second, minute after minute, and year after year. Every process at work on the planet changes over time. On the surface, landforms develop and disappear in response to geologic and geomorphic processes. Common landforms in some regions include stream floodplains, stream terraces, sand dunes, and rock outcrops.

Sediments on the surface are modified by various processes. How the sediments are transformed to soil is related to the additions, losses, translocations, and transformations that occur at a particular site. Major factors affecting soil development are climate, topography (% slope and slope aspect), biotic activity, type of soil parent material, and time.

Landscapes and soils undergo periods of stability and instability. Changes in the processes influencing the development of a landscape or

soil affects this development. The result of the many events in the developmental history of landscapes and soils are the landscapes and soils which are present today.

Soils and landforms are related chronologically. Older landforms are distinguished from younger landforms on the basis of geomorphic parameters like distance from streams and elevation above streams. Soil morphology is also important in differentiating between older and younger landforms as well as older and younger soils. Rock outcrops can be the oldest landforms within a landscape. Outcrops of differing ages are recognizable by landscape position and position in the rock-stratigraphic sequence.

A better understanding of the development of a landscape or soil can be accomplished by determining when events occurred during this development. Clues concerning the chronological development of a landscape can be found in the sediment which the landforms of a landscape are made of. Carbon-14 bearing material can be radiocarbon dated to about 70,000 years ago. Present landscapes can contain landforms and soils much older than 70,000 years.

Technological and scientific advances during the last 30 years have produced numerous dating techniques. The use of radioisotopes to date geologic materials is a common practice today by geochronologists. Isotopes of uranium, thorium, lead, argon, potassium, and others are used for dating. Sophisticated instrumentation is also commonplace.

One of these techniques is the uranium fission-track dating of glass shards from volcanic ash deposits. Shards millions of years old can be dated. The ability to date volcanic ash deposits make them potentially useful time marker beds for interpreting landscape and soil

development in a much broader timeframe than possible with radiocarbon dating.

The technique of dating volcanic ash can be applied east of the Southern High Plains eastern escarpment in an area where vast terrace deposits line the major streams. During the formation of these terraces as well as the formation of the Great Plains, immense volcanic eruptions occurred in the western United States which added deposits of volcanic ash to the Great Plains and terrace deposits. Lenses of ash have been preserved in some places making them potential time markers for interpreting landscape and soil development for this plains border region.

The primary objective of this research is to establish the ash beds of the Southern High Plains border region as time markers for interpreting the geomorphic history of the region. To accomplish this it is proposed to 1) locate volcanic ash beds in the southern High Plains border region, 2) collect samples of these ash deposits, and 3) uranium fission-track date glass shards from the collected samples. These interpretations will result in an increased knowledge of 1) long-term erosion rates, 2) the time factor in soil profile development, 3) the ages of geomorphic features, particularly the large, economically important, constructional terraces dated by the ashes, and 4) climatic changes that occured during the formation of these terraces. These interpretations will also lead to more useful soil and surficial geology mapping and improved utilization, management, and conservation of the sediments associated with the ashes.

The Southern High Plains Border Region

Description

The Southern High Plains is a part of the central United States known as the Great Plains. This vast, rolling, mostly grass-covered plain formed as a result of the uplift of the Rocky Mountains. The sediment displaced by the uplift was mobilized and transported by the wind, streams, and gravity. Eventual deposition as fan, channel, sand dune, floodplain, and terrace deposits created the Great Plains. Formation of these plains started approximately 70 million years ago and continues to the present (Trimble, 1980). The uplift of the Rockies started in the north and continued over time to the south because older deposits of the Great Plains are found in the northern part of the region.

The Southern High Plains border region in this study encompasses parts of Oklahoma, Kansas, and Texas. Figure 1 (p. 5) shows the major rivers draining the region as well as some of the larger towns of the region.

The predominantly Permian-aged bedrock of of the region is covered by discontinuous deposits of unconsolidated sediment of alluvial and eolian origin. Broad, constructional terraces and well developed sand dune belts line the major rivers draining the region. These deposits vary in thickness from less than ten feet in some places to hundreds of feet in others. Sediment size ranges from coarse gravels to clays.

The main rivers draining the region, including south-central Kansas, Oklahoma, and the eastern half of the Texas Panhandle are the Arkansas, Salt Fork of the Arkansas, Cimarron, North Canadian (Beaver),

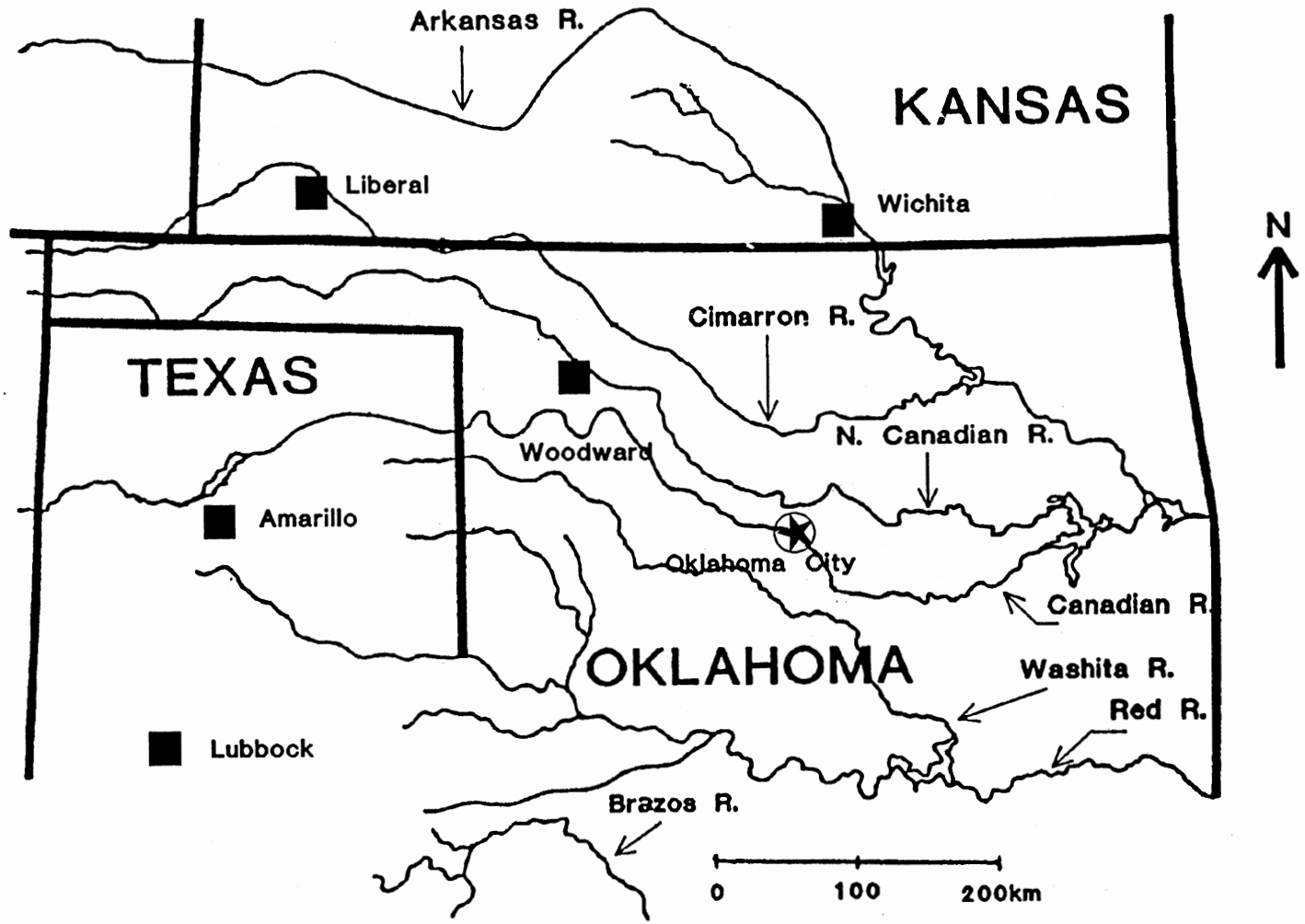


Figure 1. Map Showing Major Rivers and Towns Within Study Area

Canadian, Washita, North Fork of the Red, Salt Fork of the Red, and Prairie Dog Town Fork of the Red. The Arkansas and Canadian have sources in the Southern Rocky Mountains, the Cimarron originates in the Raton uplift region of New Mexico and Colorado whereas the others originate in the Southern High Plains of Texas, Oklahoma, and Kansas.

Major bedrock outcrops occur as interesting geomorphic features within the region. They include the Cambrian-aged, igneous Wichita Mountains of southwest Oklahoma, the gypsum-capped, Permian-aged Glass Mountains which run in a general north-south line across the western part of the region, and the Pennsylvanian-aged, limestone Arbuckle Mountains of south-central Oklahoma. Each of these groups of mountains rise high above the surrounding plains as markers of past geologic times and indicators of the affects of geomorphic processes on bedrock.

Economics

The terraces are economically important. Terrace surfaces and floodplains are planted in wheat, cotton, or grain sorghum annually. Livestock is raised where crops are not grown. Oil and natural gas wells extending into the Permian basin dot the landscape in many places. Gypsum is mined for building purposes. Numerous lakes, built behind large dams, are available for recreational purposes. Major cities like Tulsa, Oklahoma City, Enid, and Lawton are built on terrace sediments as are many other smaller towns. The alluvium and terraces are major shallow aquifers and water sources for parts of the area (Oklahoma Geological Survey, 1979, p. 8).

Soils

The effects of Jenny's (1941) factors of soil formation, (climate, topography, biotic activity, parent material, and time) are seen in the soils of the region. Soils have formed in material weathered from the Permian shales, sandstones and gypsum beds and in the gravels, sand, silts and clays brought to the region from the High Plains by the rivers and the wind. Soil development continues on the flat, agriculturally influenced fields, in the pastures and meadows between the plowed fields, and under the groves of black locust, mesquite, elm, cottonwood, and oak. Human activty, domestic animals, wildlife, and microorganisms influence soil development. Soil has developed on the flat tabletop-like surfaces of the stream floodplains and terraces, the concave and convex slopes of the hills, or the steep slopes of the High Plains escarpment and bedrock outcrops. Variation in the annual rainfall, mean annual soil temperature and annual wind speed occurs across the region. This variation plus the influence of time is reflected in the differences in soil development, for example, between the surface soil of a recent stream levee deposit and the surface soil on an old terrace deposit that caps a bedrock divide between two major rivers.

Mollisols are the most common soil order found in the region (Gray and Roozitalab, 1976, page 5). Characteristically the mollisols have an organic-rich topsoil and a base-rich subsoil. The type of mollisol present at any particular location is dependent on the conditions the soil has formed under. Gray and Roozitalab (1976) provide an analysis of the distribution, classification, and characterization of key Oklahoma soils. Gray and Galloway (1969, Fig. 11, 15, 16, 17, 20, 27, pp. 32-37) indicate soil associations derived from terrace material and

describe these soils and other soils of the region.

Stratigraphy

Permian-aged rocks are the bedrock for most of the study area in western Oklahoma. In the far eastern part of the state rocks associated with the Ouachita and Ozark mountains are of older Paleozoic age. Cretaceous rocks are found ocasionally in the northwestern and western parts of the area setting above the Permian sediments. In the western part of the area, Tertiary sediments of Miocene and Pliocene age cover the Permian and/or Cretaceous rocks but are absent in the central and eastern parts of the area. Some volcanic ash deposits can be found in these Tertiary deposits.

All across the area, Pleistocene and Holocene sediments of widely differing ages rest upon the underlying Permian, Cretaceous, or Tertiary sediments. Most of the volcanic ashes are found in the Pleistocene sediments. Holocene sediments occur along the floodplains of the major rivers and on low terraces and floodplains of the smaller streams which dissect the larger Pleistocene terrace deposits lining the major rivers or cut through the bedrock where Pleistocene terraces are not found. Sand dune belts of Holocene and Late Pleistocene age occur along the north side of the major rivers as evidence of the prevailing southwestern winds and previous time periods of aridity.

