STATE GEOLOGICAL SURVEY OF KANSAS

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PETROGRAPHIC COMPARISON OF PLIOCENE AND PLEISTOCENE VOLCANIC ASH FROM WESTERN KANSAS

BY ADA SWINEFORD AND JOHN C. FRYE

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ABSTRACT

Lenticular, discontinuous deposits of volcanic ash occur in western Kansas in at least two stratigraphic positions within the Pliocene Ogallala formation and in one or more within the Pleistocene strata. To explore the feasibility of stratigraphic correlation by petrographic differences in the volcanic ash, we have studied 30 samples from 7 Pliocene localities and 34 samples from 17 Pleistocene localities. A color comparison showed a consistent difference. Chemical analyses showed a lower percentage of iron in the Pleistocene ash. The specific gravity of the Pleistocene ash is lower than that of the Pliocene ash. A refractive index of about 1.501 was common to the ash from all but two localities studied. Diagnostic characteristics of individual shards from the Pleistocene samples are numerous elongated vesicles, smaller radius of curvature, and greater abundance of rodlike fragments. Minor differences within the group suggest the occurrence of three ash falls within the Pliocene. All but two samples of Pleistocene ash are believed to represent a single fall.

INTRODUCTION

Somewhat more than 90 percent of the surface area of western Kansas is mantled by deposits of Pliocene, Pleistocene, and Recent age. The volcanic ash deposits studied occur as lentils in several stratigraphic positions within the Ogallala formation of Pliocene age and the younger Pleistocene strata. For many years Kansas has been a leading state in the commercial production of volcanic ash, or "pumicite," and a large number of deposits of this material have been located and recorded. In 1928 Landes (pp. 19-46) referred to 109 known localities of volcanic ash in 29 Kansas counties, and in 1942 Schoewe (in Jewett and Schoewe, 1942, p. 170) reported at least 115 localities of ash in 36 Kansas counties. Since the publication of these reports, several additional localities have been found. However, most of the deposits of major commercial value have been known for many years, and one of the largest pits has been in operation for nearly 40 years (Pl. 1A).

Prior to the past decade and a half, the surficial mantle of western Kansas was generally considered to belong largely to the Ogallala formation. Recent detailed studies have resulted in the placement within the Pleistocene of a large percentage of these deposits, and, further, in the subdivision of the Pleistocene strata in different parts of the state into named stratigraphic units (Frye, 1945). The most extensive ash horizon of southwestern Kansas, the "Pearlette ash," occurs within the Meade formation, and Hibbard (1944) has collected vertebrate fossils of definite Pleistocene age from below this ash at many localities. Other deposits of ash within the Pleistocene strata may be in the same or somewhat different stratigraphic positions. In northern Kansas, particularly in Norton County, extensive deposits of ash occur within the part of the Ogallala formation known as the *Krynitzkia* zone, and ash that may also belong to the Ogallala but in a higher stratigraphic position was observed in one section. Volcanic ash is known to occur in several stratigraphic positions within the Tertiary and Quaternary formations beyond the boundaries of Kansas in the Great Plains region.

The present petrographic study was undertaken to determine if significant differences exist among the various ash deposits, and if so, to determine whether these differences could be correlated with age and thus be of value for stratigraphic purposes. Bentonite beds have long been used as stratigraphic markers because of their continuity and position independent of facies changes. The chief petrographic problem in the stratigraphic use of bentonites has been the positive identification in the clay of volcanic material, such as glass shards and characteristic volcanic minerals (Pirsson, 1915; Ross, 1925, 1928) and they have been differentiated chiefly upon their relative stratigraphic positions. Unaltered volcanic ash offers a greater possibility of correlation on the basis of physical characteristics than does bentonite. In a region of continental Tertiary and Quaternary deposition such as the Central Great Plains, where individual members of formations cannot be traced over long distances, a petrographic approach to a study of the ash may supply information where other data are absent. The purposes of this paper are (1) the discussion of several properties of volcanic ash which may be used to differentiate between ash falls, with suggestion of their limitations; and (2) the application of some of these criteria to volcanic ash deposits in Kansas. As a prime objective was to determine differences between deposits of different ages, only samples from lentils whose stratigraphic position was established by paleontological or stratigraphic methods were considered.

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PETROGRAPHY OF VOLCANIC ASH

The type of material found in volcanic ash deposits depends on the kind of source rock emitted by the volcano or volcanoes, and the modification of this source material by selective transport and by contamination during transport or deposition. Differential alteration also is a factor that may modify the characteristics of an ash deposit. In earlier petrographic studies of volcanic ash, several characteristics have been described, among which color, particle size and shape, composition, types of inclusions or vesicles, and degree of alteration have been given most attention. These properties will be discussed individually in terms of their value for purposes of correlation, and possible effects of selective transport, contamination, and alteration will be pointed out.

Composition

Both lithology and chemical composition are generally used in the description of volcanic ash deposits. Mineral and chemical composition have been employed in determining source area (Merrill, 1885; Turner, 1892), in studying the degree of magmatic differentiation over a period of years (Falconer, 1902; Bonney, 1903), in determining the genetic relationship of two volcanic regions (Teall, 1902), and in distinguishing between beds of ash in a related series (Powers, 1941; Allison, 1945). The refractive index of glass particles has been used to estimate their chemical composition (George, 1924, pp. 364-366; Allison, 1945), to determine their source (Herold, 1937), and to determine variations within and between formational members (Bailey, 1926, pp. 118-120). The fact that composition has been considered of paramount importance in the description of volcanic ash is illustrated by the wide use in descriptive studies of Pirsson's (1915) classification of tuff, based on composition, as vitric, crystal, and lithic. More recently, Wentworth and Williams (1932, pp. 21-24) have reviewed several classifications of the pyroclastic sediments based in part on composition, but the classification proposed by them depends primarily on particle size and origin.

Minor differences in composition may prove to be of value in detailed studies. Montgomery (1895) noted that several ash deposits in Utah and northwestern Colorado gave a slight acid reaction in water, which he attributed to a sulfur compound.

Diller (1884) observed that selective transport plays an important role in determining the relative abundance of volcanic mineral grains and glass particles in an ash fall inasmuch as the thin glass particles are carried farther from the volcano by wind. This condition was shown by him to produce an increase in percentage of silica with greater distance from the vent; consequently, ash at a great distance will be more acidic than the magma from which it was derived, and ash close to the volcano less acidic if crystallization had begun at the time of eruption. In reporting an ash fall from which samples were collected at points at least 250 miles apart, Smith (1912) found no variation in the quantity of ash, but noted slight variations in the amount of magnetite present. The chemical composition cannot be expected to be diagnostic of a particular ash bed over large distances unless the vent is remote or volcanic mineral grains are absent. It is believed that selective transport had little sorting influence on the refractive index of the glass shards from the samples examined by us.

Contamination by sediments during transport or deposition or during reworking of ash may mask the volcanic mineral suite, but under most circumstances the presence of nonvolcanic minerals indicates that contamination has taken place.

Particle Size

Size of the particles is commonly noted in descriptions of volcanic ash beds, and in at least two instances (Todd, 1897; Buttram, 1914, pp. 48, 49) ash coarser than that of near-by deposits has been assigned to a different horizon. Dorell (1938) found that mechanical analyses were of value in the correlation of bentonite beds in the Pierre shale of eastern Colorado, and wrote, "The size distribution of bentonites is of value in correlation only in areas of uniform deposition."

Decrease in average size in a direction away from the source has been reported by many geologists (Barbour, 1898; Capps, 1915; Landes, 1928, p. 17; Landes, 1928a, p. 936). Buttram (1914, p. 48) observed a general decrease in size of ash particles toward the east in Oklahoma, except for samples from one locality. This led him to the conclusion that the anomalous locality represented a different ash fall—a hypothesis which was supported by additional evidence from particle shape. Particle size of unweathered ash in any one deposit is determined not only by distance from the source but also by size of particles emitted from the volcano, velocity of transporting wind, and, in the case of subaqueous deposits, water velocity.

