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THE MIOCENE TROUBLESOME FORMATION IN MIDDLE PARK, NORTHWESTERN COLORADO

PART I: STRATIGRAPHY

PART II: PETROGRAPHY AND CHEMISTRY OF ASH BEDS

By

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Open-file report

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The Miocene Troublesome Formation in Middle Park, northwestern Colorado, by G. A. Izett, 42 pages, 7 figures, and 4 tables

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PART I

STRATIGRAPHY

Tuffaceous sedimentary rocks of late early and late Miocene age that range in thickness from about 0 to 1,000 feet compose the Troublesome Formation which underlies about 100 square miles of low grass- and sage-covered lands east of Kremmling, Colo. (fig. 1). The Troublesome Formation was studied as part of a U.S. Geological Survey areal mapping program started in 1961 in the Kremmling and Hot Sulphur Springs quadrangles in Middle Park, Colo., to evaluate mineral resources on public lands. The results of the work in the Hot Sulphur Springs quadrangle (Izett, 1968) are soon to be published, and the fieldwork in the Kremmling quadrangle is nearing completion. The first part of the report concerns the stratigraphy of the Troublesome Formation, and the second part describes the petrography and chemistry of the many volcanic ash beds in the Troublesome and certain other Miocene ash beds in the Western Interior.

It is a pleasure to acknowledge the help of G. E. Lewis and R. W. O'Donnell of the U.S. Geological Survey who aided in collecting fossils and assisted in the paleontologic-stratigraphic study of the Troublesome Formation. The writer appreciates the cooperation of Peter Robinson of the University of Colorado who was invited in 1964 by G. E. Lewis and the writer to quarry, screen, and study the mammalian microfossils of the Troublesome. N. M. Denson of the U.S. Geological Survey collected some of the samples of ash beds, described later in the report, from Wyoming and Nebraska and provided useful stratigraphic information.

The Troublesome Formation of Middle Park, Colo., is lithogenetically allied with terrestrial lower to upper Miocene rocks exposed elsewhere in northwestern Colorado and southern Wyoming, and a sketch map (fig. 2) shows the approximate distribution of the Miocene sedimentary rocks. The distribution of the rocks suggests that the Miocene rocks are only remnants of once more extensive deposits. For example, the Miocene rocks that presently underlie the North Park syncline were probably once continuous with the Miocene rocks of Saratoga Valley, but post-Miocene deformation that includes movement along faults such as the large fault that lies on the north side of the North Park syncline (Hail, 1965; D. M. Kinney, oral commun., 1967) and subsequent erosion have isolated the once continuous Miocene rocks. The importance of post-Miocene faulting in northwestern Colorado and of how the faults have influenced the distribution of Miocene rocks has not been widely recognized. Locally, outcrop margins of Miocene rocks are bounded by faults including the rocks in Big Creek and Cunningham Parks (Montagne and Barnes, 1957), the rocks of the Troublesome Formation, and the Miocene rocks along the Colorado River west of Gore Canyon.