Volcanic Ash Deposits

Occurrence and Composition

Beds of volcanic ash (Fig. 2, p. 9) are found within the unconsolidated alluvial and eolian sediment of the High Plains border

Figure 2. Volcanic Ash Bed in Ellis Co., Oklahoma (Ash 24 this study)

region. These beds are sometimes exposed along terrace escarpments, road cuts, and mining excavations. Thickness of the ash lentils range from less than 1 meter to greater than 10 meters and the areal extent of the deposits is estimated at between 0.5 and 200 hectares.

The ash beds are composed primarily of silt and sand-sized glass shards (Fig. 3, p. 11). Glass-mantled minerals (microphenocrysts) such as quartz, sanidine, hornblende, zircon, and ilmenite are also present in the beds. Detrital material incorporated during transport and deposition of the beds make up another small portion of the deposits. The high purity of the ash deposits suggests that subsequent transportation after initial deposition was minimal.

The ash deposits are usually stratified fine beds of differing thickness and particle size. Thickness of beds range from less than one cm to as much as 20 cm and the particle size of the beds ranges between silt and fine sand (>0.002 mm diameter to <0.25 mm diameter). Directly above the relatively pure ash lentils are stratified beds of ash and soil material, on top of which rests a sequence of soil profiles or a single soil profile at the ground surface. Below the ash, poorly and somewhat poorly drained soil profiles are described (Fig. 4, p. 12).

Ash deposits are found along all the major through-flowing streams of the region. Elevation above stream for the ash deposits ranges from 9 to 157 meters. Distance from major streams ranges from <1 km to >24 km. Table 1 (p. 13) summarizes some of the geomorphic characteristics for each of the ash beds sampled for this study.

Uranium Fission-Track Dating

Ages of the shards in the ash beds can be measured using the

Figure 3. Photomicrograph of Shards from a Volcanic Ash in Harper Co., Oklahoma (Ash 21 this study)

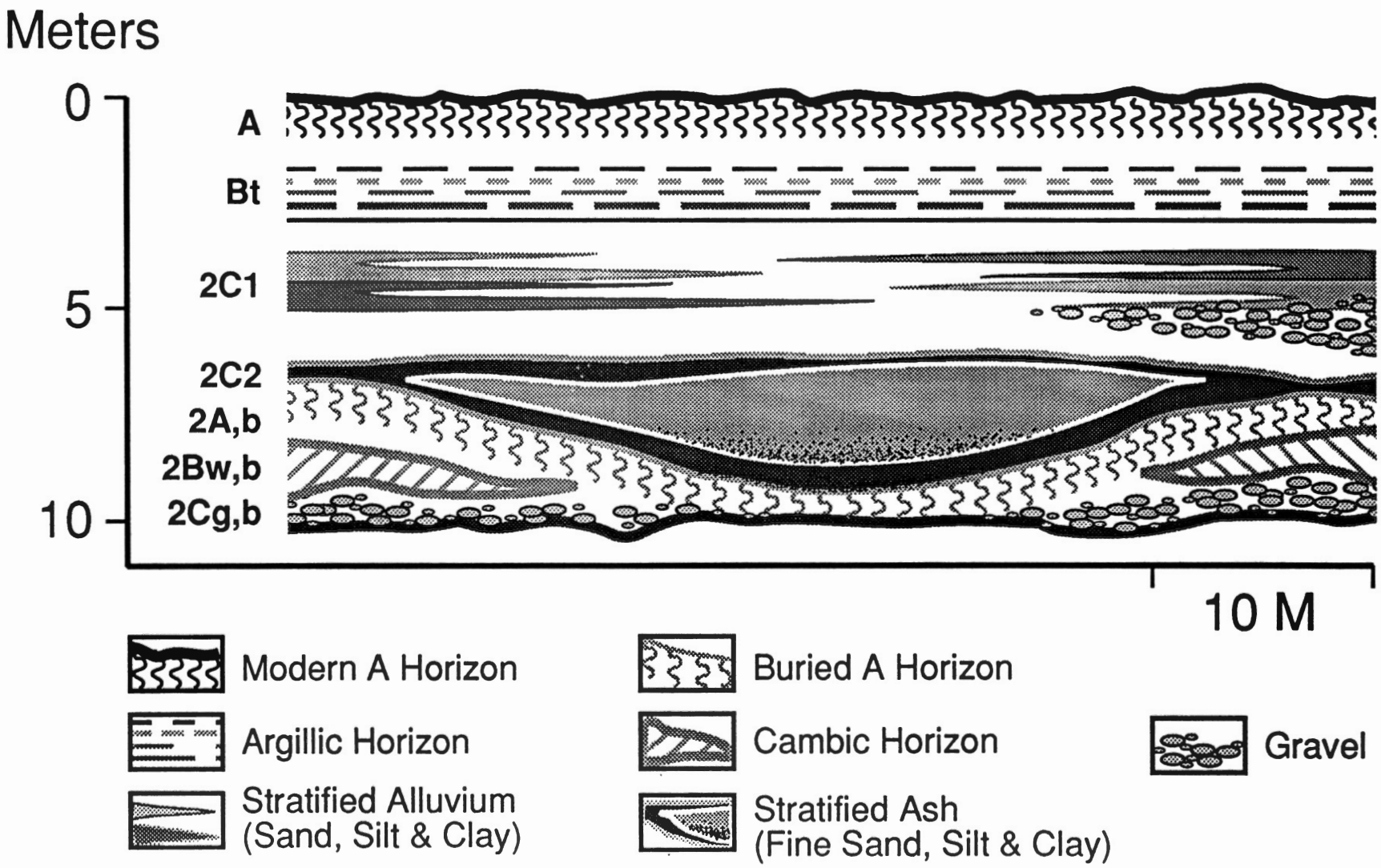


Figure 4. Idealized Stratigraphic Schematic of a Typical Ash Deposit

TABLE I

GEOMORPHIC CHARACTERISTICS OF SAMPLED ASH DEPOSITS

Ash Number	Elevation (m) Ash	Stream	Distance from Stream (km)	Major Stream Basin	Underlying Geology
1	549	530	1	Arkansas	Tertiary
2	561	546	1	Arkansas	Tertiary
3	792	738	12	Cimarron	Tertiary
4	600	591	1	Arkansas	Tertiary
5	750	713	2	Cimarron	Tertiary
6	546	512	2	Arkansas	Tertiary
7	640	616	2	Arkansas	Permian
8	466	457	0.5	Arkansas	Permian
9	759	735	3	Cimarron	Tertiary
10	482	472	0.3	Arkansas	Permian
11	399	378	5	Arkansas	Permian
12	744	701	3	Cimarron	Tertiary
13	543	509	4	Washita	Permian
14	668	652	3	N. Canadian	Tertiary
15	597	552	15	N. Canadian	Permian
16	543	524	2	Canadian	Permian
17	533	515	6	Red	Permian
18	664	628	3	Cimarron	Tertiary
19	908	750	24	Canadian	Tertiary
20	579	472	20	Washita	Permian
21	695	658	2	N. Canadian	Tertiary
22	719	652	12	Canadian	Tertiary
23	664	620	5	Cimarron	Tertiary
24	668	616	1	Canadian	Tertiary
25	756	725	6	N. Canadian	Tertiary
26	628	607	1	Red	Tertiary
27	448	421	8	Red	Permian
28	466	445	2	Red	Permian
29	366	347	6	Cimarron	Permian
30	244	226	1	N. Canadian	Pennsylvanian
31	479	460	3	Arkansas	Permian
32	213	198	3	N. Canadian	Pennsylvanian
33	241	216	11	N. Canadian	Pennsylvanian
34	323	283	12	Canadian	Pennsylvanian
35	652	597	13	N. Canadian	Tertiary

uranium fission-track dating method because they contain small amounts of U^{238}. The natural or spontaneous fission of a U^{238} atom creates a damage channel or fission-track in the glass which can be seen in transmitted light at moderate (200-500X) magnifications after the shard has been etched with 24% hydrofluoric acid (HF). Figure 5 (p. 15) is an SEM photomicrograph of fission-tracks on glass.

Dating of the shards involves determining values for three variables (the spontaneous track density, the induced track density, and the neutron dose) in an age equation. The U^{238} fission track or spontaneous track density is the number of fission tracks per unit area on shards that have not been irradiated. The U^{235} fission track or induced track density is the number of fission tracks per unit area on shards that have been irradiated. Fission-tracks on the non-irradiated glass are caused by the natural, spontaneous decay of U^{238} atoms. Fission-tracks on the irradiated glass are caused by induced decay of U^{235} atoms by bombardment of the glass with thermal neutrons. Some spontaneous tracks can also be seen on the glass that has been irradiated. The neutron dose is the number of thermal neutrons per unit area per second bombarding the shards during the irradiation. The neutron dose is measured by including glass dosimeters of known uranium content in the irradiation and counting the number of fission tracks per unit area on the dosimeter after the irradiation. The spontaneous track density is dependent on the age of the glass and its original uranium content. The induced track density is dependent on the present uranium content of the glass and the neutron dose. The ratio of spontaneous tracks to induced tracks is entered into an age equation which includes the measured neutron dose, total uranium and U^{238} fission decay

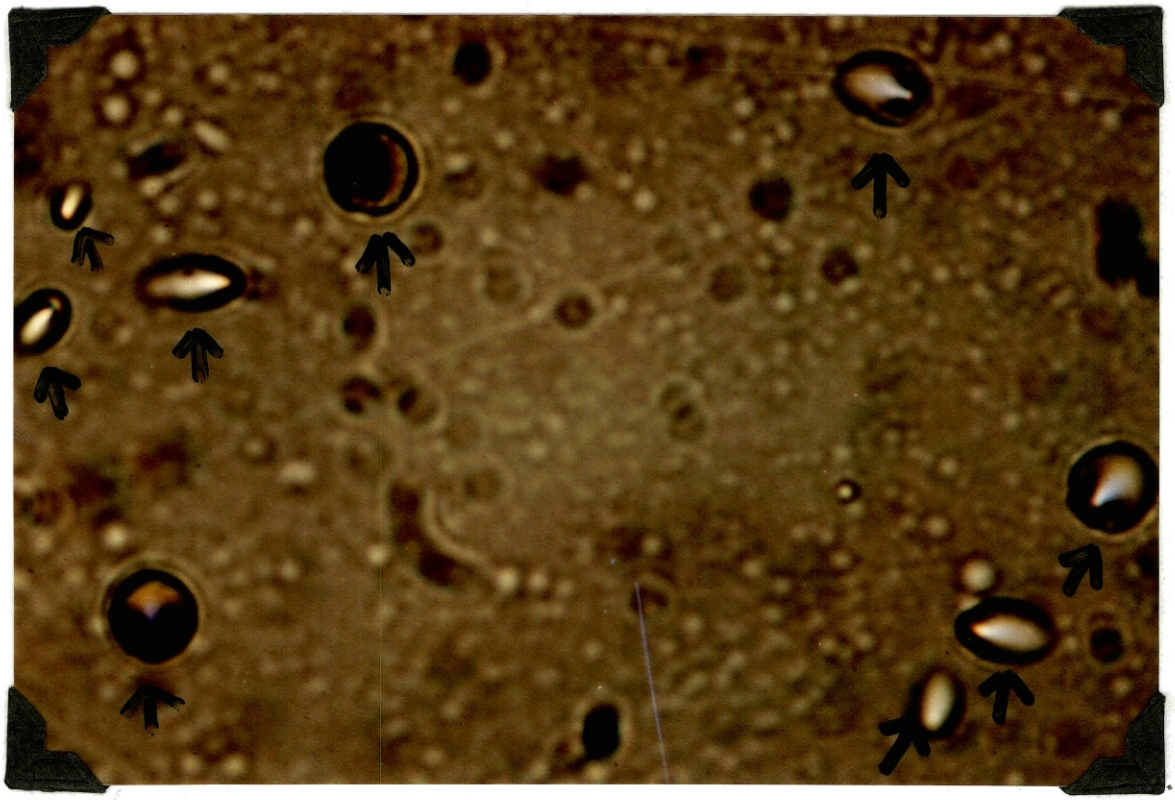


Figure 5. Fission-Tracks on Glass (500X magnification).
Field width is 0.29 mm.

constants, the natural isotopic ratio of U^{235} to U^{238}, and a probability constant for the induced decay of U^{235} and an age is calculated. The result of the measurements and calculations is an estimate of how much of the U^{238} has undergone natural decay by fission which is directly related to how old the glass or glass shards are because spontaneous fission of U^{238} occurs at a constant rate. The age coincides with the time the molten lava ejected from the volcano, solidified and became ash.