Particle Shape

Pirsson (1915, pp. 194-198) described glass particle shape in some detail, and Ross (1928, p. 146) later wrote that glassy fragments assume three principal habits, as follows:

> One type is composed of fragments of glass that once inclosed rounded bubbles and consists of curved or lune-shaped fragments of the bubble walls, or Y-shaped fragments that were formed where three bubbles were in close proximity, and of double-concave plates that formed the wall between two adjoining bubbles. A second type is made up of nearly flat glass plates that were formed by the fragmentation of the walls that inclosed large flattened lens-shaped vesicular cavities. The third type has a fibrous structure and represents pumice fragments with minute elongated vesicular cavities and the inclosing glass walls. . . .

Neither Pirsson nor Ross, however, indicated that particle shape could be used in the differentiation of ash falls. Buttram's observation of a different particle shape in one locality in Oklahoma has already been noted. He described the shape of ash particles from this locality as "angular and lenticular," and from other localities merely as "angular." Barbour (1898, p. 25) found that some ash beds in the Great Plains had flat, nonvesicular, glassy scales, and that ash from other beds seemed to be "as vesicular, as angular, and as well suited to purposes of abrasion as the best pumice of our markets." Woolsey (1906, p. 478) in his description of volcanic ash near Durango, Colorado, wrote that the particles were flat glassy scales, and were not as good as some other ash for cleaning purposes. The effect of selective transport on particle shape of volcanic glass deposits remains to be investigated. Local concentration of unbroken bubbles where ash has fallen into water is possible.

Types of Vesicles and Inclusions

The presence or absence of vesicles in glass shards is closely related to the shapes of the particles. The vesicles may be spherical, flattened with circular outline, or greatly elongated, and in some cases curved. They may be pear-shaped or round at one end and tapering at the other, and they may be arranged in groups as described by Ross (1928, p. 146). Hanna (1926, p. 94) described glass flakes from a core in Louisiana as "minutely perforated."

Mineral inclusions may be either primary or produced by alteration of the glass. Alteration products are generally recognized as nonvolcanic minerals and may not be valid means of comparison.

Degree of Alteration

The term alteration as used here refers to the effects of devitrification and weathering, which may occur singly or simultaneously. Altered glass shards are characterized by a clouded or mottled appearance of the glass and abundance of polarizing particles and inclusions, and are generally associated with cemented aggregates, the composition of which is difficult to determine by petrographic methods. The amount of alteration which has taken place is a conceivable means of correlation where deposits are of greatly different ages; if other conditions are equal, the degree of alteration should be closely related to the age of the ash. The value of the relative degree of alteration of the ash as a means of correlation may be tested by comparison of samples of known age.

Color

The colors of the deposits have commonly been described in papers concerning volcanic ash. In most instances the color description is megascopic. Color was used by Landes (1928a, pp. 932, 933) in his comparison of Tertiary and Pleistocene ash deposits of Kansas and by others in detailed descriptions of series of ash beds (Gardner, 1923; Wanless, 1923, pp. 231-236; Bailey, 1926; Allison, 1945). Colors described have included white, light to dark gray, bluish gray, brown, buff, pinkish, red, and green. Several factors that may control or modify the color of an ash deposit include original composition, particle size, introduction of nonvolcanic material in the form of either clastics or cement, and weathering or devitrification.

Original composition of the ash.—Studies of recent ash falls show that there is great variation, that consecutive falls from the same source are sometimes different in color (Fry, 1912), and that there may be a progressive change in color during one fall (Flett, 1902). Most vitric ash is lighter in color than crystalline ash, although the basaltic ash known as palagonite consists of particles of brown glass (Pirsson, 1915, p. 199).

Particle size.—Barbour (1898, p. 24) found that the coarser ash in Colorado, Wyoming, and Montana was dirty and ochreous, whereas the finer ash of Kansas, Nebraska, and South Dakota was white in color, thus implying that the color becomes lighter with decrease in size. Flett (1902) found no color differences between size grades in ash that fell on Barbados after the eruption at St. Vincent. Bonney (1903) on the other hand, found that the finest fraction of volcanic dust from the Soufrière showed a distinct "warm-brown" tint, whereas the sample as a whole was of a dull dark-brown color speckled with a lighter tint. Color comparisons of volcanic ash samples should be made on the same size fraction.

Contamination by nonvolcanic material.—Rowe (1903, p. 7) in Montana and Buttram (1914, p. 30) in Oklahoma observed that no two volcanic ash beds had exactly the same tint, and Buttram attributed the lack of uniformity to adulteration with other substances. The presence of sand or silt may give volcanic ash a buff, yellowish, or reddish tint. Small insects trapped by an ash fall produce a brownish color. Color comparisons should be preceded by microscopic examination, and those samples or size fractions containing a large amount of foreign material should not be used.

Weathering and devitrification.—Alterations of volcanic glass to montmorillonite or beidellite may give the sample a yellowish or greenish tint. Some other forms of alteration apparently make the ash whiter. Color comparisons for purposes of correlation should be restricted to fresh ash.

CHARACTERISTICS OF PLIOCENE AND PLEISTOCENE VOLCANIC ASH

Stratigraphy

The oldest volcanic ash studied by us is Pliocene in age and occurs low within the Ogallala formation of Norton County, Kansas (Pl. 1B). Exposures of Ogallala along the south bluffs of Prairie Dog Creek were studied by M. K. Elias and John C. Frye during the summer of 1945. A maximum of 6.5 feet of ash occurs in this area and its characteristics are shown by sample no. 1, Table 1 (Pl. 1C). The ash occurs at the top of Elias' (1942) *Krynitzkia coroniformis* zone and below his *Biorbia* zone, as do all but one of the Ogallala volcanic ash localities studied from Kansas. A stratigraphic section measured south of Almena, Kansas, is given below.

Section measured south of Almena, W½ sec. 16, T. 2 S., R. 21 W., Norton County, Kansas, by M. K. Elias and John C. Frye

		Thickness, feet
Pleistocene		
22.	Silt and fine sand, buff, contains nodules of calcium carbonate	4.+
Ogallala formation		
21.	Limestone, porous, hard, light cream; contains abundant gastropod molds	3.0
20.	Covered. Two feet of mortar bed exposed about midway	35.0
19.	Sand, silty, fine to medium, loosely cemented with calcium carbonate; contains *Biorbia fossilia* (Berry), *Berryochloa amphoralis*, and *Celtis willistoni* (Cockerell)	6.4
18.	Covered. Unconsolidated silt and sand, buff, poorly exposed at a few places	32.0
17.	Sand, coarse to fine, and some silt; cemented with calcium carbonate	1.0
16.	Sand, fine to medium, buff; contains a small amount of calcium carbonate cement	5.0
15.	Volcanic ash, sandy at base (becomes impure to south); upper part locally cemented with calcium carbonate	6.5
14.	Silt and sand cemented with calcium carbonate, roughly bedded; contains *Krynitzkia coroniformis* Elias	6.5
13.	Partly covered. Calcareous clay silt, greenish gray at top; buff silt and very fine sand with calcium carbonate concretions in middle; and greenish-gray calcareous clay silt at base	20.0
12.	Silt, sand, and calcium carbonate	4.0
11.	Sandy silt, buff, locally unevenly cemented with calcium carbonate	0.7
10.	Silt, sand, and calcium carbonate, massive, light greenish buff	6.9
9.	Sand, fine to medium, pale greenish tan	3.7
8.	Silt, sand, and clay, calcareous, greenish brown	3.0
7.	Silt, clay, and sand, greenish brown	1.8
6.	Sand and some gravel	3.0
5.	Sand, clay, and silt, greenish brown	2.5
4.	Sand, medium, poorly sorted, uncemented, brown	3.0
3.	Covered	4.0
2.	Limestone, porous, hard, white; contains gastropod molds	1.0
1.	Covered to level of railroad tracks. Top of Cretaceous occurs in this interval	13.0
		166.0

The Ogallala of Nebraska has been considered by Lugn (1939, pp. 1258-1264) as a group with the following formations, in ascending order: Valentine, Ash Hollow, Sidney, and Kimball. The fossil seed *Krynitzkia coroniformis* Elias is considered by Elias (1942, p. 138) to be characteristic of the lower Ash Hollow, and he considers the zone of *Biorbia fossilia* (Berry) to occur immediately above the *Krynitzkia* zone and to include the middle and upper parts of the Ash Hollow (Elias, 1942, pp. 139-145). Thus the extensive Ogallala volcanic ash of Norton County, Kansas, probably occurs within the lower part of the Ash Hollow formation of Nebraska classification and somewhat below the mid point of the Ogallala formation as used in Kansas.