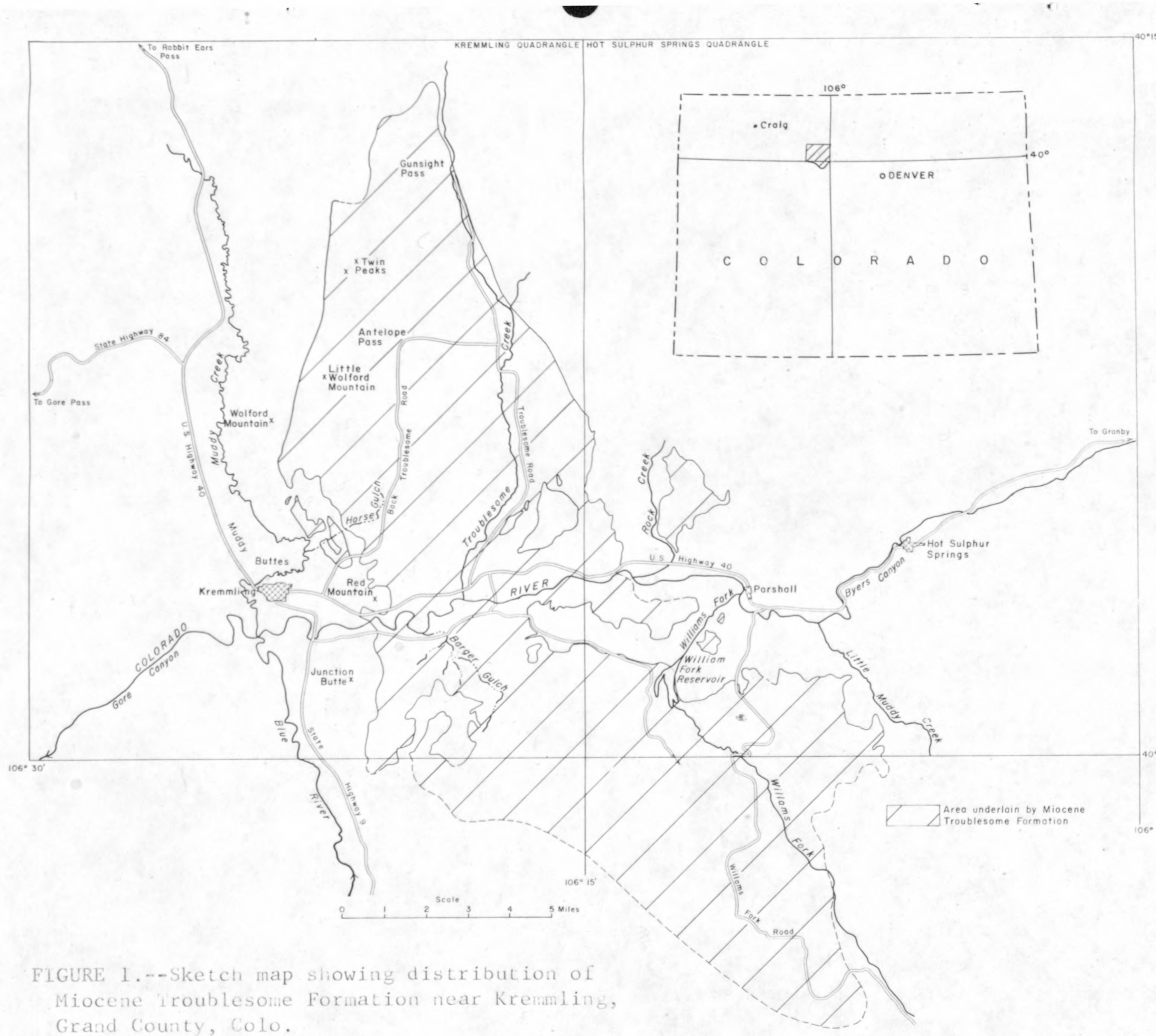


FIGURE 1.--Sketch map showing distribution of Miocene Troublesome Formation near Kremmling, Grand County, Colo.

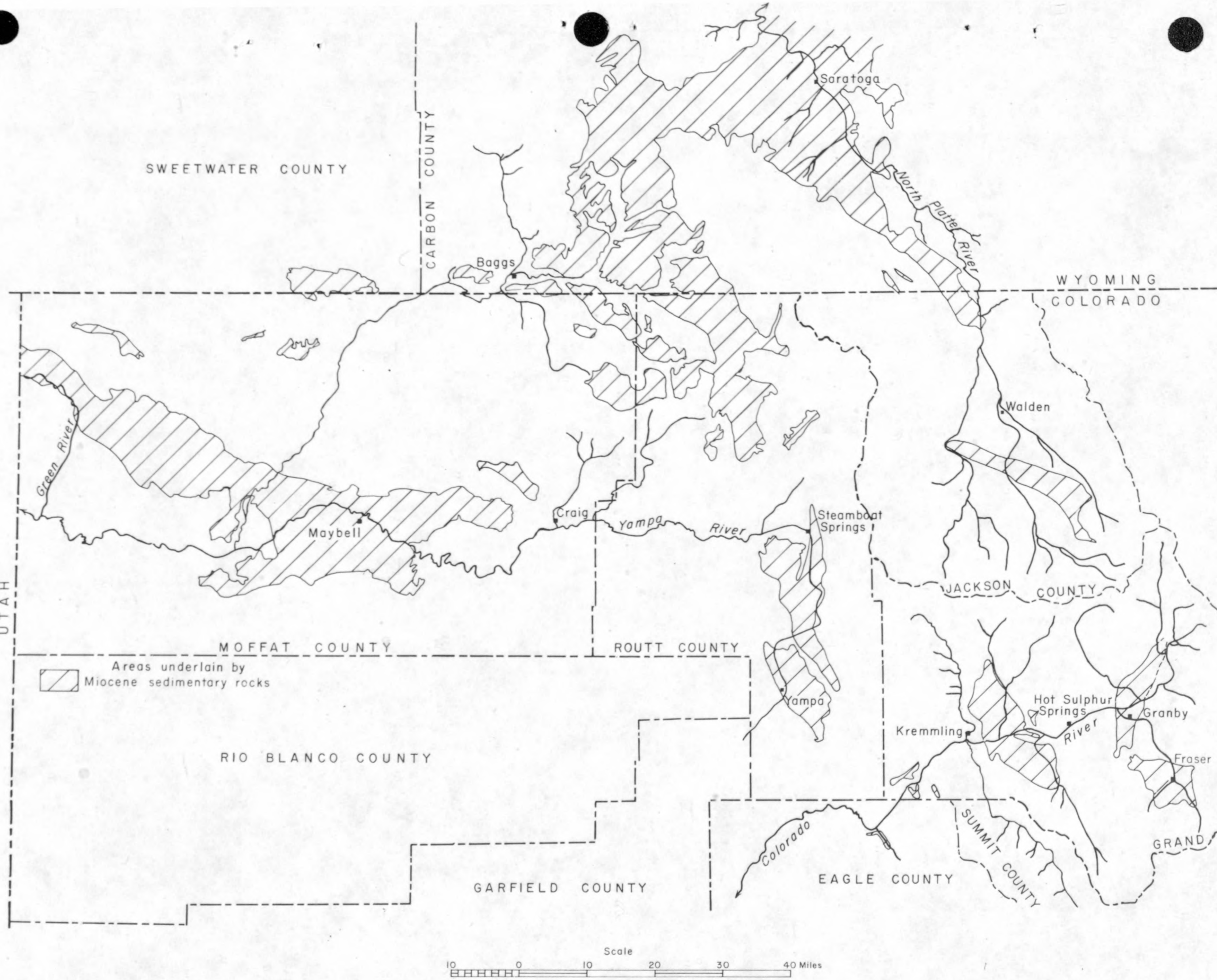


FIGURE 2.--Sketch map showing distribution of Miocene sedimentary rocks and major rivers of northwestern Colorado and south-central Wyoming. Modified after Geologic Map of Colorado (Burbank and others, 1935), Geologic Map of Wyoming (Love and others, 1955), and Buffler, 1967).

The distribution of the Miocene rocks along the large river valleys of northwestern Colorado suggests that the framework of the present drainage system was established as early as Miocene and probably as early as late Eocene time. Whether the major rivers were throughgoing in Miocene time and whether the drainage systems were integrated is not known.