Time Marker Beds

The characteristics of an ash deposit which are useful in identifying its source and interpreting how it relates to other ash deposits (i.e. whether or not it is ash from the same eruption) are the shard fission-track age, shard index of refraction, shard morphology, and shard chemical composition, kinds of microphenocrysts, and paleomagnetic direction and stratigraphic position of the ash bed. Previous tephrachronological research indicates that eruptions from vents hundreds of miles apart have occurred at closely spaced time intervals and that certain volcanic regions of the western U.S. have produced eruptions at widely spaced time intervals over the last several million of years. Complete characterization of an ash bed is essential for it to be used as a reliable time marker bed (Izett, 1981).

CHAPTER II

REVIEW OF LITERATURE

Introduction

Volcanic ash deposits in the Great Plains have been recognized as time marker beds which can contribute to understanding the geomorphic evolution of the region. A significant number of published reports have focused on ash deposits. This review will discuss 1) the identification of volcanic ash in the Great Plains region, 2) the use of ash beds as time markers, and 3) the fission-track dating technique and problems associated with it.

Identification of Volcanic Ash in the Great Plains

Buttram (1914) studied volcanic ash deposits found in Oklahoma. Two important observations of his were, "... the eruptions in late Tertiary or Pleistocene times in the general Rocky Mountain region gave rise to the volcanic dust of this state," and, "... our volcanic dust could have come from New Mexico or Colorado or even points farther removed." Burwell and Ham (1949), in their study of the ash as a commercial asset for brick-making, cited scores of volcanic ash localities in Oklahoma. These early reports are noteworthy in that ash was recognized and sought for economic gain.

Izett and Wilcox (1982) discussed the Pearlette ashes which

erupted from the Yellowstone caldera of northwestern Wyoming. They cited hundreds of localities of volcanic ash beds across the Great Plains and hypothesized on the age and source areas based mainly on the stratigraphic position, petrographic data, and occasional radiometric data. Also discussed were the other major source areas for Great Plains volcanic ash, particularly the Long Valley caldera of eastern California and the Toledo and Valles calderas of central New Mexico.

Use of Volcanic Ash Deposits as Time Marker Beds

Birkeland (1974) emphasized the importance of the volcanic ash beds as time markers with the statement, "... Some of the best Quaternary time lines are volcanic ash, ..., Middle to early-Pleistocene ashes are widespread in the western United States and in the midcontinent and serve as prime correlation tools over the region." Reeves (1976) supplied an interesting viewpoint when writing about the geomorphic evolution of the southern High Plains with, "... It was admittedly easier to do Quaternary stratigraphy in the area 15 years ago when any volcanic ash was simply identified as Kansan "Pearlette"." He also expressed the need for continued research on the volcanic ashes of the area. Izett (1981) described the interest in volcanic ash beds as time marker beds stating, "... In the last 10 years there has been increased interest, by many workers in a variety of earth science disciplines for tephrachronological information gathered with the goal of establishing volcanic ash beds as time-stratigraphic markers that are useful for correlation and dating of associated upper Cenozoic sedimentary deposits." He also emphasized that, "... No single, rapid scan, chemical, mineralogical, petrographical, isotopic, or

paleomagnetic method will result in establishing correlations with a high probability of success," in the same paper which included dating and extensive characterization of more than 60 ash beds from the western U.S..

Numerous studies including dating and characterization data have been done. Without the aid of a dating method, Frye et. al. (1948) concluded that most of the ash deposits of the Great Plains were of Late Kansan or early Yarmouthian age on the basis of petrographic, chemical, and stratigraphic data in a study of Pleistocene deposits of the central Great Plains and the relationship to Pleistocene glacial deposits of the midwestern United States. Izett et. al. (1970) correlated 11 volcanic ash deposits from across the Great Plains (California to Nebraska) as originating from the Long Valley caldera in eastern California using chemical and petrographic data. The Bishop Ash Bed (~0.7 m.a. (million years ago)) was proposed as a time marker for the western U.S. and stratigraphic and age relationships of several beds of Bishop Ash with other volcanic ash deposits from other source areas was discussed. Seward (1974) reported glass shard fission-track ages between 0.3 and 2.0 m.a. for several different ash deposits in New Zealand. Boellstorff (1976) fission-track dated glass shards from several volcanic ash deposits of the central Great Plains. Chemical analysis was done on the shards of Pleistocene age and definitive correlations were identified (Boellstorff, 1976). Stratigraphic relationships of ashes ~0.6 to ~11.0 m.a. and the relationship to other Tertiary and Pleistocene deposits of the central Great Plains with a goal of accurate regional correlations were also discussed (Boellstorff, 1976). Boellstorff (1978a, 1978b) reviewed problems concerning Pleistocene stratigraphy and nomenclature

caused by new age data created by the ability to give numerical ages to volcanic ash deposits. Naeser et. al. (1982) reported glass shard and zircon fission-track ages between 0.1 and 2.6 m.a. in a study of Alaskan and Yukon Territory Pliocene and Pleistocene stratigraphy. The ash deposits were used as marker beds for correlation between glacial and non-glacial deposits and deposits formed by different geomorphic agents. Johnson et. al. (1982) reported zircon fission-track ages between 1.5 and 3.0 m.a. for ash deposits in the Siwalik Group, northern Pakistan, geologic formations containing important Miocene and Pliocene faunal zones of south Asia. Westgate (1982) called the Old Crow Tephra of Alaska, "...the first extensive Pleistocene tephra to be documented in northwestern North America." Kyle and Seward (1984) suggested ash retrieved in deep sea soil cores near Antarctica was erupted from New Zealand volcanoes because of the similarities of K-Ar ages of the ash in the cores and the glass shard fission-track ages of New Zealand ash deposits. Izett and Naeser (1986) reported significantly different glass shard versus zircon fission-track ages of some Miocene ash deposits of the Espanola Basin, New Mexico. Westgate et. al. (1987) fission-track dated, characterized by petrographic and chemical means, and discussed the stratigraphic significance of several volcanic ash deposits in western Washington. The marker beds dated at ~1.0 m.a. and were collectively called the Lake Tapps tephra (Westgate et. al., 1987). Westgate et. al. (1990) fission-track dated glass shards from ash deposits around Fairbanks, Alaska to interpret the landscape development of an area much affected by eolian processes. Ages reported ranged between 0.15 and 1.9 m.a..

Studies have used ash as time marker beds for interpreting

geomorphic evolution of different areas. Fay (1959) used the location of some volcanic ash deposits in Pleistocene sediments of the Canadian River to give a late Kansan date to the time of a stream capture event on that river. Frye and Leonard (1963) gave a Kansan age to an extensive terrace deposit of the Red River in Texas based partially on the presence of volcanic ash within sediment of that deposit. Boellstorff and Steineck (1975) fission-track dated glass shards from marine deposits off the coast of southern California. The dating results and stratigraphic relationships with particular biostratigraphic markers indicated a revision of the chronology of those deposits. The fission-track age of glass shards (~3.1 m.a.) from a volcanic ash deposit taken in a deep well core of the Gulf of Mexico supported correlation of paleontological data with paleomagnetic stratigraphy of the Gulf (Beard et. al., 1976). Reheis (1987) estimated the ages of alluvial deposits of a stream in southwestern Montana based on the locations and inferred ages of ash deposits within the alluvium. Inferred ages were 0.6 and 2.0 m.a. (Izett and Wilcox, 1982). Holliday (1988) suggested the beginning of the Blackwater Draw Formation, the most extensive and economically important deposit in the southern High Plains, began ~1.5 million years ago based on the presence of Guaje Ash near the base of the formation. Carter et. al. (1990) used landscape position and ages of ash deposits dated in this study to interpret soil development and geomorphic evolution of the Rolling Red Plains of western and central Oklahoma. The same soil series were found mapped on terraces of differing ages.

Dated ash deposits have been used in the study of early man. (Gleadow, 1980; Hay and Leakey, 1982; Hall et. al., 1984; Verma, 1989).

Deposits in Ethiopia, Kenya, and India have been dated. Ages of the ashes associated with the fossil-bearing beds ranged between 1.6 and 4.0 m.a.. The Footprint Tuff of Laetoli, Ethiopia, retained thousands of fossil footprints including those of early man (Hay and Leakey, 1982). The unique mineralogy of the ash and its phenocrysts made it like cement when wet. Footprints were retained in the tuff because the tuff was buried by a substantial ashfall before they could be removed by natural forces.

Studies characterizing ash deposits by physical and chemical properties with a goal of correlating them with dated ash deposits have been done (Borchardt et. al., 1971; 1972; Sarna-Wojcicki, 1976; Sarna-Wojcicki et.al., 1979). Volcanic ash in Texas has been correlated with the Valles caldera in New Mexico (Izett et. al., 1972). Ash deposits from across the western United States have been correlated with the Long Valley caldera (Izett et. al., 1970; 1988). Ash deposits in southern California and the northeastern Pacific Ocean have been correlated with the Yellowstone caldera (Sarna-Wojcicki et. al., 1984; 1987). Ash from a 2 m.a. eruption in Yellowstone was identified 5000 km away in the Pacific Ocean (Sarna-Wojcicki et. al., 1987).

Source area volcanic material has been studied. Doell et. al. (1968), Izett et. al. (1980), and Gardner et. al. (1986) dated and analyzed volcanic material in or near the Valles and Toledo calderas. Hildreth et. al. (1984) studied volcanic material in and around the Yellowstone caldera. The studies showed that the calderas have been active for millions of years and volcanic material of equivalent age near the source can have a range in values for correlative properties, particularly chemical composition. Differential eolian sorting was

suggested as a possible reason for dissimilar values of correlative properties for volcanic material from the Long Valley caldera (Izett et. al., 1988). Francis (1983) presented a map of the areal distribution of ash from the Valles, Long Valley, and Yellowstone calderas. Hammond (1980) and Simon (1983) pointed to the bulging of the centers of the Long Valley and Yellowstone calderas as an indicator of potentially dangerous eruptions in the near future.

Late Pleistocene and Holocene age ash deposits have been identified and studied (Davis, 1985; Beget, 1985; Lowe, 1988). Carbon-14 dates on material within and around the ash were used to estimate the age of the ashes (Mehringer and Sheppard, 1984; Zoltai, 1989). Recent (1 to 5 ka (thousand years ago)) ash in Iceland was used to interpret the effect of human activity on the island. Results of interpretations indicated erosion increased significantly with increased agriculture. Sarna-Wojcicki et. al. (1988) studied soil cores of Walker Lake in Nevada which contained volcanic ash deposits and noted major changes in sedimentation pattern and rates during the history of the lake. Stratigraphic position of Recent ash deposits was used to help assess the risk factor in the placement of a high-level radioactive waste repository in southern Nevada (Wells et. al., 1990). The age of the youngest ash deposit in the area was estimated at about 20 k.a. (thousand years ago). The succession of young ash deposits in New Zealand are discussssed by Lowe and Froggatt (1990).