Four samples of Ogallala ash, nos. 22 to 25, were collected from one locality at a stratigraphic position that may be somewhat higher in the section, as fossil seeds, identified by M. K. Elias as *Biorbia fossilia* (Berry), were collected from below the ash.

A sample of volcanic ash (no. 30) was collected from the Pliocene deposits of Hemphill County, Texas, from locality 20 described by Reed and Longnecker (1932, pp. 57, 58). They assigned the beds at this locality to the uppermost part of the "middle beds" of the lower Pliocene. More recently (Wood, 1941, pl. 1, p. 12) the fauna collected from these beds has been assigned to the mid-Pliocene; therefore, this ash may be as young as, if not younger than, the extensive ash deposits of Norton County, Kansas.

Volcanic ash deposits, now considered to be of Pleistocene age, have been known from southwestern Kansas for many years. In 1896 Cragin first applied a stratigraphic name, the "Pearlette ash," to the deposits in Meade County and vicinity. In 1941, Frye and Hibbard (pp. 410-419) placed the extensive ash deposits of that area in the Meade formation of Pleistocene age, and Hibbard (1944) has described vertebrate fossils, which comprise his Cudahy fauna, from several localities immediately below the extensive ash of this region. He (Hibbard, 1944, p. 718) derived the name of the Cudahy fauna from the large volcanic ash pit (samples no. 32-39) north of the city of Meade.

Volcanic ash occurs within Pleistocene terrace deposits (Frye, Leonard, and Hibbard, 1943) of central Kansas that may represent a western extension of the McPherson formation. At several localities vertebrate fossils typical of Hibbard's Cudahy fauna have been collected from immediately below the ash. A measured section from Lincoln County, Kansas, described by Frye, Leonard and Hibbard (1943, p. 39) is given below.

Other localities of volcanic ash of known Pleistocene age occur in central and northern Kansas. In most instances the beds including these deposits have not been assigned to named stratigraphic units. At a few places in northwestern Kansas volcanic ash (samples no. 57-61) occurs within strata classified as the Sanborn formation of middle to upper Pleistocene age.

For comparative purposes two samples of Pleistocene ash from Nebraska were studied. According to E. C. Reed (personal com-

Section measured in sec. 28, T. 13 S., R. 10 W., Lincoln County, Kansas

	Thickness, feet
Quaternary	
3. Sand, fine, thin-bedded to laminated; grades upward into massive silt and fine sand; less sandy toward top, tan to reddish buff. Caliche nodules are distributed throughout the upper half	27.0
2. Volcanic ash, thin-bedded; upper part interbedded with fine sand. Upper part of interval partly covered (samples no. 51-54)	7.0
1. Sand and silt, gray, grading upward into gray, sandy, silty clay. Upper 18 inches contains rich molluscan fauna. Base of section at creek level	11.0
	45.0

munication dated December 19, 1945) the deposit near Inavale in Webster County (sample no. 62) occurs above beds classed as Upland formation and below deposits assigned to the Loveland formation, and the deposit mined by the LaRue-Axtell Pumice Company near Eustis (sample no. 63) occurs at the base of or immediately below deposits classed as Loveland formation. A sample of ash from Beaver County, Oklahoma (sample no. 64) was collected from beds of Pleistocene age that have been assigned to the Meade formation.

Sampling and Laboratory Procedure

The geographic distribution of the volcanic ash deposits sampled for this study is shown in Figure 1. The Pleistocene samples are from an area extending 250 miles in a north-south direction, from northwestern Oklahoma to Nebraska, and about 150 miles east-west, from McPherson County to Seward County, Kansas. All but one of the Pliocene samples studied were collected from Norton County, Kansas. However, samples no. 30, from Hemphill County, Texas, and no. 1, from Norton County, Kansas, represent a north-south range of about 275 miles.

Field samples were collected wherever possible from vertical faces of commercial pits and fresh road cuts. Where natural exposures were used, care was taken to clear away slump material so that representative samples would be obtained. Where the exposures were adequate, a sequence of channel samples was taken through the entire thickness of the bed, supplemented by spot samples at several positions. At localities where this was not possible, channel samples were collected from the exposed thickness, and spot samples only were collected at a few places. Fifty-three samples from 13 localities were collected by us; 12 samples from 12 localities were obtained from the industrial minerals file of the State Geological Survey of Kansas, and furnished by Norman Plummer, S. C. Happ, R. H. Dott, and the LaRue-Axtell Pumice Company.

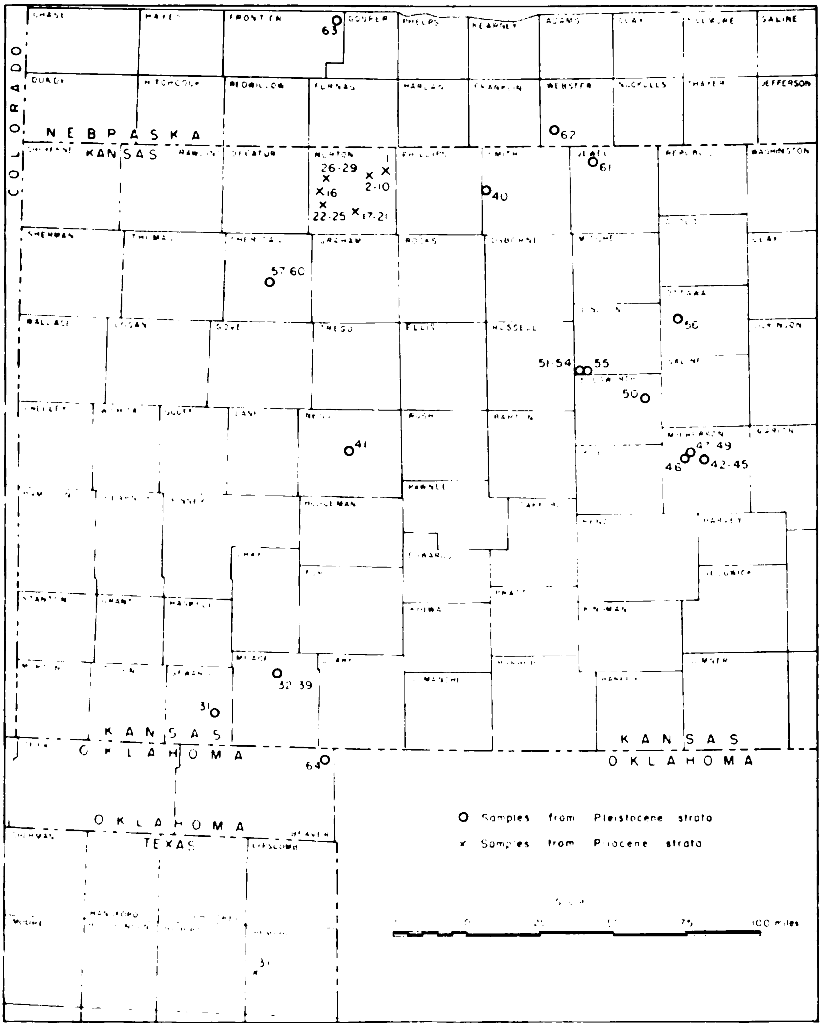

Fig. 1. Map of western Kansas and adjacent area showing locations of ash deposits studied.