The Troublesome Formation was deposited in a small intermontane basin, here named the Troublesome basin. This basin is one of several small basins that formed in Miocene time in Middle Park and that were filled chiefly with tuffaceous sediments stripped from the adjoining highlands after a regional episode of middle Tertiary volcanism. Locally derived material including granitic and volcanic-rock fragments were shed from the highlands and locally form important units in the Troublesome. The Troublesome basin is about 25 miles long, trends north, and the axis lies west of Troublesome Creek in the Kremmling quadrangle. The basin extends south from near Gunsight Pass to well south of the 40th parallel. Arms of the basin extend east from the Kremmling quadrangle into the Hot Sulphur Springs quadrangle (fig. 1).

Upper Tertiary rocks in the Kremmling area were called "lake beds" by Marvine (1874, p. 157) and North Park Formation by Burbank and others (1935) who assigned a Miocene(?) age to the formation. Later, Lovering and Goddard (1950, p. 41) used the name Troublesome Formation, a name that had been applied by Richards (1941) to the poorly understood basin-fill sedimentary rocks near Kremmling, Colo.; they suggested that most of the rocks might be of Oligocene age and "locally [the formation] was reworked in Miocene and early Pliocene time." Lovering (1930, p. 74) found mammalian fossils, dated by Cook as of Arikaree age, in the Troublesome Formation of the Granby anticline area. Present knowledge of the age of the Troublesome dates from 1962, when the writer found well-preserved diagnostic fossil mammals identified by Lewis as comparable to the fauna of the Hemingford Group of Lugn (1939). The name Troublesome Formation is used for the Miocene rocks in Middle Park, rather than other available formation names including North Park, Browns Park, Pawnee Creek of Matthew (1901), or Arikaree used for Miocene rocks in surrounding areas, owing to faunal and lithic correlation problems that await regional solution. Sedimentary petrographic studies of the Arikaree, Ogallala, and other upper Tertiary formations of the High Plains and Rocky Mountains, such as the one made by Sato and Denson (1967), should aid in the solution of correlation problems on a regional scale.

The Troublesome Formation mantles the older rocks in the area and effectively conceals many of the pre-middle Tertiary geologic relations. In general, the formation is poorly exposed, but good exposures are south of the Colorado River in Barger Gulch and north of the river in the Gunsight Pass, Twin Peaks, and Antelope Pass areas. Other good exposures occur along Troublesome Creek and the Back Troublesome Road. Isolated exposures occur in roadcuts, in gullies, and in the headwall scarps of landslides. Complete exposed sections of the formation that could be used as reference sections for the mapped area are rare, and stratigraphic relations for much of the area must be inferred from isolated outcrops. A complete well-exposed section, designated a reference section of the Troublesome (Izett, 1968), occurs in the SW¼ sec. 24, T. 1 N., R. 80 W., and the SW¼ sec. 19, T. 1 N., R. 79 W., in Barger Gulch in the Kremmling quadrangle. The section in Barger Gulch does not contain all lithic phases of the Troublesome, but it characterizes the bulk of the formation.

The Troublesome constitutes a mappable lithogenetic unit composed of beds that locally show abrupt lithic changes which reflect local changes in source rocks. One part of the formation, here called the siltstone facies, is characterized by orange-gray chert-bearing clayey siltstones that contain many thin beds of ash, including several zones of white ash beds that occur near the base and the middle of the formation and zones of gray to olive-gray ash in the upper part of the formation. The siltstone facies forms the bulk of the formation and is exposed throughout much of the Troublesome basin.

Another part of the Troublesome, here called the conglomeratic facies, is typified by varicolored conglomeratic swelling claystones that commonly contain silicified splintery fossil wood. It is exposed mainly north of the Colorado River and on the west and east edges of the Troublesome basin. In all areas studied, the Troublesome consists entirely of rocks included in either the conglomeratic facies or the siltstone facies--nowhere are the facies superposed in vertical section that would definitely establish their precise stratigraphic relation. Interpretation of field relations and fossil evidence, however, suggest that the conglomeratic facies is for the most part a lateral equivalent of the siltstone facies.

Age and Correlation

The Miocene age of the Troublesome Formation is based on its content of mammalian vertebrates and its stratigraphic position. The formation overlies rocks dated radiometrically as latest Oligocene (Izett, 1966; fig. 3) and unconformably underlies conglomerate and mudstone containing _Dipoides_ (Peter Robinson, written commun., 1966) of late Pliocene age (Izett, 1968). Many well-preserved skeletal parts, jaws, and skulls of mammals useful for dating purposes were found in the Kremmling area on some of the bare slopes of the Troublesome. A preliminary list of mammalian vertebrate fossils found in the Troublesome is given in table 1.

A large percentage of the fossil mammals were found in thin volcanic ash beds, and these ash beds are important prospecting sites. Among the possibilities that could explain the relation between ash beds and fossil mammal remains are: (1) animal remains were quickly covered by ash and

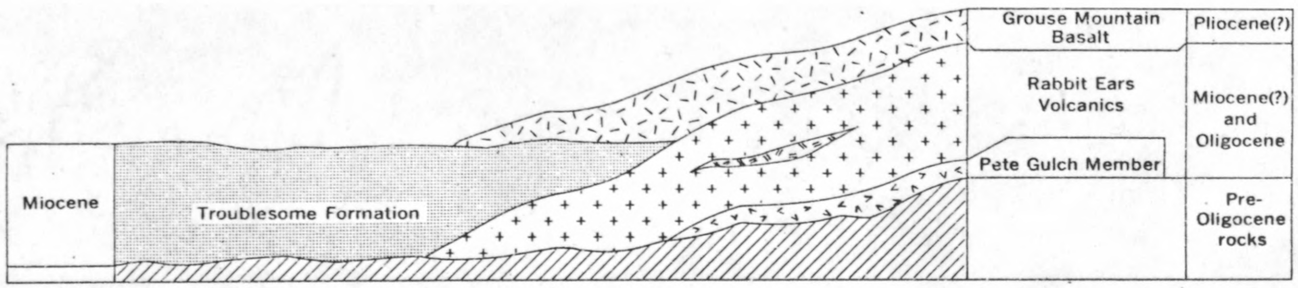


FIGURE 3.--Schematic section showing relation between extrusive volcanic rocks and Troublesome Formation in Middle Park, Colo.