The Uranium Fission-Track Dating Method

Development of the Technique

Fleischer and Price (1964a) credited Silk and Barnes (1959) with

the initial observation of damage trails created by fission fragments. Damage tracks were observed with an electron microscope. Price and Walker (1962a, 1962b, 1962c, 1963a, 1963b) are then credited with the advance of the fission-track dating technique by chemically etching tracks and making them visible with an optical microscope. They also found naturally occurring tracks in mica, and identified U^{238} as the most probable source of natural fission-tracks. Fleischer and Price (1963, 1964a) applied the previously mentioned works of Price and Walker and devised a method of dating geologic glasses. Fission-track dating was applied to other minerals (Fleischer and Price, 1964b) and Fleischer et. al. (1964) used fission-tracks to date zircon crystals. Fleischer et. al. (1965) described a method of obtaining neutron dose measurements required in the dating technique using U-contaminated glass dosimeters. Dose values were estimated using the uranium concentration of the dosimeters and the fission-track density on the dosimeters after the irradiation. Naeser (1969) described a method of dating zircon crystals by the fission-track method using sodium hydroxide to expose the fission tracks and a muscovite detector on the zircon crystals to record the fission tracks created by the irradiation. Boellstorff (1976) described a fission-track method for dating glass shards extracted from volcanic ash deposits. More recent discussions of the uranium fission-track dating methods are found in Naeser and Naeser (1984, 1988), Naeser (1979), and Naeser et. al. (1981). Colman et. al. (1987) characterized fission-track dating as a radiogenic method of dating which produces numerical age results.

Problems Associated with Fission-Track Dating Glass Shards

Annealing. Experiments by Storzer and Wagner (1969) and Fleischer and Price (1964) showed that at elevated temperatures (60-600°C) and over short periods of time (<10 days) fission-tracks in glass could become shorter and the diameters reduced or completely lost. The term thermal annealing was applied to this phenomenon. Evidence of annealing included mean diameters of natural tracks being less than mean diameters of induced tracks (Storzer and Wagner, 1969, 1971) and mean lengths of natural tracks being less than mean lengths of induced tracks (Seward, 1979). Extrapolation of the corrected track width data into ambient temperature ranges (0-30°C) over geologic time (millions of years, Storzer and Wagner, 1971) seemed to confirm annealing. Thermal annealing of the glass shards was blamed for inconsistent glass fission-track versus zircon fission-track or K-Ar ages on materials from the same ash bed (Seward, 1979; Naeser et. al., 1980; Westgate et. al., 1987; Naeser and Naeser, 1988). Methods for correcting the ages of thermally lowered glass were proposed (Storzer and Wagner, 1971; Storzer and Pompeau, 1973; Durani and Bull, 1985; Westgate, 1989). These methods required heating the samples at a high temperature for longer periods of time (isothermal plateau annealing correction) or at increasingly higher temperatures for equal amounts of time (isochronal plateau annealing correction) until a constant ratio of induced to spontaneous tracks is reached. This ratio is then applied to an age equation. Fission-track ages of glass shards, even if experimentally corrected, were to be termed minimum ages because of complete annealing of some tracks (Naeser et. al., 1980; Naeser and Naeser, 1984).

Annealing Age Reduction Questioned. Boellstorff and Steineck (1975) and Boellstorff (1980) questioned the need for correction of glass shard fission-track ages. Their reasons include 1) similar spontaneous versus induced track diameter reductions (~15%) on glasses of widely differing ages, 2) similar fission-track ages on different mineral portions (glass versus zircon) from the same ash deposit, 3) inconsistencies in the results of the annealing experiments where predicted track diameter reductions were not detected by the experimenters, 4) the difference in energy between U^{235} and U^{238} which should result in larger induced fission-tracks and, 5) age corrections which gave absurd results when analyzed with other time-stratigraphic units and biostratigraphic units. Boellstorff and Alexander (1980) illustrated how the use of inadequately calibrated National Bureau of Standards (NBS) uranium glass dosimeters (Carpenter and Reimer, 1974) could cause anomalously young glass ages. The NBS standards are calibrated with gold and copper foils. Glass dosimeters calibrated with gold and copper foils were shown to give 30-40% lower neutron dose values as compared to dose values measured with dosimeters calibrated with natural uranium foils.

The ability to determine accurate numerical ages for the ashes by the fission-track method increases the potential for accurate interpretations of Pleistocene geomorphic evolution in the region and assessing the importance of the time factor in soil development. The questions regarding annealing and dosimetry in previous studies must be addressed to assess the accuracy of the dates.

CHAPTER III

MATERIALS AND METHODS

Introduction

The uranium fission-track dating method used in this study is the technique described in Boellstorff (1976). Dr. Boellstorff, a tephrachronologist formerly for the Nebraska Geological Survey now working for the Amoco Production Research Co. Research Center, P.O. Box 3385, Tulsa, Ok., 74102, visited the Soil Genesis and Classification laboratory at Oklahoma State University and provided valuable instruction on dating the glass shards. He also supplied the glass standards used to measure the neutron dose received by the irradiated glass shards, the Borcher's standard ash used to check the neutron dose measurements and the polyethylene vials and quart bottle in which the shards were irradiated.

The steps in the procedure for shard dating will be described in detail and chronological order. These steps are 1) sample collection, 2) sample cleaning, 3) sample irradiation, 4) sample fission-track etching, and 5) sample fission-track counting and age calculation. Appendix A (p. 64) lists assumptions made using the technique.

Sample Collection

Legal descriptions for the locations of the ash deposits are cited in Frye et. al. (1948), Burwell and Ham (1949) and Izett and Wilcox

(1982) except for Ash 14 which was located on the U.S. Geological Survey 7.5 minute quadrangle map for Gage, Oklahoma as a caliche pit. Upon arrival at a sample site, the ash bed containing the coarsest glass shards was located. The thickness of this zone ranged from 25 to 100 centimeters. This coarse ash bed was then "quarried back" using a pick mattock and sharpshooter type shovel (tile spade) to avoid sampling shards which may have been altered or "annealed" by direct exposure to sunlight as suggested by Naeser et. al. (1980). After quarrying back at the place in the ash bed from which a sample was to be taken, five, labeled, 2 liter plastic sample bags were filled with ash from the coarse ash zone. This procedure yielded 6-7 kilograms of ash from each site.

Sample Cleaning

Drying and Sieving

The contents of all the bags were air dried on butcher paper for 3 days to 2 weeks depending on the moisture content of the ash at the time it was sampled. The ashes were crushed by hand with a metal roller to facilitate drying. Air-drying made the sieving easier and more efficient, whereas oven-drying would severely damage the shards and make them unusable for dating. When drying was complete, the ash was stored in the original sample bags.

The air-dried ash was then sieved using 140 and 60 mesh (106 and 250 micron diameter sieve openings), 20 cm wide sieves on a rotap-type sieve shaker for five minutes to extract the 0.1-0.25 mm diameter, fine sand-sized shards. One bag of ash (approximately 20% of the original sample) was kept unaltered for future analyses needed to help correlate

the ashes with each other and other ash deposits.

Hydrofluoric Acid Cleaning and Resieving

A 10 cm^3 portion of the extracted shards (fine sand-size, 0.1-0.25 mm diameter) was etched with room temperature, 5% hydrofluoric acid for 1 minute in a liter-size plastic beaker. A swirling motion was used to ensure that the acid would come in contact with as many shard surfaces as possible. The acid cleans the shards by etching off (removing) silt and clay particles which had become adhered to them. The acid-shard mixture was immediately diluted with 500 mL of distilled water and the mixture poured over a 8 cm diameter, 270 mesh (53 micron diameter sieve opening) sieve. The shards not passing through the sieve were washed from the sieve onto a filter paper in a Buchner funnel set in a 500 mL filtering flask attached to a vacuum, washed with distilled water, and finally lightly rinsed with acetone from a squeeze bottle to speed drying. The clean ash was then transferred onto a cover glass and the cover glass set in a desiccator containing desiccant. Usually 100 cm^3 of ash cleaned in this manner provided enough shards to complete the dating (30 cm^3) although with some ashes which contained significant quantities of detrital grains more than twice that amount was cleaned.

Resieving was done after the cleaned ash had dried in the desiccator. The ash was shaken in eight cm diameter, 140 and 60 mesh (106 and 250 micron diameter sieve openings) sieves on a portable sieve shaker to again extract the fine sand-sized shards and remove the clay, silt, and glass particles which were not removed during the wet sieving.

Care was taken during the cleaning process to avoid contamination

between samples, including cleaning all sieves in an ultrasonic cleaner after each ash was sieved.

Purity Check and
Heavy Liquid Separation

The clean ash was checked for purity with a petrographic microscope. Three hundred grains were counted from each ash. Ashes with 20% or more impurities (usually detrital anisotropic or opaque minerals) were cleaned by heavy liquid separation. The ash (20-30 g) was poured into a 2.45 g/cm^3 density mixture of s-tetrabromoethane and acetone in a 500 mL separatory funnel, the funnel was thoroughly shaken by hand, and the mixture was left overnight to separate. The next day the clean ash (glass shards) was vacuumed from the top of the separation mixture with a homemade vacuum into a filter flask, poured from the flask onto a filter paper in a Buchner funnel on a filtering flask under vacuum, washed with acetone, transferred to a cover glass, and set in a dissecator to dry.

Sample Irradiation

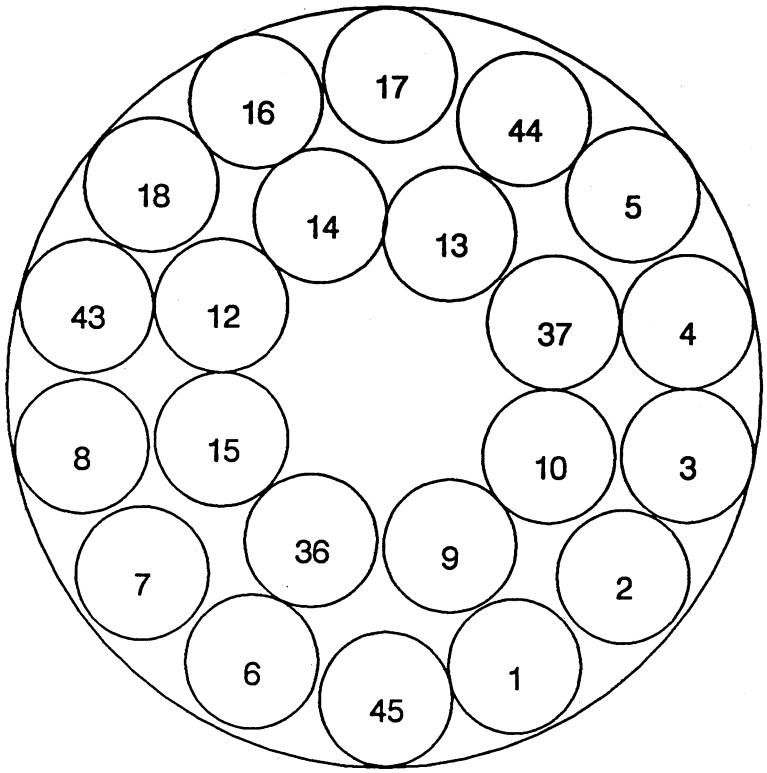
Packaging

Clean shards were poured into two 15 cm^3 plastic vials. One vial was labeled Ps for the spontaneous track separate and the other vial was labeled Pi for the induced or irradiated track separate. The Ps vial was set aside until the sample etching step. The Pi vial was packed upright into a liter-size polyethylene bottle along with the Pi vials from the other ashes to be dated and the vials containing the standards. The standard vials contained 2, 5 cm^3 vials. One of the smaller vials