In the laboratory the samples were dried and split and sieve analyses were made. Each sample was studied by use of binocular and petrographic microscopes, and megascopic color comparisons of several size grades were made. The chemical composition of selected samples was determined by Frances Schloesser in the laboratory of the State Geological Survey of Kansas.

Sieve analyses were made by use of a Ro-Tap sieve shaker equipped with screens of half Wentworth grades from 0.71 mm to 0.062 mm. About 40 grams of sample was placed on the screens and agitated for 10 minutes. The error in the coarser fractions resulting from aggregates was corrected by visual estimate by binocular microscope.

The amount of alteration, particle shape, general appearance, and percentage of contaminating materials were studied by use of a binocular microscope. A petrographic microscope was used to determine minerals present as original constituents of the ash, as contaminant, and as alteration products. The internal texture of the individual shards and their refractive indices were also studied under the petrographic microscope. Early in the investigation all size grades of several samples were studied in this manner to ascertain if these features varied with particle size. It was determined that particle size had no significant effect and the size grades 0.088 mm to 0.125 mm and 0.125 mm to 0.177 mm were selected for detailed study. Refractive indices were determined by the immersion method with central illumination. Liquids used were at intervals of 0.005 and were checked frequently with thermometer and refractometer. Comparisons of the various samples were made under similar conditions, so that any error would repeat itself. Thus, although the absolute error in the estimation of refractive index may have been ± 0.003 or ± 0.004, the relative error was more nearly ± 0.001 and certainly less than ± 0.002.

Color determinations were made of the size grade finer than 0.062 mm by megascopic comparison with the Ridgway (1912) color plates. This size grade was used because it constituted the major grade of most samples, it contained the smallest percentage of extraneous material, and preliminary observation showed the color differences between Pliocene and Pleistocene ash to be at a maximum in this grade.

Specific gravity determinations of nine samples containing little detrital material or alteration products were made by pycnometer. The size grades 0.177 to 0.125 and 0.088 to 0.062 mm were used.

Petrographic Characteristics

Composition.—Abraded grains of quartz and other substances believed to be contaminants were excluded in considering the composition of the ash. Substances entering into the composition of the ash are the shards, their included minerals and alteration products, and possibly a few volcanic mineral grains. One sample from Webster County, Nebraska (no. 62) contained a considerable number of biotite flakes. As detrital quartz grains were rare in this sample, the biotite is believed to have been part of the ash fall.

Twenty-seven partial chemical analyses of samples from 13 localities were made. Of these analyses, 18 were of Ogallala ash and 9 of Pleistocene material. The results are shown in Table 2. For the 27 analyses, silica ranged from 70.58 to 75.50 percent; alumina from 10.42 to 14.98 percent; lime from 0.07 to 1.64 percent; and loss on ignition from 2.60 to 8.51 percent. In each case, the extreme limits are furnished by samples of Ogallala ash, and the range of the Pleistocene samples lies entirely within the range of the Pliocene samples. Ferric oxide presents an exception, as this ingredient ranged from 1.66 to 3.09 percent in the Pliocene samples with an average of 2.26, whereas the range of the Pleistocene samples was 1.43 to 2.07 percent with an average of 1.68 percent. Only two samples of Pliocene ash contained less than 1.97 precent, whereas only one sample of Pleistocene ash contained more than this amount.

In all samples most of the shards had approximately the same refractive index; that is, the range was less than 0.003. The ash from all localities, except two of Pliocene age, had a refractive index of 1.499 to 1.502. Of the Pliocene samples, nos. 26 to 29 had a refractive index of about 1.506 to 1.507. These samples were collected from a natural exposure in the NW¼ NE¼ sec. 36, T. 2 S., R. 25 W., Norton County, Kansas, and the beds immediately above the ash yielded fossil seeds identified by M. K. Elias as *Biorbia fossilia* (Berry). This stratigraphic position below beds containing *Biorbia* indicates that it may be at the same horizon as the ash at the Calvert mine and elsewhere in Norton County, but as the zone of *Biorbia* is quite thick in this region and as no *Krynitzkia* were found at this locality, its position might be as much as 35 to 40 feet

TABLE 1.—*Location, stratigraphic position, and petrographic characteristics of volcanic ash samples.*

Sample No.	Type of sample[1]	Location	Stratigraphic position	Color[2] (<.062 mm)	Dominant refractive index	Remarks
1	Ch. 2.5′ from pit	SW¼ NW¼ sec. 16, T. 2 S., R. 21 W., Norton County, Kansas	Pliocene. [Ogallala fm., above *Krynitzkia* and below *Biorbia*.]	23′′′′′f	1.500-1.502 (?)	Shard outlines anisotropic. Small calcite inclusions in most particles, which are otherwise clear.
2	S. 14′ above no. 7	NW¼ SW¼ sec. 23, T. 2 S., R. 22 W., Norton County, Kansas	Pliocene. [Ogallala fm.; *Krynitzkia* collected from the ash.]	NGf[3]	1.500-1.502	Most shards clear. Trace quartz sand. Commercial pit of Wyandotte Chemicals Corporation.
3	S. 10′ above no. 7	do	do	do	do	do
4	S. 7.5′ above no. 7	do	do	do	do	do
5	S. 5′ above no. 7	do	do	do	do	do
6	S. 2.5′ above no. 7	do	do	do	do	do
7	S. 1′-3′ above base	do	do	do	do	do
8	Ch. 6′-12′ from bottom	do	do	do	do	do
9	Ch. bottom 6′	do	do	do	do	do
10	Refined product	do	do	do	do	do
11	S. 3′ above base 25 yards N. of road	SW¼ SE¼ sec. 2, T. 3 S., R. 25 W., Norton County, Kansas	Pliocene [Ogallala fm.]	23′′′′′g	do	Altered. Few vesicles. Much calcite.
12	S. 1′ above base	do	do	23′′′′′f	do	Most shards clear.
13	S. bottom 1″	do	do	18′′′′b	do	Several vesicles, some calcite. Many insects, giving brown color.
14	Ch. 4′-6′ from base, 150 yds. N. of road	do	do	23′′′′′g	do	Altered, few vesicles. Ca. 1% quartz sand.

15	Ch. 2'-4' from bottom	do	do	23''''f	do	Altered. Few vesicles.
16	Ch. bottom 2'	do	do	23''''g	do	Most shards clear.
17	Ch. 5'-7' from bottom	NE¼ SE¼ sec. 27, T. 4 S., R. 23 W., Norton County, Kansas	Pliocene [Ogallala fm.]	23'''f	do	Altered. Few vesicles. Ca. 25% quartz sand.
18	Ch. 3'-5' from bottom	do	do	do	do	Altered. Few vesicles. Trace quartz sand.
19	Ch. 2'-3' from bottom	do	do	do	do	Altered. Few vesicles.
20	Ch. 1'-2' from bottom	do	do	do	do	do
21	Ch. bottom 1'	do	do	NGg	do	do
22	Ch. 20" to top of bed	NE¼ sec. 2, T. 4 S., R. 24 W., Norton County, Kansas	Pliocene. [Ogallala fm., immediately above *Biorbia*]	19"f	(?)	Altered. Trace of quartz sand.
23	Ch. 8"-20" from bottom	do	do	21''''g	1.500-1.502	Somewhat altered. Trace of quartz sand.
24	Ch. 2"-8" from bottom	do	do	18''''g	do	Most shards clear; a few altered.
25	Ch. bottom 2"	do	do	do	do	do
26	Ch. 2'-3' from bottom	NW¼ NE¼ sec. 36, T. 2 S., R. 25 W., Norton County, Kansas	Pliocene [Ogallala fm., immediately below *Biorbia*.]	23''''g	1.506-1.507	Altered. Few vesicles. Ca. 6% quartz sand.
27	Ch. 1'-2' from bottom	do	do	do	do	Somewhat altered. Few vesicles. Trace quartz sand.
28	Ch. bottom 1'	do	do	do	do	do
29	S. middle of bed	do	do	do	do	do
30	Ch. lower 2'	Hemphill County Texas (Reed and Longnecker locality 20)	Pliocene. [Ogallala fm.; Hemphill fauna collected from lower part of the ash and beds below.]	NGg	1.495-1.497	Altered. Few vesicles.
31		T. 33 S., R. 32 W., Seward County, Kansas	Pleistocene [Meade fm.]	17'''f	1.499-1.501	Groups of elongate vesicles common.