TABLE 1.--Preliminary list of fossil vertebrates from the Troublesome Formation of Miocene age near Kremmling, Grand County, Colo.

[Identifications by G. E. Lewis except where noted.]

TROUBLESOME FORMATION	
Upper part	Lower part
Mesogaulus sp. (advanced)	*Metechinus marslandensis*[1]
heteromyid[1]	?*Limnoecus*[1]
Monosaulax sp.[1]	insectivores, several[1]
canoid carnivores	chiropteran[1]
feloid carnivore[1]	ochotonid[1]
mastodon	?*Desmatolagus* sp.[3]
Merychippus sejunctus?	*Mesogaulus* sp. (primitive)
Merychippus spp.	*Miospermophilus bryanti*[1]
?*Anchitherium* sp.[1]	sciurid[1]
Parahippus sp.[2]	*Grangerimus* sp.[1]
?*Moropus* sp.	geomyids[1]
Aphelops profectus	heteromyid[1]
Aphelops sp.	cricetids[1]
entelodont	*Plesiosminthus* sp.[1]
Protolabis angustidens	?*Amphicyon* sp.
?*Alticamelus* sp.	smaller carnivores
?*Oxydactylus*	*Merycochoerus*, 2 spp.
Brachycrus sp.	?*Merychyus* sp.
?*Paracosoryx* sp.	?*Oxydactylus* sp.
	?*Alticamelus* sp.
	?blastomerycine
	merycodont

[1] Identified by Peter Robinson.

[2] Identified by T. D. A. Cockerell (1908).

[3] Identified by M. R. Dawson.

preserved; (2) animals were killed directly by air-fall ash; and (3) animals were starved by having their food supply covered. Inasmuch as most ash falls were probably thin, it seems unlikely that animals were killed directly by the ash fall or that many animals starved. The writer believes that the chief reason for the great numbers of fossils in ash beds is that bones were covered quickly by the ash and preserved in a silica-rich environment.

The lower part of the Troublesome in the mapped area is typified by the occurrence of two species of the oreodont _Merycochoerus_, by _Merychyus_-like oreodonts, and by primitive species of the rodent _Mesogaulus_.

The upper part of the formation in the Kremmling quadrangle contains a large fauna that includes remains of the oreodont _Brachycrus_; several species of horses including _Merychippus sejunctus_?; the rhinoceros _Aphelops_; several types of camels including _Protolabis angustidens_, ?_Alticamelus_, and ?_Oxydactylus_; and an advanced species of the mylagaulid _Mesogaulus_.

The genus _Merycochoerus_, which occurs in the lower part of the Troublesome, is a diagnostic fossil of the Marsland Formation of Nebraska of Lugn (1939). _Brachycrus_, which occurs in the upper third of the Troublesome in the Kremmling area, is a diagnostic fossil oreodont of the Sheep Creek Formation of Nebraska of Lugn (1939).

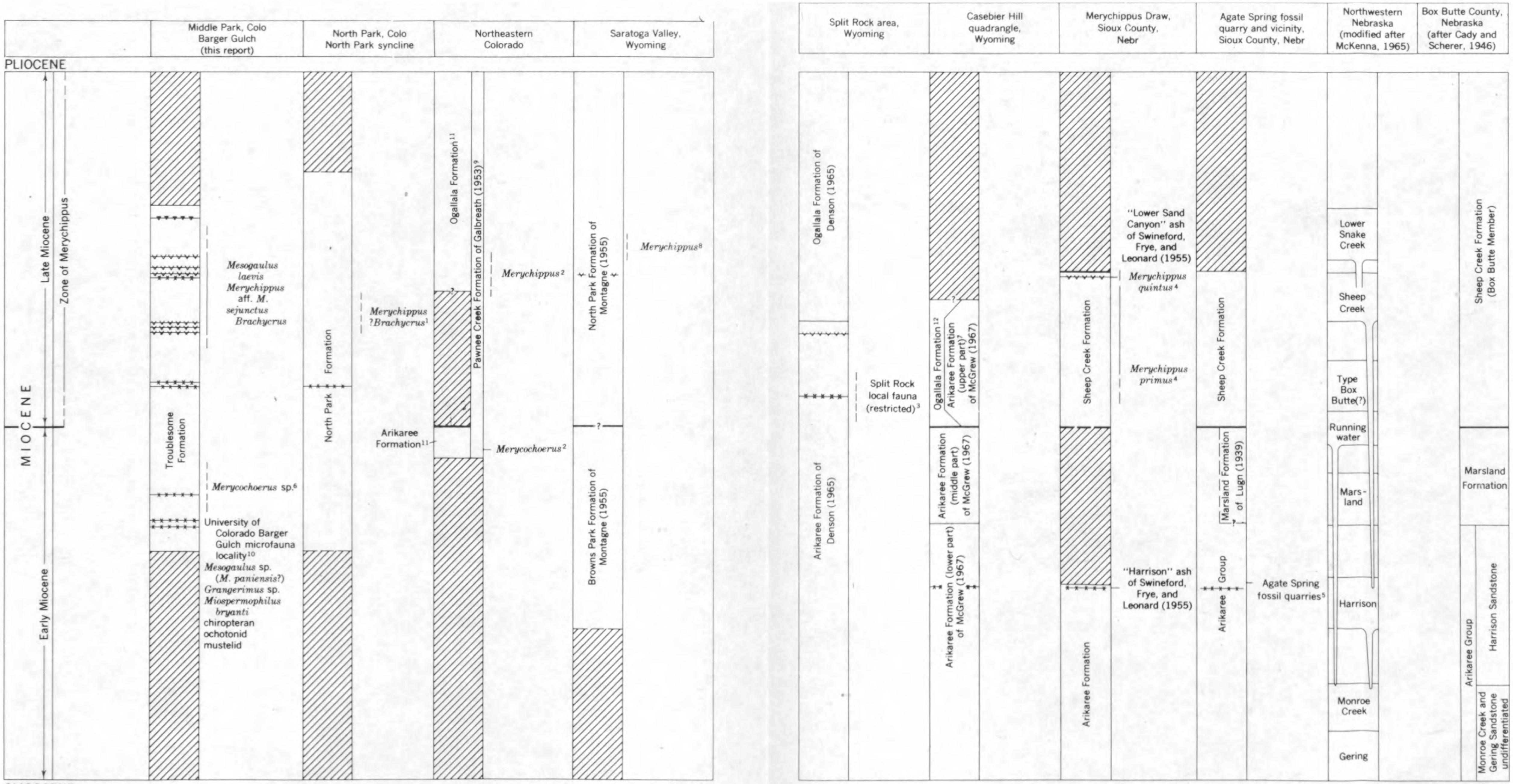
A marked contrast occurs between the character of the fauna of the lower and upper parts of the Troublesome Formation. The lower part of the formation contains only a small assemblage of larger vertebrates, and they occur only in small numbers as contrasted to the upper part of the formation which is characterized by numerous larger vertebrates. The lower part of the formation has not yielded to date (1968) fossil horse remains, whereas the upper part is typified by the abrupt appearance of large numbers of fairly advanced merychippine horses. Seemingly, the larger vertebrates did not migrate in large numbers into Middle Park until late Miocene time.