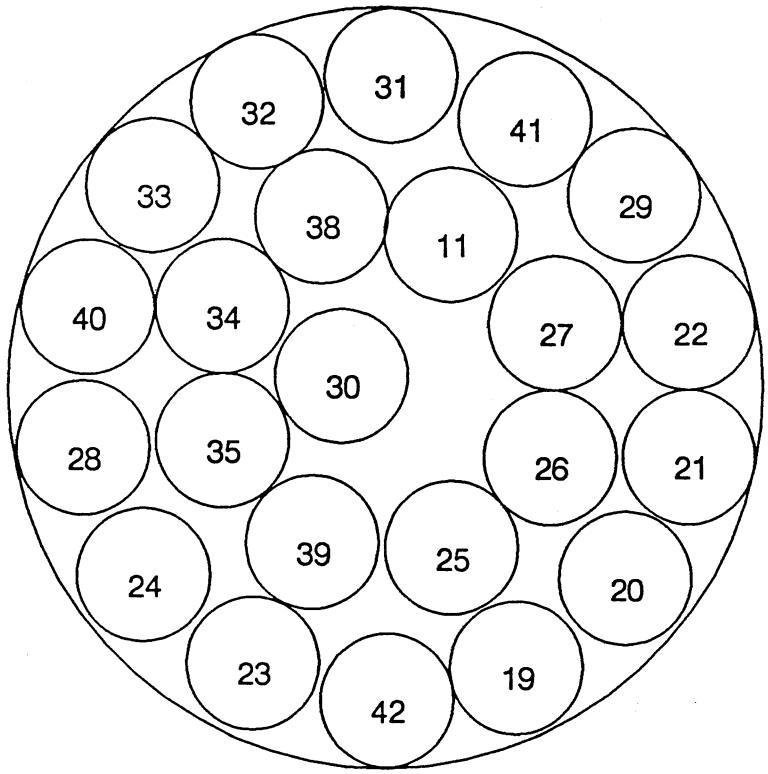
was filled with Borcher's standard glass shards. The other vial held a glass standard which was a 0.5-cm x 1.0-cm x 2.0-cm wafer of known uranium content (0.7 ppm, Boellstorff 1986, personal communication). The positions of each of the larger vials in the bottle was recorded (Fig. 6, p. 32). Arrangement of the standards within their vials and placement of the large standard vials was done strategically to attain measurements and checks of the neutron dose received throughout the bottle (Table II, p.33). For example, standard vials 36 and 37 were placed to evaluate the neutron dose received by the shards in vials packed in the inner circle of the lower level of the bottle (see Fig. 6, p.32 and Table II, p. 33). The neutron dose measured by glass standard 36 was used to date the Borcher's standard glass shards in standard vial 37 and the Borcher's standard glass shards in vial 37 were used to check the neutron dose measured by glass standard 36 (Table II, p.33). The same system was used in placing the other standard vials (i.e. glass standard 43 was used to date Borcher's standard glass shards 44 and 45 and glass standards 44 and/or 45 were used to date Borcher's standard glass shards 43 in evaluating the neutron dose received by shards vials in the outer circle of the lower level of the bottle (Fig. 6, p.32 and Table II, p. 33)). Packing material was added to the bottle to secure the vials in their positions during shipping.

Irradiation

The liter-size bottle was shipped to the Director of the Neely Research Center, Neely Research Center, Georgia Institute of Technology, 900 Atlanta Drive N.W., Atlanta, Georgia, 30318, Attention: Dr. Ratib Karam, for irradiation. The bottle was placed in slot V43 of the



Lower Level



Upper Level

Figure 6. Positions of Large Vials In Irradiated Bottle.

TABLE II

ARRANGEMENT OF STANDARDS WITHIN THEIR VIALS

Lower Level, Inner Circle

Vial 36 - $\frac{BG}{GS}$, Vial 37 - $\frac{GS}{BG}$,

Lower Level, Outer Circle

Vial 43 - $\frac{GS}{BG}$, Vial 44 - $\frac{BG}{GS}$, Vial 45 $\frac{BG}{GS}$

Upper Level, Inner Circle

Vial 38 - $\frac{BG}{GS}$, Vial 39 - $\frac{GS}{BG}$

Upper Level, Outer Circle

Vial 40 - $\frac{BG}{GS}$, Vial 41 - $\frac{GS}{BG}$, Vial 42 - $\frac{GS}{BG}$

BG = Borcher's Standard Glass Shards
GS = Glass Standard

reactor and bombarded with thermal neutrons for 30 minutes while revolving once per minute with the energy level of the reactor at 250 kilowatts. After irradiation the bottle was returned in the same condition as it had been sent.

Sample Etching

Etching the Glass Standards

Each glass standard was affixed to a glass microscopic slide with clear liquid adhesive (Eukitt) and a drop of toulene. The glass standards were then frosted with a 6-micron grit polishing compound and polished to an optical finish on a grinding wheel using cerium oxide as the polishing agent. Frosting and polishing was done to remove any tracks caused by surficial uranium contamination. The glass slides were attached to a 50 cm strip of 2.5 cm wide masking tape. The tape was folded over at each end to make handles. The slides and tape were placed in a 8.0 cm x 15.0 cm x 20.0 cm plastic tray. The standards were then etched with 48% HF at room temperature for 5 seconds while the slides were moved back and forth in the tray using the tape. The acid etching the standards was immediately diluted by dipping the standards in a liter of distilled water in a plastic beaker. The wafers were washed with a mild detergent and a toothbrush to remove a white precipitate that formed during the etching. Fission-tracks on the glass standards were now visible with the microscope and ready to be counted.

Etching the Glass Shards

The shards were etched for 2 minutes with 24% HF at 20°C while swirling. One cm^3 of the Ps shards was etched first and one cm^3 of Pi

shards immediately followed. The etching was done in labeled 250 mL plastic beakers. Enough HF was used to cover the shards. Care was taken when placing the shards in the bottom of the beaker so that all of the shards would be etched similarly. After two minutes, the acid was diluted with approximately 150 mL of distilled water. This was decanted off manually and the acid was diluted again with distilled water. This was repeated 3 or 4 times. The shards were stored in their beakers filled with distilled water during the fission-track counting procedure.

Sample Fission-Track Counting and Age Calculation

Glass Standard Fission-Track Counting and Dose Calculation

The fission-tracks on the glass standards were counted first. Using a petrographic microscope at 512X magnification fitted with a 0.281 mm diameter eyepiece reticule and a continuous point-count microscope stage, the number of tracks per unit area was measured without counting any area on the standard more than once (see Appendix C, p. 69). The density of tracks per cm^2 on the glass standards was applied to the calibrated neutron dose equation supplied by Dr. Boellstorff for the glass standards of:

$$\emptyset = (1.13 \pm 0.03) \times 10^{11} \text{ pi} \qquad (1)$$

where $\emptyset$ is the neutron dose and pi is the density of fission-tracks per cm^2 on the glass standards. The dose equation is determined from the uranium content of the glass. The uranium content of the glass standards used was measured using x-ray fluorescence and the Fleischer et. al. (1965) glass standard as the standard for uranium. From the uranium content of the standards, the uranium content of Fleischer's

standard, and the dose equation for Fleischer's standard, the dose equation for the standards was calculated.

Dose Calibration and Shard Fission-Track Counting

Neutron dose measurements were checked by dating Borcher's standard glass shards. The Borcher's ash deposit has been consistently dated at approximately 2 million years old by several researchers (Boellstorff, 1976). Ps and Pi Borcher's shards were etched as described previously. A small quantity of shards in water was eye-droppered on to a microscope slide and covered with a cover slip. The fission-tracks on the shards were counted with the same microscope at the same magnification, (except when the average shard diameter was smaller), with a 92 micron diameter eyepiece reticule and the same microscope stage in a manner similar to counting tracks on the glass standards. No part of any area on any shard was counted more than once. Enough areas were observed to count 100 Ps tracks. The number of Pi tracks in the same number of areas observed to count 100 Ps tracks was counted (see Appendix C, p. 69). The age of the glass was calculated using the equation (Boellstorff, 1976, after Fleischer and Price, 1964a):

$$A = 14.95 \times 10^{9} \log \left[1 + \left\{(9.50 \times 10^{-18})\ (\emptyset)\ \frac{Ps}{Pi}\right\}\right] \qquad (2)$$

where A = the age of the glass, $\emptyset$ = the neutron dose, Ps = the number of Ps tracks counted and Pi = the number of Pi tracks counted. The equation includes constants for the fission decay of U^{238} (6.87×10^{-17} yr^{-1}), the total decay of uranium (1.54×10^{10} yr^{-1}), the isotopic ratio of U^{235} to U^{238} (7.26×10^{-3}), and the cross-section for thermal neutron

induced fission of U^{235} (582×10^{-24} cm^2). The cross-section is an areal expression of the probability that a U^{235} atom will undergo fission during irradiation.

The glass standard calculated neutron doses were checked by dating Borcher's standard glass shards packed at the same level in the bottle as the glass standard as discussed earlier (Fig.6, p.32 and Table II, p.33). When the age calculations were in agreement with the recognized age of the Borcher's standard shards (~ 2 m.a.), the dose measurements were assumed to be adequate for use in dating shards of unknown age.

Dating the Shards of Unknown Age

Ps and Pi shards were etched as previously described. Fission-tracks on the Ps and Pi portions were counted using the same technique as was with the Borcher's shards (see Appendix C, p. 69). The counting results were entered into the age equation for an age estimate. The standard error of the age was estimated using the equation (after Izett and Naeser, 1976):

$$s.e = A \left(\frac{1}{Ps} + \frac{1}{Pi} \right)^{1/2} \qquad (3)$$

where s.e = the standard error of the age, A = the calculated age, Ps = the number of spontaneous tracks counted, and Pi = the number of induced tracks counted. This equation was used because the uranium is believed to be distributed randomly throughout the glass and Poissonian statistics could be applied to the dating technique.

CHAPTER IV

RESULTS AND DISCUSSION

Introduction

Glass shards from 35 volcanic ash deposits in the study area were sampled and fission-track dated (Figure 7, p. 39). Ash deposits in the river basins of the Arkansas, Cimarron, North Canadian, Canadian, Washita and Red were dated. Twenty of the ash beds are in Oklahoma, 12 in southern Kansas, and 3 are along the eastern edge of the Texas Panhandle. Appendix B (p. 66) gives the sample number, location, and type of exposure from which it was sampled for each of the dated ashes.

Neutron Dose Calculation and Calibration

Neutron doses calculated from the fission-track counts on the glass standards were between $1.09 \times 10^{14} \pm 2.90 \times 10^{12}$ and $1.24 \times 10^{14} \pm 3.28 \times 10^{12}$ neutrons/cm^2 (Table III, p. 40). Measured ages for the Borcher's shards as standards were between 1.66 ± 0.18 and 2.21 ± 0.25 m.a. (Table IV, p. 41). The average age for the Borcher's shards that Dr. Boellstorff gave to me to use as standards in this study was determined as 1.96 ± 0.22 m.a., which is in close agreement with the results of Boellstorff (1976). Because of the results from dating of the Borcher's shards as standards, the mean of the calculated doses ($1.16 \times 10^{14} \pm 3.08 \times 10^{12}$ neutrons/cm^2) from the glass standard fission-track counts was used in the age equation to calculate ages for shards