TABLE 1.—*Location, stratigraphic position, and petrographic characteristics of volcanic ash samples (continued)*

Sample No.	Type of sample[1]	Location	Stratigraphic position	Color[2] (<.062 mm)	Dominant refractive index	Remarks
32	Ch. 3′-4′ from top	Sec. 2, T. 31 S., R. 28 W., Meade County, Kansas	Pleistocene. [Meade fm., immediately above horizon of Cudahy fauna.]	17‴f	1.499-1.501	Groups of elongate vesicles common. Commercial pit of Cudahy Packing Company.
33	Ch. 4′-6′ from top	do	do	17‴g	do	do
34	Ch. 6′-8′ from top	do	do	do	do	do
35	Ch. 8′-10′ from top, 7′ from bottom	do	do	do	do	Groups of elongate vesicles present.
36	S, 3′ below top, 100 yds. N. of 32-35	do	do	17‴f	do	Groups of elongate vesicles common.
37	S, 5′ below top	do	do	17‴g	do	do
38	S, 7′ below top	do	do	dc	do	do
39	S, 1.5′ above bottom, 400′ S. of 32	do	do	White	(?)	Altered. Few vesicles noted.
40		NW¼ sec. 31, T. 3 S., R. 15 W., Smith County, Kansas	Pleistocene	17‴f	1.499-1.501	Groups of elongate vesicles common.
41	S	S½ NW¼ sec. 30, T. 18 S., R. 23 W., Ness County, Kansas	Pleistocene	do	do	do
42	Ch, 3′-4′ from bottom	Cen. sec. 20, T. 18 S., R. 3 W., McPherson County, Kansas	Pleistocene [McPherson fm.]	do	(?)	Groups of elongate vesicles common. Shard outlines anisotropic. Small commercial pit.
43	Ch, 1′-3′ from bottom	do	do	17‴g	1.499-1.501	Groups of elongate vesicles common. A few calcite inclusions.
44	Ch, bottom 1′	do	do	do	do	do

45		NW¼ sec. 20, T. 18 S., R. 3 W., McPherson County, Kansas	Pleistocene [McPherson fm.]	do	do	Groups of elongate vesicles present, but rare.
46	S, middle of exposure	Road ditch SE¼ sec. 16, T. 18 S., R. 4 W., McPherson County, Kansas	Pleistocene. [Below Pleistocene loess and above McPherson fm.]	18‴f	1.499-1.502	Groups of elongate vesicles common.
47	Ch, 2′-4′ above bottom of pit	NW¼ SW¼ sec. 15, T. 18 S., R. 4 W., McPherson County, Kansas	Pleistocene. [McPherson fm.]	17‴g	1.499-1.501	Groups of elongate vesicles common. Small commercial pit.
48	Ch, bottom 2′ of pit	do	do	do	do	do
49	S, natural exposure 3′ below 48	do	do	do	do	do
50	S	SW¼ sec. 22, T. 15 S., R. 7 W., Ellsworth County, Kansas	Pleistocene. [Pleistocene terrace deposits (McPherson fm.)]	do	do	Groups of elongate vesicles present but not common.
51	Ch, 2′-5′ from bottom	Sec. 28, T. 13 S., R. 10 W., Lincoln County, Kansas	Pleistocene. [Pleistocene terrace deposits (McPherson fm.). Immediately above horizon of Cudahy fauna.]	do	do	Groups of elongate fluid inclusions common. Trace quartz sand.
52	Ch, 1′-2′ from bottom	do	do	17‴f	do	Groups of elongate fluid inclusions present.
53	Ch, bottom 1′	do	do	17‴g	do	Groups of elongate fluid inclusions present. Shards somewhat altered.
54	3.5′ composite ch.	do	do	do	do	Groups of elongate fluid inclusions fairly common. Some alteration.
55	Ch, 6.3′	W½ SE¼ sec. 27, T. 13 S., R. 10 W., Lincoln County, Kansas	do	do	do	Groups of elongate fluid inclusions common. Small commercial pit.

TABLE 1.—*Location, stratigraphic position, and petrographic characteristics of volcanic ash samples (concluded)*

Sample No.	Type of sample[1]	Location	Stratigraphic position	Color[2] (<.062 mm)	Dominant refractive index	Remarks
56	1′ ch from middle bed	NE¼ NW¼ sec. 29, T. 10 S., R. 5 W., Ottawa County, Kansas	Pleistocene. [Immediately above large molluscan fauna.]	17‴g	1.499-1.502	Altered. Elongate fluid inclusions rare, but present.
57	6′ above bottom of exposure	NW¼ sec. 34, T. 8 S., R. 28 W., Sheridan County, Kansas	Pleistocene. [Sanborn fm.]	do	1.499-1.501	Groups of elongate vesicles common. Small commercial pit.
58	3′ above bottom	do	do	do	do	do
59	Bottom of exposure	do	do	38″g	do	do
60	Cross-bedded lens at level of 58	do	do	17‴g	do	Groups of elongate vesicles very abundant.
61		Cen. N. line, SW¼ sec. 33, T. 1 S., R. 9 W., Jewell County, Kansas	do	17‴f	do	do
62		NE¼ SE¼ sec. 19, T. 2 N., R. 12 W., Webster County, Nebraska	Pleistocene. [Below Loveland fm. and above Upland fm.]	21‴f	1.500-1.502	Greatly altered. Groups of elongate vesicles present. Much biotite. Trace quartz sand.
63	S	S½ NW¼ sec. 20, T. 8 N., R. 24 W., Frontier County, Nebraska	Pleistocene. [At base of or immediately below Loveland fm.]	17‴f	1.498-1.501	Groups of elongate vesicles common. Commercial pit of LaRue-Axtell Pumice Company.
64	S	W½ sec. 5, T. 5 N., R. 28 ECM, Beaver County, Oklahoma	Pleistocene. [Meade fm.]	17‴g	1.499 (?)	Greatly altered; individual glass shards rare. Groups of elongate vesicles present. Commercial pit.

[1] Ch, channel sample; S, spot sample; blank space indicates that method of sampling is unknown.
[2] Color notations from Ridgway (1912).
[3] Neutral gray.