To what part of Miocene time the Troublesome should be assigned awaits solution of a complex regional problem involving confusion of nomenclature, faunal correlation, and time-stratigraphic subdivisions of Miocene rocks in classic areas of the Great Plains. This problem most recently has been summarized by McKenna (1965). Izett and Lewis (1963) assigned a middle Miocene age to the Troublesome in view of its faunal affinities to the Hemingford Group of Lugn (1939), designated by him as upper Miocene. But the rocks included in the Hemingford Group have been variously considered late Miocene by Schultz (1938, p. 444) and Lugn (1939, p. 1253-1254), middle Miocene by Wood and others (1941), late Miocene by Elias (1942, pl. 17), and middle to late Miocene by Schultz and Stout (1961). The conflicting age assignments result not so much from diverse opinion on faunal correlation as from (1) whether a twofold or a threefold time division of Miocene is followed, (2) confusion of time and stratigraphic units, and (3) lack of definitive faunal breaks associated with stratigraphic breaks in Miocene rocks. Izett and Lewis (1963), with reference to the classification of Wood and others (1941), designated the Troublesome as middle Miocene in age. But the formation should be assigned a late early and late Miocene age with reference to a twofold time division based on the range of the horse Merychippus. The twofold time division is more consistent with the two physical rock units (Arikaree and Ogallala) recognized by Darton (1903) and more recently used by Sato and Denson (1967).

If a twofold stratigraphic division of the Miocene is chosen and the top of the lower division is placed at the top of the Marsland Formation of Lugn (1939), the Troublesome Formation would be lower and upper Miocene. In a threefold division of the Miocene, chosen in accordance with the usage of Wood and others (1941), the boundary between the lower and middle Miocene is placed at the base of the Marsland Formation of Lugn (1939) and the boundary between the middle and upper Miocene is placed at the base of the "lower Snake Creek" of Matthew (1924) and Schultz and Stout (1961). According to this arrangement, the Troublesome would be middle and upper Miocene. The writer believes that a twofold time division of the Miocene best suits the stratigraphic and faunal relations. Seemingly one of the chief faunal differences between the lower and the upper Miocene rocks in the Western Interior is that the upper Miocene rocks, as defined here, contain the first primitive merychippine horse remains. No stratigraphic break has been found in the Troublesome to mark the position of the early Miocene-late Miocene time boundary as defined at the first appearance of primitive merychippine horses.

Figure 4 shows the writer's interpretation of correlation of Miocene rocks in Colorado, Nebraska, and Wyoming. The correlations are tentative and await completion of study of samples of ash beds collected by the writer in Colorado, Nebraska, and Wyoming. Preliminary results of petrographic study of ash beds in the Troublesome and selected ash beds in Miocene rocks in Wyoming and Nebraska are given later in the report.

A twofold division of Miocene time based on the range of the horse Merychippus is shown in figure 4. The diagrams taken from McKenna (1965) and Cady and Scherer (1946) are not strictly time diagrams, but they are shown to present the views of these authors on stratigraphic succession of Miocene rocks in western Nebraska.



EXPLANATION

Olive-gray ash bed

Chalky-white ash bed

Silver-gray ash bed

[1] Hail and Lewis (1960, p. 260)
[2] Galbreath (1953, p. 22, 32-34)
[3] Love (1961, p. 19) (includes only microfauna locality)
[4] Osborn (1918, p. 102); McKenna (1965, p. 11-12)
[5] Cook (1915)
[6] Not found in Barger Gulch, but inferred position of fossil projected into section
[7] McGrew (1967) correlated the upper part of the Arikaree Formation with the Sheep Creek Formation of Nebraska
[8] Montagne (1955, p. 47)

[9] "In northeastern Colorado, rocks assigned to the Pawnee Creek Formation by Galbreath (1953) are Ogallala, except at Martin Canyon where he included the so-called 'Martin Canyon beds' in the 'Pawnee Creek'" (N. M. Denson, written commun., 1966)
[10] See reference section of Troublesome Formation, unit 9, in text
[11] Sato and Denson (1967)
[12] Ogallala Formation of Matthew and Cook (1909, p. 363, lines 8-9) and Matthew (1924, p. 61)

FIGURE 4.--Correlation diagram showing an interpretation of time relations of Miocene rocks in Middle Park, Colo., and selected areas in Colorado, Nebraska, and Wyoming. (After Izett, 1968.)