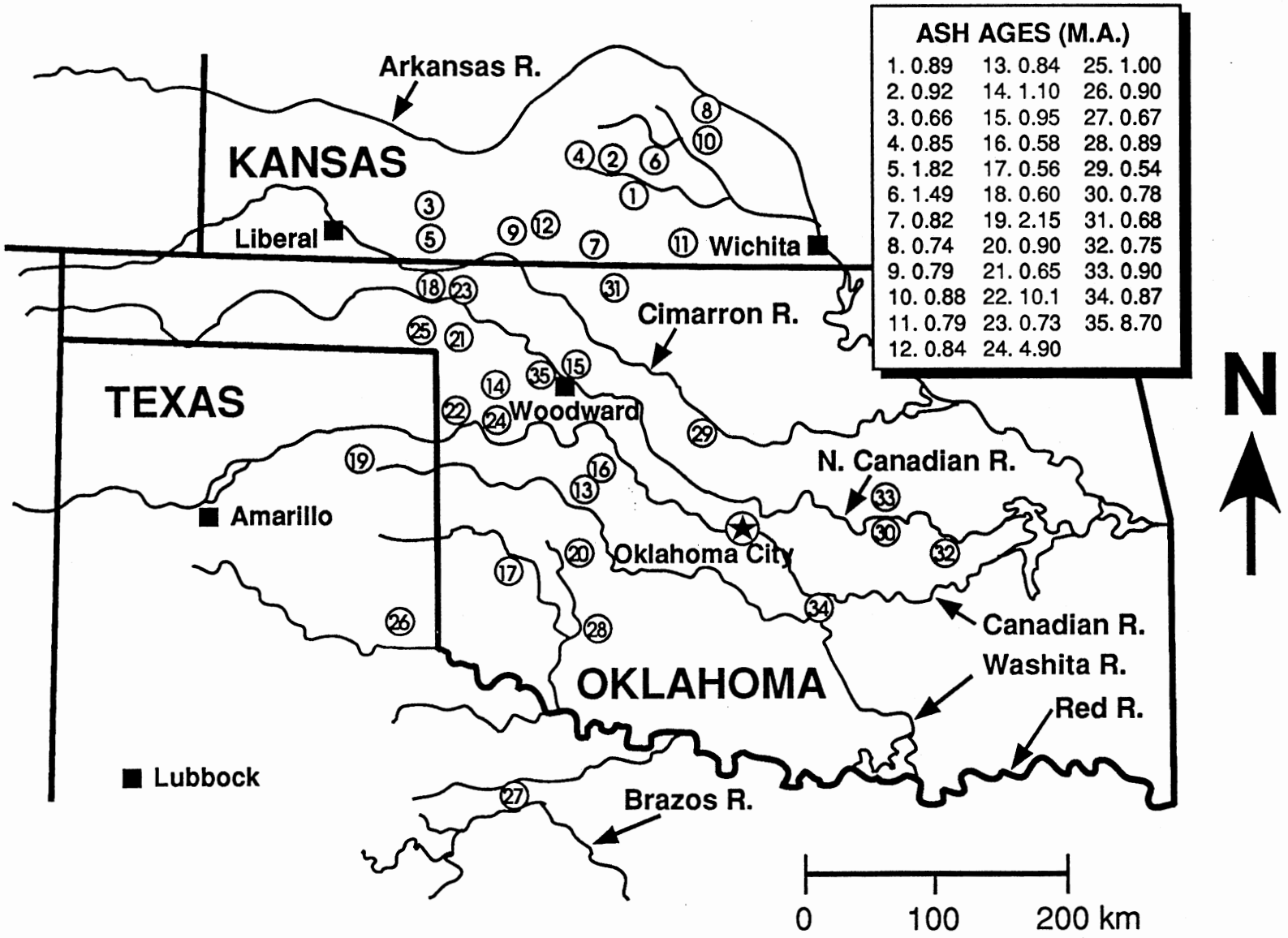


Figure 7. Map Showing Locations and Glass Shard Ages of Dated Ash Deposits

TABLE III

SUMMARY OF FISSION-TRACK DATA FOR THE GLASS STANDARDS

Standard No.	Tracks Counted	Fields Counted	Pi (tracks/cm^2)	$\sigma((1.13 \pm .03) \times 10^{11} \rho_i)$ (neutrons/cm^2)
36	154	237	1,050	$1.19 \times 10^{14} \pm 3.15 \times 10^{12}$
37	50	231	1,049	$1.18 \times 10^{14} \pm 3.15 \times 10^{12}$
38	89	142	1,011	$1.14 \times 10^{14} \pm 3.03 \times 10^{12}$
39	121	199	984	$1.11 \times 10^{14} \pm 2.95 \times 10^{12}$
40	149	248	962	$1.09 \times 10^{14} \pm 2.89 \times 10^{12}$
41	140	223	1,016	$1.14 \times 10^{14} \pm 3.05 \times 10^{12}$
42	149	228	1,057	$1.19 \times 10^{14} \pm 3.17 \times 10^{12}$
43	152	257	956	$1.08 \times 10^{14} \pm 2.87 \times 10^{12}$
44	154	231	1,077	$1.22 \times 10^{14} \pm 3.23 \times 10^{12}$
45	92	135	1,095	$1.24 \times 10^{14} \pm 3.28 \times 10^{12}$
Average	133	213	1,026	$1.16 \times 10^{14} \pm 3.08 \times 10^{12}$

TABLE IV

SUMMARY OF FISSION-TRACK DATA FOR BORCHER'S ASH STANDARDS

Standard No.	Ps Tracks Counted	Pi Tracks Counted	Fields Counted	Ps (Tracks/cm^2)	Pi (Tracks/cm^2)	ζ ($\times 10^{14}$ neutrons/cm^2)	Age (m.a.)	Standard Error (m.a.)
36	102	459	189	8,116	28,404	1.18	2.08	0.23
37	103	468	208	7,447	25,665	1.19	2.08	0.23
38	101	471	210	7,232	26,495	1.11	1.87	0.21
39	105	447	194	8,139	26,510	1.14	2.16	0.24
40	103	495	205	7,555	28,755	1.16	1.88	0.21
41	100	506	195	7,712	31,309	1.09	1.66	0.18
42	103	458	203	7,630	26,297	1.09	1.95	0.22
43	101	447	178	8,532	29,230	1.23	2.21	0.25
44	101	445	201	7,556	25,736	1.08	1.96	0.22
45	100	473	194	7,751	28,912	1.08	1.78	0.20
Average	102	467	198	7,767	27,731	1.14	1.96	0.22

Notes: Densities reported for Ps and Pi are twice true densities because tracks on both sides of the shards are observed with the microscope.

from all 35 ash deposits.

Fission-Track Ages of Glass Shards from Sampled Volcanic Ash Deposits

Ages of the shards from the sampled ash deposits ranged from 0.54 ± 0.06 to 10.1 ± 1.5 m.a. (Fig. 7, p. 39). Table V (p. 43) summarizes the fission-track data for the ash deposits dated. Twenty-nine of the 35 ashes yielded shard ages between 0.5 and 1.1 m.a. Shards sampled from the Borcher's ash deposit (Ash 5) dated 1.82 ± 0.20 m.a. Ash 3 (0.66 ± 0.07 m.a. in this study) was previously glass shard fission-track dated by Boellstorff (1976) at 0.64 ± 0.07 m.a. and Naeser and others (1973) fission-track dated zircon crystals from it at 0.6 ± 0.07 m.a., 0.7 ± 0.35 m.a., and 0.9 ± 0.25 m.a. (Lava Creek B Ash). Naeser and others (1973) reported a mean of several zircon fission-track ages of 1.9 ± 0.1 m.a. for the Borcher's ash deposit (Huckleberry Ridge Ash).

Comparison of Ages with Other Dated Ash Deposits

The fission-track glass shard ages of the Pleistocene ashes in this study are consistent with ages reported on material from ash in similar deposits by other tephrochronologists. Figure 8 (p. 46) shows the distribution of ages measured in this study, ages measured by other tephrachronologists on ashes dated in this study, and ages of volcanic material from probable source areas for the ashes dated in this study (after Izett, 1981). Green Mountain Reservoir Ash and Bishop Tuff are from the Long Valley caldera of eastern California, the Bandelier Tuffs, Cerro-Toledo Rhyolites, and Guaje Ash are from the Toledo and Valles calderas of central New Mexico, and the Lava Creek B, Mesa Falls, and

TABLE V

SUMMARY OF FISSION-TRACK DATA FOR DATED ASHES

Ash No.	Ps Tracks Counted	Pi Tracks Counted	Fields Counted	Ps (Tracks/cm^2)	Pi (Tracks/cm^2)	U (ppm)	Age (m.a.)	Standard Error (m.a.)
1	100	903	481	3,126	25,104	8.6	0.89	0.09
2	100	875	413	3,641	28,218	9.6	0.92	0.10
3	100	1,177	429	3,505	37,752	12.9	0.66	0.07
4	100	938	334	4,502	37,729	12.9	0.85	0.09
5	101	498	188	8,079	31,755	10.9	1.82	0.20
6	100	580	209	7,195	34,536	11.7	1.49	0.16
7	100	972	425	3,538	30,854	10.6	0.82	0.09
8	100	1,071	449	3,349	32.520	11.0	0.74	0.08
9	100	1,003	371	4,053	36,601	12.5	0.79	0.08
10	100	911	386	3,896	32,594	10.8	0.88	0.09
11	101	1,015	437	3,476	31,486	10.8	0.79	0.08
12	77	733	315	3,676	31,316	10.7	0.84	0.10
13	105	1,002	426	3,706	31,663	10.8	0.84	0.09

TABLE V (CONTINUED)

Ash No.	Ps Tracks Counted	Pi Tracks Counted	Fields Counted	Ps (Tracks/cm^2)	Pi (Tracks/cm^2)	U (ppm)	Age (m.a.)	Standard Error (m.a.)
14	90	674	322	4,203	27,273	9.3	1.10	0.12
15	100	851	346	4,346	32,639	11.2	0.95	0.10
16	100	1,321	524	2,870	35,040	12.0	0.58	0.06
17	100	1,378	506	2,972	37,980	13.0	0.56	0.06
18	63	813	286	3,312	39,434	13.5	0.60	0.07
19	100	433	166	9,059	30,166	10.3	2.15	0.24
20	59	528	334	4,108	32,656	11.2	0.90	0.12
21	100	1,202	487	3,089	34,028	11.6	0.65	0.07
22	102	174	40	38,345	27,068	9.3	10.1	1.5
23	100	1,081	404	3,722	36,514	12.5	0.73	0.08
24	81	199	33	36,910	53,771	18.4	4.90	0.71
25	100	817	282	5,149	36,924	12.6	1.00	0.11
26	100	894	473	3,180	25,243	8.6	0.90	0.10

TABLE V (Continued)

Ash No.	Ps Tracks Counted	Pi Tracks Counted	Fields Counted	Ps (Tracks/cm^2)	Pi (Tracks/cm^2)	U (ppm)	Age (m.a.)	Standard Error (m.a.)
27	100	1,169	690	3,370	36,022	12.3	0.67	0.07
28	100	906	677	3,435	27,687	9.5	0.89	0.09
29	100	1,428	575	2,615	34,730	11.9	0.54	0.06
30	100	1,015	658	3,534	32,339	11.1	0.78	0.08
31	100	1,145	467	3,220	33,649	11.5	0.68	0.07
32	100	1,059	383	3,926	37,652	12.4	0.75	0.08
33	100	893	411	3,659	29,014	9.9	0.90	0.10
34	52	481	205	3,814	31,469	10.8	0.87	0.13
35	102	186	71	23,721	19,535	6.7	8.70	1.3

Notes: 625X magnification was used to count ashes 20, 27, 28, 30, and 35 because of smaller average shard size. 1.16×10^{14} neutrons/cm^2 was the dose used for all age calculations. Ash 28 was etched for 70 sec. and ashes 30 and 35 were etched for 90 sec. with 24% HF.