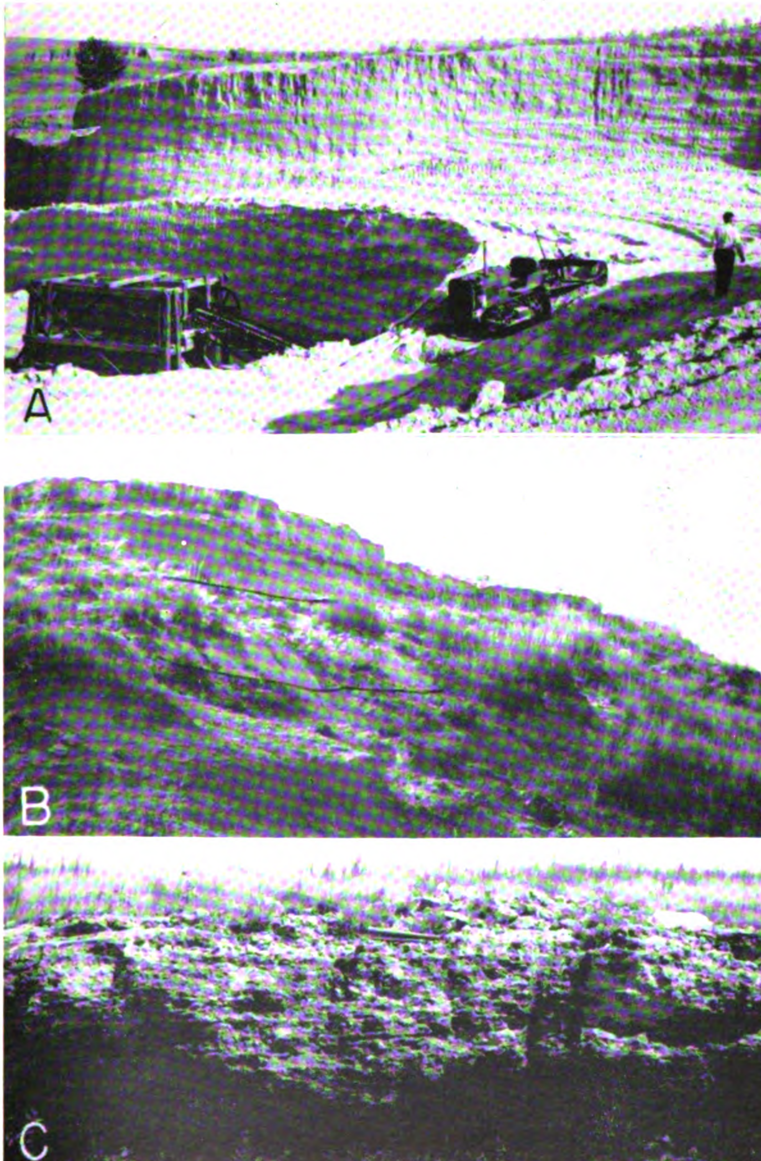

PLATE 1. Ogallala volcanic ash exposures in Norton County, Kansas. *A*, Mine of Wyandotte Chemicals Corporation at Calvert (samples no. 2-10); *B*, exposure of Ogallala showing volcanic ash in place below beds from which *Biorbia fossilia* was collected, NW¼ NE¼ sec. 36, T. 2 S., R. 25 W., Norton County, Kansas (samples no. 26-29); *C*, cemented upper part of volcanic ash bed exposed in measured section near Almena, Norton County, Kansas. Sample no. 1 collected about 100 yards north in small abandoned pit.

TABLE 2.—*Chemical composition of 27 samples of volcanic ash from Kansas and Texas*

Sample No.	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO[1]	Alk[1]	Ignition loss
1	73.80	13.09	2.46	1.11	(6.50)		3.04
2	72.09	11.68	2.42	0.62	(8.14)		5.05
3	72.50	10.42	2.34	0.67	(9.07)		5.00
5	72.48	11.64	2.20	0.07	(8.96)		4.65
6	71.73	14.04	2.22	0.65	(6.92)		4.44
7	72.00	10.80	2.25	0.63	(9.91)		4.41
8	72.41	12.09	2.38	0.59	(6.56)		5.97
9	72.47	13.61	2.16	0.68	(5.92)		5.16
10	72.56	11.99	2.39	0.78	(6.63)		5.65
13	70.97	11.75	1.97	1.64	(8.10)		5.57
14	70.58	14.98	1.66	1.10	(7.34)		4.34
15	71.53	11.57	2.49	1.07	(9.29)		4.05
16	71.37	13.46	3.09	0.83	(6.62)		4.63
22	73.87	12.75	2.22	1.14	(5.94)		4.08
23	72.10	13.16	2.22	0.84	(7.03)		4.65
24	74.31	12.90	1.66	1.41	(7.12)		2.60
26	75.50[2]	11.15	2.06	1.26	(6.25)		3.78
30	71.55	12.30	2.54	0.93	1.85	(2.32)	8.51
31	74.34	12.40	2.07	0.64	0.65	5.59	4.24
35	72.64	12.06	1.67	0.74	(8.65)		4.24
36	71.95	12.65	1.43	0.80	(9.04)		4.13
39	71.26	13.13	1.50	0.80	(9.13)		4.18
41	71.16	11.70	1.47	1.46	0.38	(9.97)	3.86
51	72.77	13.87	1.82	0.87	(7.52)		3.15
52	73.02	13.20	1.77	0.70	(8.04)		3.27
56	73.30	14.46	1.54	1.00	0.21	5.64	4.60[3]
60	72.83	14.38	1.84	0.56	(4.86)		5.53

[1] Calculated values indicated by parentheses.
[2] This sample contains about 6 percent quartz sand.
[3] Includes moisture.

higher within the Ogallala. Sample no. 30, from Hemphill County, Texas, had an index of about 1.496. In several samples we observed a few shards with indices that diverged more than 0.004 from the refractive index of most of them. In the case of most Pleistocene samples this divergence was below the normal, while in a few Pliocene samples some shards possessed indices higher than the normal. One sample (no. 46) collected from a thin bed lying stratigraphically above the widespread ash in McPherson County seems to have a very slightly higher index than that of the other Pleistocene samples, and has a few grains higher, rather than lower, than the average index.

A refractive index of about 1.50 is to be expected in natural glass containing 71 to 75 percent SiO_2, as has been shown by George (1924, p. 365). He wrote that weathering and partial oxidation may cause considerable variation in the refractive index in a single specimen, but found no variations "in those rocks which under the microscope appear to be pure glass and uniform in color."

Particle size.—The results of sieve analyses made of each sample studied are presented in Table 3. These analyses are not significant with regard to geographic distribution or age. Sequence samples collected at three Pliocene localities showed the lower part of the bed to be coarser textured than the upper part of the deposit. In all but nine samples more than 50 percent of the sample by weight passed through the 0.062 mm sieve. It was noted in samples showing the effects of alteration (samples no. 26, 39, 62, and 64) that the finest fraction contains a sizable percentage of monomineral grains. This indicates that such alteration has resulted in reducing the average grain size of the sample, where aggregates are not considered.

Particle shape.—A consistent difference in the shape of the individual shards of Pliocene and Pleistocene ash was observed (note Fig. 2). The shards of Pliocene ash are flatter than those of Pleistocene ash, they generally possess fewer ridges caused by the juncture of glass bubbles, and the bubble walls are thinner. These features give the Pliocene ash a platy or micaceous appearance when compared under the microscope with the more angular Pleistocene material, and give the Pliocene ash a noticeably less gritty "feel" when rubbed between the fingers. Elongate fibrous glassy fragments (Fig. 2, *j*) similar to the third type described by Ross (1928, p. 146) were observed in the Pleistocene samples.

Types of vesicles and inclusions.—A marked difference was found to occur consistently in the internal texture of ash shards of the two different ages (note Fig. 3). The Pleistocene ash is characterized by many shards containing numerous elongated vesicles, commonly arranged in clusters or groups, whereas the ash shards from the Ogallala contain very few vesicles, and the few that were observed were not consistent as to shape. In some instances elongate parallel vesicles were found to be open at one or both ends where they intersect the surface of the shard (Fig. 3, *l*). At several Pleistocene localities the characteristic vesicles were most abundant in shards from the upper part of the deposit. Few mineral inclusions were found in the fresh shards of all samples studied.

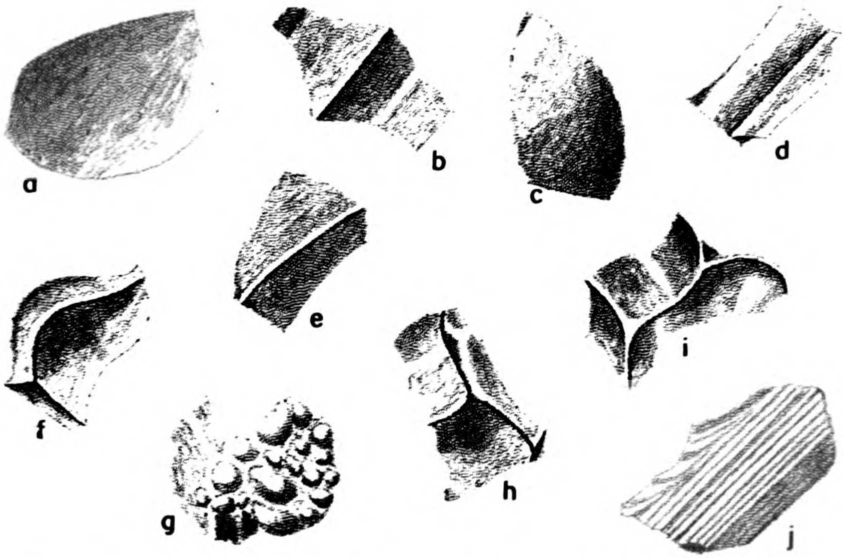

FIG. 2. Characteristic shards of Kansas volcanic ash, by reflected light: *a–e*, Pliocene ash from sample 7; *f–j*, Pleistocene ash from sample 47. Shards were selected to show significant differences between the two ages of ash. X 72.