PART II

PETROGRAPHY AND CHEMISTRY OF ASH BEDS

Introduction

The Troublesome Formation is generally tuffaceous in the sense that it contains beds of glassy air-fall volcanic ash in at least 15 stratigraphic levels. The ash beds can be divided into several groups based on their color, shard shape, and chemical and petrographic properties. From study of the Miocene ash beds it was found that it is difficult to distinguish between members of each group on the basis of their chemical properties and their total phenocryst assemblage. The fact that the Miocene ash beds can be grouped suggests that volcanic centers can give rise through perhaps a million years' time to many ash beds whose bulk chemistry is similar. Although the bulk chemistry of a group of ash beds shows little change, slight changes in the chemical properties of some ferromagnesian minerals such as hornblende and pyroxene may allow in some cases distinction between members of a group.

Well-preserved fossil mammalian remains were found at many stratigraphic levels associated with ash beds in the Miocene sequence in the Troublesome in Middle Park, and in general the fossils provide satisfactory correlation of fossil-bearing Miocene rocks in Middle Park with Miocene rocks in surrounding areas. To supplement and perhaps to refine the faunal correlations and especially to make possible correlations with Miocene rocks that contain ash beds but lack diagnostic fossils, the petrography and chemistry of the cleanest ash beds were systematically studied. Many ash beds in the Troublesome and other Miocene formations have yet to be studied, and before any correlations or firm statements on the petrography of the ash beds can be made much more detailed work is needed.

The Miocene ash beds of the Troublesome are petrographically and chemically similar to other ash beds that occur in Miocene rocks in the Western Interior. Figure 5 shows some of the localities where Miocene ash beds have been reported and demonstrates the wide distribution of the ash beds wherever Miocene rocks occur. The episodic volcanism that produced the Miocene ash beds is only part of a long history of volcanism in the Western Interior that began in Mesozoic time and has continued intermittently into Quaternary time.

The potential importance of ash beds as precise time-stratigraphic markers has been recognized since the early geological surveys, but detailed petrographic study of the ash beds has only recently been attempted (Swineford and others, 1955; Powers and others, 1958; Powers and Wilcox, 1964; Steen and Fryxell, 1965). Because an ash fall marks an instant of geologic time and may occur in areas of different environment, the ash bed can provide direct correlation of completely different

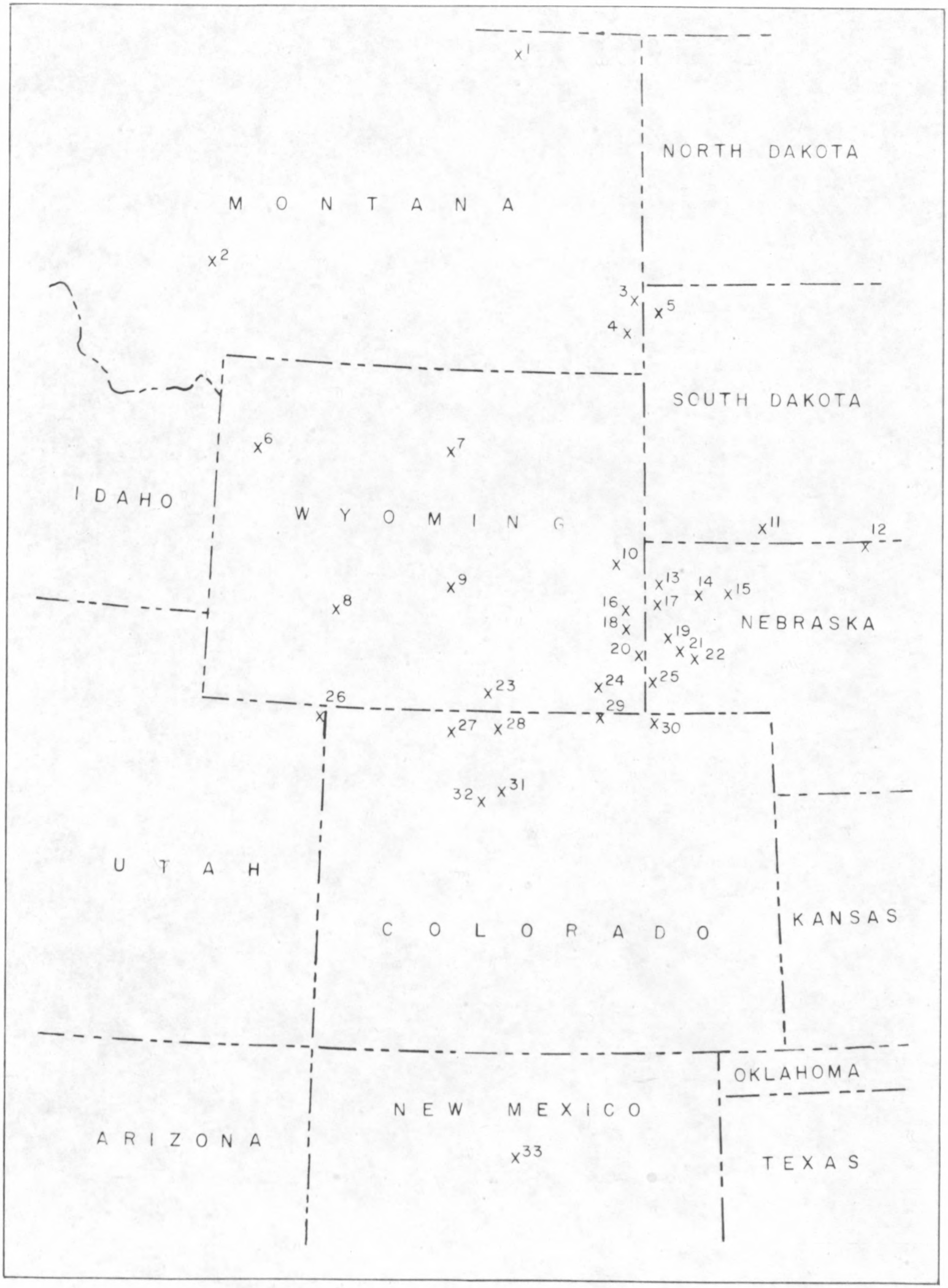


FIGURE 5.--Some reported occurrences of ash beds in Miocene rocks in the Western Interior.