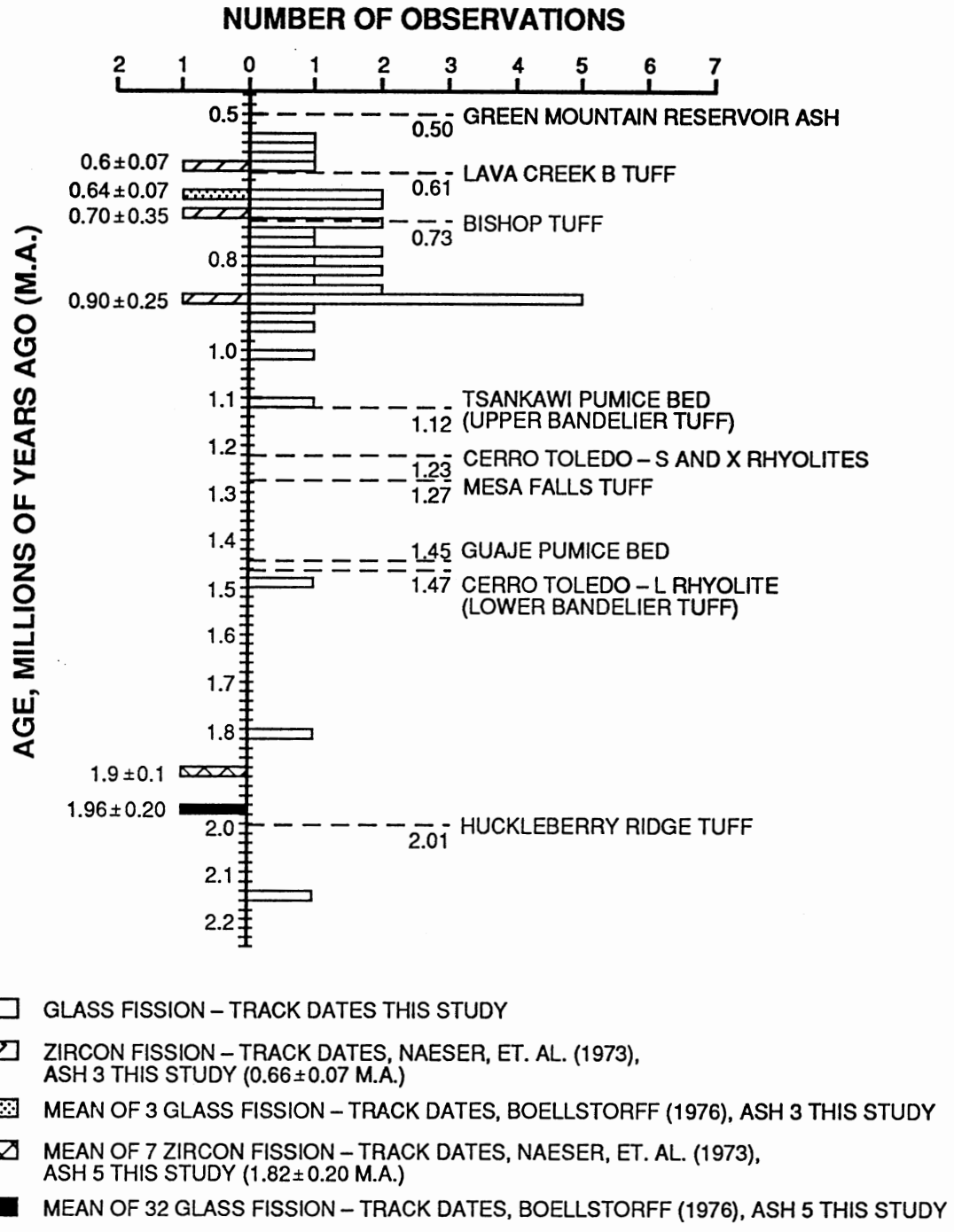


Figure 8. Frequency Distribution of Glass Shard Ages For This Study

Huckleberry Ridge Tuffs are from the Yellowstone caldera of northwestern Wyoming. Boellstorff (1976) referred to the Lava Creek B Ash as the "Pearlette restricted," the Bishop Ash as the "Hartford", the Mesa Falls Ash as the "Coleridge" and the Huckleberry Ridge Ash as the "Borcher's". Ashes 22, 24, and 35 provide glass fission-track ages that are Tertiary and similar to other ashes found in the High Plains (Boellstorff, 1988, written communication).

Accuracy of Calculated Glass Shard Fission-Track Ages

The important question pertaining to the accuracy of the fission-track dates from glass shards is whether or not the glass has annealed or has annealed significantly enough to alter the fission-track ages. The ages measured in this study are representative of the ages of the ash deposits meaning that the glasses have not been significantly annealed. The reasons for this conclusion are 1) the lack of evidence of any high temperature climatic episodes during the Pleistocene epoch, 2) the burial of the ash deposits by tens and hundreds of feet of sediment which should protect the ash from extreme surface temperature changes and, 3) the work of Boellstorff (1980) and Boellstorff and Alexander (1980) which question the annealing theory by pointing out the potentially inaccurate dosimetry of those researchers who have measured anonymously young glass shard ages because of the use of inadequately calibrated National Bureau of Standards glass standards, and discrepancies and inadequacies in the annealing experiments and proposed correction methods.

The standard error of the ages was made with the assumption that

the uranium is randomly distributed throughout the glass and an error estimate for a single age measurement could be made using Poisson statistics. Multiple age determinations need to be made to account for error caused by the technique as suggested by Swinehart and Boellstorff (1976) but time constraints allowed only a single age determination to be made on each set of sampled shards dated in this study.

CHAPTER V

SUMMARY AND CONCLUSIONS

Concerning the Fission-Track Dating Technique

An accurate estimate of the ages of the volcanic ash deposits is the purpose for dating glass shards from the deposits by the uranium fission-track technique. Attainment of accurate ages is dependent on proper field sampling and laboratory procedures. Each step in the method is important. Some of the more important steps and points which were considered critical to the accuracy of the ages reported in this paper are:

1. Sample volcanic ash deposits. If possible, carry a microscope with at least 100X magnification potential to ensure what is sampled is volcanic ash. Gleyed (gray) deposits in bedrock and unconsolidated materials, calcium carbonate, and gypsum can be mistaken for ash. The lower specific gravity, bright white color, and association with unconsolidated materials of "High Plains" lithology characterize an ash at an outcrop within this Rolling Red Plains study area.

2. Sample the coarsest shards possible. The ash deposits are typically stratified in layers of differing particle size. Identify the beds containing the coarsest shards. This will result in a surplus of shards for dating. Coarser shards withstand the HF treatments (remain large) and fill the eyepiece reticule better making the fission-track counting easier and less time consuming.

3. Quarry back before sampling to avoid sampling annealed shards. Remove 0.5 to 1.0 meters from the face of the deposit at the sampling spot before sampling. The surface of the face of an exposed deposit can be subjected to much higher temperatures than the material which it protects.

4. Maintain the purity of the ash. Mixing of the ashes may not be visible with the naked eye or a microscope and result in inaccurate shard ages. Ultrasonic cleaning of sieves between ashes during sieving procedures, washing of beakers and funnels between ashes during cleaning procedures, and separate funnels for each ash during packaging were steps taken to maintain the purity of the ashes.

5. Use glass standards (dosimeters) for measuring the neutron dose which have been calibrated using uranium foil rather than gold or copper foil. Boellstorff, (1980) showed how National Bureau of Standards dosimeters which have been calibrated using gold or copper foil (Carpenter and Reimer, 1974) give significantly smaller neutron dose measurements than dosimeters calibrated with uranium foil. The dosimeters used in this study were supplied by Dr. Boellstorff. Other sources are not known at this time.

6. Date shards from the Borcher's ash deposit to test the neutron dose measurements. The Borcher's ash has been proposed as an interlaboratory standard (Boellstorff, 1976). If possible, retrieve a sample from the Borcher's Badlands of Meade Co., Kansas. The Borcher's ash is also known as the Huckleberry Ridge or Pearlette Type B ash. Deposits of the Borcher's ash are found across the central Great Plains (Izett and Wilcox, 1982).

7. Include enough standards to measure the neutron dose throughout

the bottle. In this study, 10 standard vials were included with the 35 unknowns. Two levels of vials were packaged in the irradiated bottle. Each level had an inner and outer circle of vials. Inner circles contained 2 standard vials and outer circles contained 3 (Fig. 6 and Table II). Standard vials were placed in the circles at different positions (not next to each other) to obtain a better measure of the neutron dose throughout the bottle.

8. Be certain the dosimeters are polished to an optical finish before etching them. Check them at the magnification and with the microscope to be used for counting the fission-tracks. Inadequacies in the optical finish may result in inaccurate track density measurements and make necessary repolishing of the dosimeters and recounting of the fission-tracks on them.

9. Etch the glass standards in the 48% HF for as close to 5 seconds as possible. Several practice runs make accuracy of the actual run easier.

10. Etch the Ps and Pi fractions in 24% HF at 20°C. Keep the HF in a 20°C water bath during the etching. The temperature of the HF was determined by measuring the temperature of the same amount of distilled water as HF in the same type of container which held the HF. This container was always placed next to the HF during storage so the water would be affected by the same temperature fluctuations as the acid was. The acid and water containers were usually refrigerated for a short while and then allowed to warm to 20°C before being placed in the water bath and considered ready for the etching procedure.

11. If necessary, change the etching time for the shards. Some of the ashes are almost completely dissolved after the standard 2 minute

etching. Try etching times between 1 and 2 minutes until a satisfactory etch is achieved. Always etch the Ps and Pi fractions for the same amount of time.

12. Count no area on the glass standards or shards more than once. Check the distances in the point-counting procedure to be certain there is no overlap between counted areas.

13. Know what fission tracks look like. Shards can be pumaceous or vesicular and contain features such as small vesicles which may resemble fission-tracks. Become familiar with the look of a fission-track and count them on the glass standards and shards using this knowledge to limit the inaccuracy of the ages caused by misidentification of fission-tracks.

Concerning the Measured Glass Shard Fission-Track Ages

Glass shard ages for most of the ash deposits are between 0.5 and 1.1 million years (Fig. 8, p. 46). Previous tephrachronological research indicates eruptions have occurred in all of the major calderas (Yellowstone, Long Valley, Toledo, and Valles) of the western United States during this timespan. The region studied in this paper could contain ash from any or all of these calderas. Between 0.5 and 1.1 million years ago the region experienced an increase in the deposition of volcanic ash. Whether this was the result of increased volcanic activity, a change in the transport mechanism, or something else is not known.

In reference to Fig. 8 (p. 46), 13 of the ash deposits have glass shard ages between 0.80 and 0.95 million years. These ages are

confusing because they are not synchronous with radiometric ages reported for eruptions from the major calderas (i.e., are they 0.73 million year old Bishop ash from the Long Valley caldera or are they 1.12 million year old Tsankawi ash from the Toledo and Valles calderas?). Possible reasons for the discrepancies are 1) inaccuracy of the ages reported in this paper, 2) inaccuracy of previously reported ages, 3) inadequacy of a single age measurement as reported in this paper which does not account for error caused by variation in the technique (i.e., the mean of several age measurements may be needed on one ash and this would then indicate an ash was from a documented eruption and a single measurement may not be accurate enough.), and 4) these ashes could be from an undocumented source area or evidence of other eruptions at a major source area has been lost.

How the ashes were deposited is still uncertain. Wind or water could have deposited any of the ashes. High purity of the ashes suggests little reworking of the ash before it was deposited where it is located at present. Initial deposition was by the wind as high-altitude winds slowed or changed direction. One hypothesis is that the ash was deposited as a blanket on the landscape and washed into low spots on the landscape as concentrates of storm runoff and streamflow (Buttram, 1914).

All of the ashes with Tertiary glass shard ages (Ashes 22, 24, and 35) are located in the part of the region mapped as part of the Southern High Plains. The sediments enclosing these ashes include coarse gravels and thick layers of bentonite. They are part of the Ogallala Formation.

Major Tertiary and Quaternary formations in which the ashes are located include the Meade, Sanborn, and Kingsdown Loess of southern

Kansas and northwestern Oklahoma, the Ogallala, and the Seymour of northern Texas and the Tule, Blackwater Draw, and Blanco of the Texas Panhandle. Many of Oklahoma's Quaternary sediments are yet unnamed or correlated with named deposits in other states.

Whether associated with aeolian, alluvial, or lacustrine sediments, the dated ash deposits mark a point in time and are unique references to help interpret soil genesis and geomorphic evolution of the region. Ashes are found in all the major river basins so that geomorphic comparisons between basins with the ashes as time markers are possible. Ash is also found in most of the major land resources areas of western and central Oklahoma. Interpretations of soil and landscape development within and between these areas are also possible.