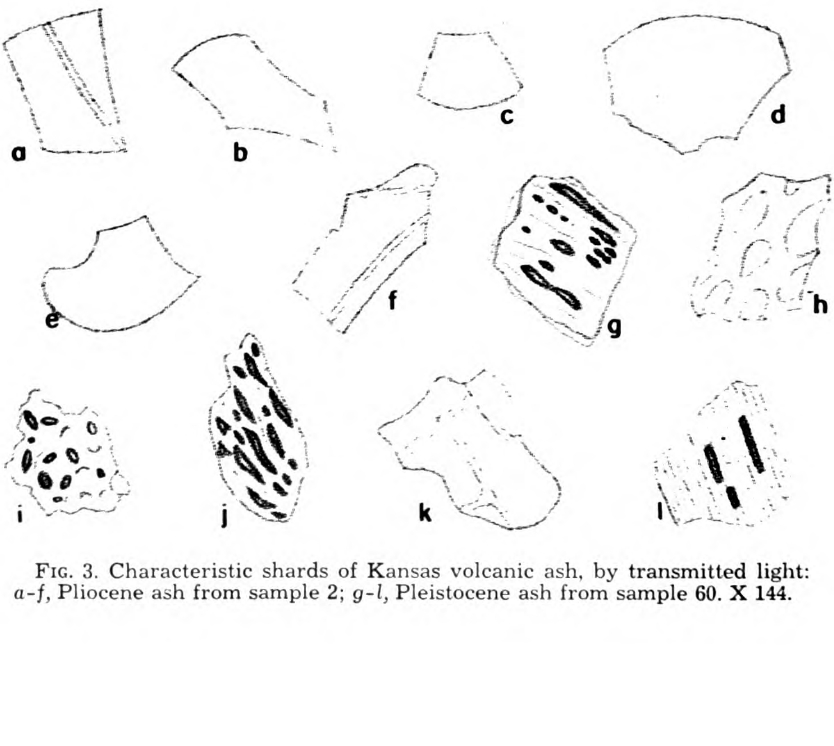

FIG. 3. Characteristic shards of Kansas volcanic ash, by transmitted light: *a–f*, Pliocene ash from sample 2; *g–l*, Pleistocene ash from sample 60. X 144.

Color.—As was described by Landes (1928a, pp. 932, 933) a recognizable color difference between the samples of the two ages was observed. In general, the Pleistocene ash has more orange-yellow and less gray than does the Pliocene ash. The Ridgway color notation for each sample is given in Table 1.

Degree of alteration.—In all cases where alteration minerals were recognizable with a petrographic microscope they displayed no stratigraphic or geographic significance. All alteration features, except color changes, were common to volcanic ash of both ages. A larger percentage of the Pliocene than of the Pleistocene samples studied showed effects of alteration. In one sample of each age alteration took the form of narrow anisotropic boundaries around the thin edges of the glass shards. The most altered samples contained many aggregates, yellowish brown or white in color, the composition of which was not determined. Judging from the few altered samples studied, the color of the deposits is modified by alteration to produce tints of yellow, orange-yellow, and green in the Pliocene deposits, whereas paler tints or even white result in the Pleistocene deposits. It is possible that this difference is due to the greater percentage of iron in the Pliocene ash.

Specific gravity.—Values for the specific gravity of 7 Pliocene and 11 Pleistocene samples are given in Table 4. No significant differences were found between size grades except in sample no. 60. The specific gravity of the Pliocene samples studied ranges from 2.33 to 2.39, and that of the Pleistocene samples from 2.20 to 2.32.

The differences in specific gravity between Pliocene and Pleistocene samples may be due to one or both of two factors: (1) the presence of numerous vesicles in the Pleistocene ash, and (2) the higher percentage of iron in the Pliocene material. George (1924, p. 363) plotted specific gravity of natural glasses against percentage of iron oxides and other constituents, and showed that glasses containing less than 2 percent iron oxides had a specific gravity of less than 2.33, whereas those with more than 2 percent had a higher gravity. The fact that in the samples here described iron oxide content alone is not the controling factor as to gravity is shown by the lack of consistency of relationship of iron content to gravity in the samples determined, particularly in those of Pleistocene age (Fig. 4).

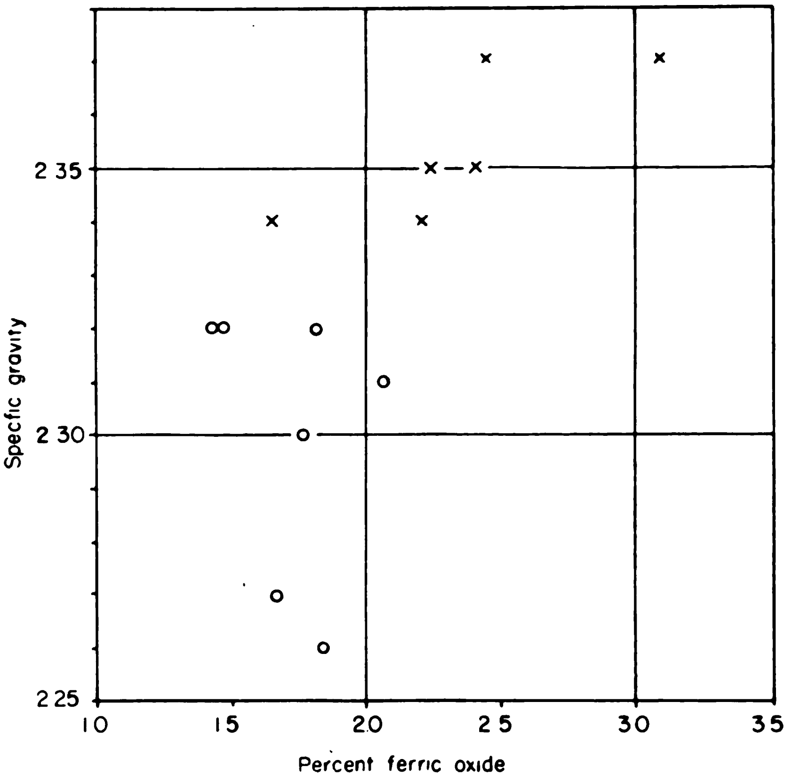

FIG. 4. Relation of specific gravity (0.088-0.062 mm fraction) to percentage of ferric oxide in several volcanic ash samples. Pliocene samples are designated by crosses, Pleistocene samples by circles.