Locations of Miocene Ash Localities of Figure 5

No. on fig. 5	Rock unit	Location	Reference	Sample No., this report
1	Flaxville gravel	Valley County, Mont.	Denson and Gill (1965)	-----
2	Sixmile Creek Fm.	Toston quad., Mont.	Robinson (1967)	-----
3	Arikaree Fm.	Long Pine Hills, Mont.	Denson and Gill (1965)	-----
4	do.	Finger Buttes, Carter County, Mont.	do.	-----
5	do.	East Short Pine Hills, Harding County, S. Dak.	do.	-----
6	Colter Fm.	Jackson Hole, Wyo.	Love (1956, p. 1905)	-----
7	Miocene rocks	Big Horn Mtns.	Darton (1906, p. 67)	-----
8	Arikaree Fm.	Oregon Buttes, Wyo.	Masursky (1962, p. 20)	-----
9	Split Rock Fm. of Love (1961)	Split Rock area, Wyo.	Love (1961)	DW9-8, DW4-10, DW4-11
10	Arikaree Fm.	Near Manville, Wyo.	N. M. Denson (unpub. data)	DW6-39
11	do.	Wounded Knee area, S. Dak.	Macdonald (1963)	-----
12	Valentine Mbr. of Ogallala Fm.	Valentine area, Nebraska	Swineford and others (1955, p. 251)	-----
13	Arikaree Fm.	Near Agate, Nebr.	Evernden and others (1964, p. 178)	74, 75
14	Miocene rocks	About 6 mi. S. of Marsland, Nebr.	---------------	78
15	Sand Canyon age rocks	Sand Canyon, Nebr.	Elias (1942, p. 130)	80
16	Arikaree Fm.	Casebier Hill quad., Wyo.	McGrew (1967)	-----

Locations of Miocene Ash Localities of Figure 5--continued

No. on fig. 5	Rock unit	Location	Reference	Sample No., this report
17	Sheep Creek age rocks	Whistle Creek quad., Wyo.	Evernden and others (1964, p. 184)	73, 66G23
18	Arikaree Fm.	YBO quad., Wyo.	-----------------	DW5-23
19	do.	Scotts Bluff Nat. Monument, Nebr.	Evernden and others (1964, p. 186)	67
20	do.	66 Mtn., Wyo.	Peter Robinson (unpub. data)	------
21	do.	Near Chimney Rock, Nebr.	Evernden and others (1964, p. 186)	71, 72
22	do.	Roundhouse Rock, Nebr.	do.	------
23	North Park Fm.	Saratoga Valley, Wyo.	N. M. Denson (unpub. data)	------
24	Ogallala Fm., Trail Creek fauna of Voorhies (1965)	North of Cheyenne, Wyo.	do.	------
25	Arikaree Fm.	Southwest of Harrisburg, Nebr.	do.	------
26	Browns Park Fm.	In Browns Park, Utah	Hansen (1965, p. 119)	------
27	Miocene rocks	Shield Mtn., Colo.	K. G. Segerstrom (unpub. data)	------
28	North Park Fm.	North Park syncline, Colo.	Hail (1965, p. 79)	------
29	Ogallala Fm.	Gangplank area, Colo.	N. M. Denson (unpub. data)	------
30	Upper Miocene rocks	Pawnee Buttes area, Colo.	Galbreath (1953, p. 22)	------
31	Troublesome Fm.	Near Kremmling, Colo.	This report	------
32	Browns Park Fm.	Along Piney Creek, Colo.	G. A. Izett (unpub. data)	66G62, 66G66
33	Santa Fe Fm.	Espanola Valley, N. Mex.	Denny (1940, p. 682)	------

rock sequences and of markedly different coeval faunas. That many samples of ash beds are worthless for correlation purposes owing to contamination and alteration of the glass shards to clays and zeolites is obvious; nevertheless, the phenocrysts of some ash beds may survive alteration and may be useful for correlation. Careful study of as many petrographic and chemical properties of ash beds as can be made may allow correlation of certain ash beds or zones of ash beds, but because petrographic and chemical features of ash beds can be duplicated through large stratigraphic thickness as shown later in the report, extreme caution is necessary when correlating individual ash beds on a regional scale.

Among the petrographic features studied were measurement of the refractive index of the glass shards and of optical properties of phenocrysts in the ash. Only those minerals that are either enclosed in volcanic glass or have glass adhering were regarded with certainty as primary constituents of the ash. Because the ash beds are glassy quench products of explosive volcanism probably far removed from the depositional area and because much of the phenocryst content of the ash beds may have been winnowed out during transportation, the amount of phenocrysts in the ash beds is generally small.

Chemical analyses were made of the ultrasonically cleaned glass shards separated from the phenocrysts and detrital minerals. Only the glass shards were submitted for chemical analysis in order to provide a common denominator for comparison among ash beds. Serious errors can be made by attempting to compare analyses made on bulk samples of ash; the errors arise from the fact that most ash beds contain various amounts of detrital minerals. Furthermore, the proportion of phenocrysts in a particular ash probably varies with distance from source and, accordingly, bulk chemical analyses of samples from near the source may differ from bulk analyses several hundred miles downwind. For this reason the phenocrysts should be removed from the ash before chemical analysis.