Future Research

Complete characterization and correlation of the ashes with each other, other ash beds, and the source areas based on multiple lines of evidence is needed. Accurate correlations will result in increased knowledge of the evolution of the region and identification of deposits of similar age across the area. One goal of this research is a surficial geology map of Oklahoma using the dated ash deposits as references to help recognize unconsolidated landforms of differing age.

The percentage of ash deposits in the western United States that have been dated is small. Izett and Wilcox (1982) attempted to correlate some of ash deposits with the Yellowstone caldera without dating them using only topographic, some chemical data, and limited existing age information. Glass shard fission-track dates on the hundreds of volcanic ash deposits of the western United States coupled

with accurate correlations could produce a model for the geomorphic evolution of a vast expanse of land important to the nation's welfare.

Soils research on the sediments associated with the ashes should contribute to a better understanding of the effects of time on soil development. Descriptions and interpretations of buried soil sequences above the ash horizons within individual landforms such as the large terrace deposits of western and central Oklahoma should increase the understanding of climatic changes and improve stratigraphic correlations. Estimates of the amount of erosion that has occured since the deposition of the ashes are also possible. Time, climate, deposition, and erosion of sediments contribute to the dynamic surface of the earth and impact the soil, a resource absolutely necessary for human survival.

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APPENDIXES

APPENDIX A

ASSUMPTIONS USED TO DATE THE SHARDS

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Several assumptions were made in measuring fission-track glass shard ages for the volcanic ash deposits dated in this study and the making of conclusions based on the dating results. These assumptions were:

1. The ash sampled at each locality came from the same eruption. No mixing of ashes occured prior to or after deposition.

2. The constants in the age equation (total uranium decay, fission decay of U^{238}, isotopic ratio of U^{235} to U^{238}, and cross-section for thermal neutron decay of U^{235}) were sufficiently correct to make the age estimates accurate.

3. The measured age coincides with the time the molten lava turned to ash which is considered to be the time of the volcanic eruption.

4. The ash formation age is nearly coincidental with the time the ash was deposited. Not long (a few days or possibly years at most) after the eruption the ash was deposited in close proximity to where it is presently located.

5. The glass shards have not been annealed. Care is taken not to sample shards from outcrop surface exposures and not to expose them to heating after sampling.

APPENDIX B

LOCATIONS OF ASH BEDS DATED IN THIS STUDY

LOCATIONS OF ASH BEDS DATED IN THIS STUDY

Ash No.	County	7.5 minute quadrangle	Location	Type of Exposure
1	Pratt, KS	Cairo, KS	NW¼,SE¼, sec.34,T.27S.,R.12W.	Borrow pit
2	Pratt, KS	Pratt, KS	SW¼,SW¼, sec.21,T.27S.,R.12W.	Abandoned mine
3	Meade, KS	Meade, KS	SE¼,SW¼, sec.2,T.31S.,R.28W.	Abandoned mine
4	Pratt, KS	Coats, KS	NW¼,SE¼, sec.22,T.28S.,R.14W.	Abandoned mine
5	Meade, KS	Irish Flats NE, KS	NW¼,NE¼, sec.21,T.33S.,R.28W.	Terrace escarpment
6	Pratt, KS	Cunningham, KS	SW¼,SW¼, sec.23,T.27S.,R.11W.	Terrace escarpment
7	Comanche, KS	Wilmore, KS	NE¼,SE¼, sec.12,T.31S.,R.17W.	Abandoned mine
8	Reno, KS	Partridge, KS	NE¼,SE¼, sec.1,T.25S.,R.7W.	Abandoned mine
9	Clark, KS	Bloom, KS	NE¼,SE¼, sec.14,T.30S.,R.24W.	Road cut
10	Reno, KS	Arlington, KS	SW¼,NE¼, sec.14,T.25S.,R.8W.	Active mine
11	Harper, KS	Bluff City NW, KS	NW¼,NE¼, sec.29,T.33S.,R.6W.	Abandoned mine
12	Clark, KS	Simmons Creek, KS	NW¼,NE¼, sec.12,T.30S.,R.23W.	Terrace escarpment
13	Custer, OK	Custer City, OK	SE¼,NE¼, sec.15,T.14N.,R.16W.	Abandoned mine
14	Ellis, OK	Gage, OK	SE¼,NE¼, sec.33,T.22N.,R.24W.	Abandoned mine
15	Woodward, OK	Quinlan, OK	SW¼,NE¼, sec.23,T.23N.,R.17W.	Terrace escarpment
16	Custer, OK	Custer City, OK	SW¼,SW¼, sec.27,T.15N.,R.16W.	Borrow pit
17	Greer, OK	Delhi SE, OK	SE¼,SE¼, sec.9,T.7N.,R.22W.	Abandoned mine
18	Beaver, OK	Gate NE, OK	NW¼,NW¼, sec.8,T.28N.,R.28E.	Active mine
19	Roberts, TX	Dry Creek SE, TX	1 km NW of S.H. 2699	Terrace escarpment
20	Washita, OK	Dill City, OK	SE¼,NE¼, sec.4,T.10N.,R.19W.	Terrace escarpment
21	Harper, OK	Logan NE, OK	NW¼,NW¼, sec.33,T.26N.,R.26W.	Terrace escarpment
22	Ellis, OK	Arnett SW, OK	NW¼,NW¼, sec.26,T.18N.,R.26W.	Terrace escarpment
23	Harper, OK	Rosston NW, OK	NE¼,SW¼, sec.10,T.28N.,R.26W.	Terrace escarpment
24	Ellis, OK	Roll NW, OK	SW¼,NW¼, sec.11,T.16W.,R.24W.	Terrace escarpment
25	Beaver, OK	Logan, OK	NE¼,NE¼, sec.26,T.2N.,R.26E.	Active mine
26	Collingsworth, TX	Rolla, TX	1.2 km S of S.H. 1056 and Friendship Church	Terrace escarpment

Ash No.	County	7.5 minute quadrangle	Location	Type of Exposure
27	Knox, TX	Rhineland, Tx	East side of Farm Road 267 1.4 km N of State Hwy 82	Terrace escarpment
28	Kiowa, OK	Babbs, OK	SE¼,SE¼, sec.28,T.6N.,R.18W	Road cut
29	Major, OK	Isabella, OK	NW¼,SE¼, sec.28,T.20N.,R.10W.	Terrace escarpment
30	Okfuskee, OK	Okemah SE, OK	NW¼,SE¼, sec.29,T.10N.,R.10E	Active mine
31	Woods, OK	Tegarden NE, OK	NW¼,SE¼, sec.32,T.29N.,R.15W	Terrace escarpment
32	Hughes, OK	Dustin, OK	NW¼,SW¼, sec.3,T.9N.,R.12E.	Road cut
33	Okfuskee, OK	Clearview, OK	SW¼,SE¼, sec.34,T.11N.,R.10E	Road cut
34	Garvin, OK	Byars, OK	SE¼,SW¼, sec.20,T.4N.,R.3E.	Terrace escarpment
35	Woodward, OK	Fargo, OK	NW¼,SW¼, sec.23,T.23N.,R.22W.	Abandoned mine

APPENDIX C

EXAMPLES OF FISSION-TRACK COUNTS ON GLASS STANDARDS, BORCHER'S STANDARDS, AND DATED SHARDS

EXAMPLES OF FISSION-TRACK COUNTS ON GLASS STANDARDS, BORCHER'S STANDARDS, AND DATED SHARDS

GLASS STANDARD 36

0	0	1	0	0	1	1
0	1	0	1	2	1	1
0	0	2	3	1	1	1
1	0	0	0	2	0	0
3	2	2	2	0	0	1
0	0	1	1	0	1	1
0	1	0	1	1	0	1
1	1	1	0	0	2	1
0	1	1	1	0	0	1
1	0	0	1	0	0	1
1	0	0	0	0	0	1
2	1	1	3	0	0	2
1	0	1	1	0	0	0
0	0	1	0	0	0	1
1	2	0	1	0	0	0
0	1	0	0	2	1	154
1	0	1	0	0	2	
0	2	0	0	1	0	
0	1	1	1	0	0	
0	2	1	0	0	0	
0	2	1	1	2	1	
0	0	1	2	0	0	
0	1	0	1	1	1	
4	1	2	0	0	0	
0	0	0	1	1	1	
2	1	2	0	1	0	
1	0	1	0	1	1	
1	0	0	1	0	1	
0	2	0	1	1	2	
1	0	0	0	0	0	
0	1	0	2	1	1	
1	0	0	0	1	1	
1	1	0	0	0	0	
0	1	0	0	1	0	
0	0	1	0	1	1	
0	0	0	0	0	0	
0	2	2	2	0	1	

154 fission-tracks in 237 fields equals 1050 tracks per cm^2 on the glass. 1050 tracks per cm^2 applied to equation 1 (page 35) and a dose of $1.19 \times 10^{14} \pm 3.15 \times 10^{12}$ neutrons per cm^2 is calculated.

Borcher's Standard 36

Ps				Pi				
1	0	0	0	2	2	3	3	102 spontaneos tracks counted and (459-102)
0	0	1	0	2	1	3	0	induced tracks counted applied to equation
0	1	0	0	4	4	2	1	2 (page 37) gives an age of 2.08 m.a..
1	0	0	0	2	1	3	1	
1	1	0	3	3	2	4	1	Track counting results applied to equation
1	2	1	0	2	2	3	3	3 (page 38) gives a standard error of the
0	0	0	0	3	2	2	4	age of 0.23 m.a..
0	0	0	1	1	4	0	4	
0	1	0	1	3	2	5	1	A neutron dose of 1.19×10^{14} neutrons per
0	0	0	1	3	2	4	1	cm^2 measured by glass standard 37 was used
0	1	0	1	3	5	6	2	to calculate the age.
1	0	0	0	2	3	1	3	
1	0	1	0	2	3	2	3	
0	1	1	1	4	1	1	3	
1	1	0	0	1	2	2	3	
1	0	2	0	5	3	0	4	
0	0	0	0	2	4	2	3	
0	2	1	0	2	1	1	1	
0	0	0	1	4	4	1	4	
0	0	1	0	0	3	0	3	
0	0	0	1	2	1	0	6	
0	1	0	2	5	1	2	3	
0	1	0	0	7	0	4	3	
0	1	1	0	5	5	6	4	
0	1	1	1	4	1	2	2	
2	0	0	3	3	2	4	3	
0	0	1	0	4	1	3	3	
0	0	1	2	5	0	2	2	
0	1	1	1	0	2	0	2	
0	0	0	0	2	1	2	3	
3	1	0	3	1	2	2	0	
1	1	0	0	5	1	3	1	
0	0	0	0	0	1	2	3	
1	1	0	0	4	2	4	1	
1	0	2	0	4	1	1	1	
1	0	0	0	2	1	1	1	
1	0	1	1	1	5	3	2	
1	0	2	0	4	4	1	4	
1	1	0	0	2	8	1	3	
0	2	0	102	0	1	3	459	
0	1	0		0	2	4		
0	0	1		2	3	0		
0	1	1		4	3	2		
1	1	1		3	1	4		
2	1	0		2	2	4		
2	0	0		5	3	3		
2	0	0		0	2	2		
1	1	2		4	0	1		
0	0	0		2	6	3		
0	1	1		2	0	2		

Ash 22

Ps	Pi
1	6
6	4
2	6
3	5
4	4
3	3
1	3
5	5
2	9
2	2
1	6
3	4
4	4
3	3
1	6
2	3
3	4
0	12
0	5
2	5
2	5
2	3
0	1
2	7
1	3
6	7
4	6
2	3
5	2
3	5
3	5
4	5
3	1
5	3
2	0
2	4
0	6
3	5
2	2
3	2
102	174

102 spontaneous tracks and (174-102) induced tracks applied to equation 2 gives an age of 10.1 m.a..

Track counting results applied to equation 3 gives a standard error of the age of 1.5 m.a..

A neutron dose of 1.16×10^{14} neutrons per cm^2 was used to calculate the age.

VITA

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