George (1924, p. 362) showed the effect of fine pores on specific gravity determinations by grinding a specimen of pumice to several degrees of fineness and getting a variation of from 2.249 to 2.389. Sample no. 60 of the present study was collected from a small cross-bedded lens which contained coarser and more vesicular shards than the surrounding ash. The specific gravity of ash from this lens was lower than that of the comparable grade size from the surrounding ash, and in the coarser fraction possessed the lowest specific gravity of any sample determined. This observation indicates that the relative abundance of vesicles in the shards may have an important bearing on the specific gravity. Whether the dif-

Table 3. ***Size distribution of volcanic ash samples***

Sample No.	Size distribution in mm (percent by weight) .71-.5	.5-.35	.35-.25	.25-.177	.177-.125	.125-.088	.088-.062	.062
1		0.1	1.1	2.5	6.6	13.7	11.6	64.5
2		0.0	0.3	1.3	3.7	10.1	10.5	74.0
3	0.0	0.1	0.8	2.0	5.5	11.9	13.3	66.5
4	0.0	0.1	1.1	4.7	9.1	17.2	15.3	52.4
5		0.0	0.3	0.8	1.6	3.9	4.6	88.9
6		0.0	0.4	1.4	6.3	12.0	15.0	64.9
7	0.0	0.3	2.2	8.0	19.5	26.3	12.6	31.1
8	0.0	0.1	0.9	3.3	8.6	16.0	13.0	58.1
9		0.1	1.2	3.1	9.1	17.7	15.4	53.3
10		0.1	0.5	1.6	5.5	11.8	12.4	68.0
11	0.0	0.2	0.8	2.4	6.2	14.5	14.9	61.1
12		0.7	1.0	5.6	15.3	35.1	22.0	20.5
13	0.2	2.3	11.5	22.6	30.1	21.6	7.1	4.6
14	0.0	0.1	1.5	2.6	5.0	14.0	14.5	62.3
15		0.0	0.0	0.4	1.5	5.5	9.1	83.4
16	0.0	0.3	0.8	1.8	3.9	7.0	6.7	79.5
17			0.2	0.0	0.9	23.9	17.6	57.3
18			0.0	2.0	6.4	15.4	18.2	57.9
19		0.0	0.8	4.3	9.0	16.5	21.7	47.7
20		0.0	1.3	2.6	7.2	18.8	18.6	51.6
21			0.3	2.7	6.4	13.0	12.6	65.0
22				0.0	2.5	7.1	8.5	81.9
23	0.0		0.0	0.0	1.3	6.1	17.8	74.7
24			0.0	0.9	2.6	8.5	19.4	68.6
25		0.0	0.1	2.4	9.8	21.8	18.0	47.8
26					0.4	2.7	5.2	91.7
27			0.0	0.0	1.0	3.6	5.9	89.5
28				0.1	1.0	4.1	6.0	88.7
29			0.1	0.3	1.0	3.2	5.2	90.3
30		0.0	1.1	2.8	5.1	8.4	8.8	73.8
31	0.0	0.0	0.1	0.5	1.7	5.6	8.3	83.8
32		0.0	0.5	1.3	4.1	10.6	10.9	72.6
33		0.1	0.9	2.7	6.5	16.2	18.1	55.5
34		0.0	0.3	1.1	3.1	10.8	13.8	70.9
35		0.0	0.2	1.1	2.7	9.0	11.7	75.3
36	0.0	0.0	0.4	0.9	3.0	9.1	9.2	77.5
37	0.0	0.0	0.2	1.2	3.4	9.7	10.0	75.4
38	0.0	0.0	0.2	1.3	3.8	11.3	11.4	72.1
39			0.0	0.0	0.5	1.4	2.6	95.5
40			0.1	0.6	2.2	8.3	11.9	76.9
41		0.0	0.1	0.2	0.6	2.6	4.3	92.3
42		0.0	1.0	4.7	13.3	23.7	15.7	41.6
43		0.0	1.0	3.9	9.9	18.2	14.0	52.9

TABLE 3.—*Size distribution of volcanic ash samples (concluded)*

Sample No.	Size distribution in mm (percent by weight) .71-.5	.5-.35	.35-.25	.25-.177	.177-.125	.125-.088	.088-.062	.062
44		0.0	0.3	1.4	6.1	13.5	12.3	66.3
45		0.0	0.9	4.0	9.3	19.1	12.5	54.1
46		0.1	1.2	4.9	11.9	20.4	15.6	45.9
47		0.0	0.8	4.1	12.4	22.8	15.6	44.2
48			0.4	1.1	5.8	14.3	15.7	62.8
49			0.0	0.1	0.7	4.8	9.1	85.4
50		0.0	0.5	1.5	4.2	12.9	16.0	64.9
51		0.1	0.7	2.5	6.9	13.6	12.5	63.8
52		0.2	0.7	1.9	5.8	11.5	11.7	68.2
53		0.1	0.8	3.2	8.1	17.7	17.2	52.8
54		0.0	0.9	2.2	5.8	12.4	11.1	67.5
55			0.1	0.3	1.1	5.8	10.8	81.8
56		0.0	0.1	1.2	3.4	8.2	9.5	77.5
57	0.0	0.0	0.2	0.4	1.0	2.8	3.3	92.3
58			0.0	0.0	0.2	4.6	9.7	85.4
59			0.0	0.1	1.7	9.3	14.1	74.9
60		0.2	0.4	1.6	4.7	13.6	13.3	66.4
61	0.0	1.0	3.8	8.1	14.8	21.7	15.9	34.7
62				0.0	0.1	1.7	7.9	90.4
63			0.1	0.8	2.8	8.5	11.2	76.4
64			0.0	0.0	0.0	0.0	0.1	99.9

TABLE 4.—*Specific gravity of 18 samples of Kansas volcanic ash*

Sample No.	Age	Location	Specific gravity (.177-.125 mm)	Specific gravity (.088-.062 mm)
1	Pliocene	Norton County		2.37
2	do	do	2.33	2.35
6	do	do	2.35	2.34
7	do	do	2.36	2.35
16	do	do		2.37
24	do	do		2.34
29	do	do		2.36
31	Pleistocene	Seward County	2.32	2.31
33	do	Meade County	2.26	2.27
35	do	do		2.27
36	do	do	2.31	2.32
40	do	Smith County	2.27	2.29
41	do	Ness County	2.32	2.32
45	do	McPherson County	2.30	2.28
51	do	Lincoln County		2.32
52	do	do		2.30
58	do	Sheridan County	2.28	2.29
60	do	do	2.21	2.26

ferences in the ash samples are due to chemical composition or to the effect of vesicles, they appear to be of diagnostic value.

The relation shown by George (1924, p. 367) of specific gravity to refractive index is similar to that found by us. Samples on his graph with a refractive index of approximately 1.50 ranged in specific gravity from 2.20 to 2.38.

CONCLUSIONS

Volcanic ash occurs in the Great Plains of Kansas and adjacent states at several stratigraphic positions within the Pliocene and Pleistocene deposits. Although at least two different horizons of ash, which may represent three ash falls, are known from the Pliocene, and one or more, possibly representing as many as three ash falls, may occur within the Pleistocene, they can be placed in two natural groups—one of about mid-Pliocene age and the other of about mid-Pleistocene age.

Several characteristics are common to all Pleistocene samples, which serve to differentiate them from all Pliocene samples. The Pliocene ash is typified by a neutral gray color; thin, transparent, slightly curved platy shards which are relatively free from vesicles; a specific gravity of 2.33 or more; and a ferric oxide content generally more than 2 per cent. The Pleistocene ash is lighter in color; the shards are more sharply curved and include abundant elongate vesicles, commonly arranged in clusters. Rodlike or fibrous shards were found in samples from all Pleistocene localities.

Within the group of Pliocene samples, differences in refractive index of the shards from certain localities suggest that these samples have been derived from three ash falls; however, one of these localities (Hemphill County, Texas) is so remote from the others that differences in the ash alone cannot prove a difference in age. The high index samples from Norton County (nos. 26-29) have not been shown by fossil seeds to be in a different stratigraphic position than the large group of samples from that area (nos. 1-21), whereas no petrographic differences were found between Pliocene ash deposits in Norton County believed, on the evidence of fossil seeds, to be at slightly different positions within the Ogallala.

There may be as many as three ash falls within the Pleistocene strata. One is widespread and is represented by samples no. 31 to 45 and 47 to 61 from Ellsworth, Jewell, Lincoln, McPherson, Meade, Ness, Ottawa, Seward, Sheridan, and Smith Counties, in central and western Kansas; by sample no. 63 from Frontier County, Nebraska; and by sample no. 64 from Beaver County, Oklahoma. Another fall is suggested by an upper ash deposit in McPherson County (no. 46) which has a slightly different refractive index, and still another may be represented by the sample from Webster County, Nebraska (no. 62), which contains numerous flakes of biotite.

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