The glass shards which form the bulk of the ash beds are hydrated as shown on page 25 in that they contain from 5 to 7 percent volatiles, chiefly water. Ross and Smith (1955) presented evidence to show that obsidians they studied contain only a few tenths of 1 percent water, whereas perlites contain 2-5 percent water, the bulk of which was added during hydration. The glass shards of the Miocene ash beds probably contained only a few tenths of 1 percent water when extruded but were subsequently hydrated shortly after deposition. Changes in refractive index of the glass shards doubtless accompanied the hydration (compare Ross and Smith, 1955, p. 1081). The refractive indices of hydrated shards of a particular ash bed along its outcrop generally have a characteristic range and average which suggest that hydration reaches a certain level soon after deposition (compare Steen and Fryxell, 1965).

Chemical analyses (table 3) suggest that significant chemical changes accompanied hydration of the glass shards in the ash beds and probably occurred shortly after deposition of the ash (compare Lipman, 1965, and Aramaki and Lipman, 1965). Although the ash beds are quench products of volcanism and seemingly suitable targets for chemical and petrographic study, the hydration and accompanying chemical changes in the glass make petrogenetic interpretations hazardous. These chemical changes also hamper attempts at correlations based on the abundance of certain mobile elements of the glass including silicon, potassium, sodium, and calcium. Iron, titanium, and zinc seem to be useful elements for correlation and perhaps were neither added nor subtracted from the ash during hydration. Seemingly, the chemical changes that accompany hydration, especially changes in potassium content, and the poor argon retention of the thin shards make attempts at obtaining potassium-argon ages on the glass fractions of the ash hazardous. Perhaps fission-track counting methods (Fleischer and Price, 1964) will allow dating of the glass shards and phenocrysts of the ash beds.

The Miocene ash beds of the Troublesome Formation and of Miocene rocks in western Nebraska and southern Wyoming can be grouped into several distinct petrographic and chemical types, described in detail later in the report. Table 2 shows petrographic types of certain Miocene ash beds based on refractive index of glass shards, color, shard shape, and non-opaque phenocryst assemblage. Opaque phenocrysts are not listed in table 2, but glass-mantled magnetite and ilmenite were found in varying proportions in all ash beds studied. The petrographic types are arranged roughly in ascending stratigraphic order, and the ash-bed types were assigned letter designations.

Table 3 shows chemical analyses of the Miocene ash beds studied, grouped on the basis of chemical similarity, petrographic type, and stratigraphic position. The weight percent of SiO_2 and Al_2O_3 of the glass shards was determined by colorimetric techniques and the amount reported in table 3 is probably no better than ± 3 percent of the value. The elements most useful for grouping the ash beds into petrogenetic types are iron, zinc, titanium, rubidium, and strontium. Of these elements, titanium is the only element not determined by atomic absorption spectraphotometric methods. Other elements determined by atomic absorption methods and shown in table 3 are magnesium, calcium, sodium, potassium, and manganese. Uranium was determined in nine samples fluorometrically by E. J. Fennelly and in one sample (65G57) by isotope dilution methods by J. R. Dooley. The white ash beds seem to contain slightly more uranium than the gray ash beds. Semiquantitative spectrographic and quantitative spectrographic analyses were made on several of the ash samples, but significant differences among ash beds were not found, and the results are not presented here.

TABLE 2.--Petrographic characteristics of selected Miocene ash beds from Colorado, Nebraska, and Wyoming.

Age	Ash type	Sample No.	Refractive index of glass shards[1]	Nonopaque phenocrysts[2]	Color	Shard shape[3]
MIOCENE — Sheep Creek-lower Snake Creek-Box Butte	DGG	80 LW-506	Clear glass, 1.506-1.525 Lt-brn glass, 1.560-1.575 Dk-brn chunks, 1.560-1.570	P Hy, A Ap	Dk-greenish-gray (5GY 4/1)	A, B, C, D
	SG	66G43 DN5-46 DW9-8 66G17	1.503 1.500 1.506	S, P Z, Ap	Very light gray (N8)	B
	OG	65G57 66G92 66G91 66G90 66G75 66G74 66G76 65G48 73 DW4-10 66G23 66G46	1.505 1.502 1.528	Q, S, P F** Z, Ap, Chev.*	Olive-gray (5Y 4/1)	A, B, D
	UW	66G85 66G89 66G39 66G62 DW4-11 78 66G52 66G66	1.498 (66G85, 66G89) 1.506 1.497	Q, S, P B, H, A* Z, Ap, Sp, Al	White (N9)	A, B C
	GB	66G95 66G94 65G17 66G110 66G109	1.501-1.520 (1.502)	Q, S, P Z, Ap, Sp, Chev.	Light-gray (N7)	
MIOCENE — Harrison-Marsland	CW	66G69 65G34 66G135 66G36 66G35 66G165 66G164	1.497	Q, S, P B, H Z, Ap, Sp, Al	White (N9)	C
	MG	79	1.506-1.512 (1.508)		Very light gray (N8)	A
	MW	74 75	1.496-1.498 (1.497)	Q, S, P B, H Z, Ap, Sp, Al	White (N9)	C
MIOCENE — Gering	G	DN9-23	1.497-1.516 (1.500)	Q, S, P H Z, Ap	Light-gray (N7)	A
	LW	DW6-39 65 72 67 DW5-23 71	1.498-1.502 (1.499) 1.498-1.502 (1.499) 1.497-1.502 (1.498) 1.497-1.502 (1.498)	Q, S, P B, H, A* Z, Ap, Sp, Al, Pe[4]	White (N9)	A

O L I G O C E N E

[1] Where tie lines are not shown, all ash beds have about the same refractive index average and range. Figures are range; average in parentheses.

[2] A, augite; Al, allanite; Ap, apatite; B, biotite; Chev., chevkinite; F, ferro-augite; H, hornblende; Hy, hypersthene; P, plagioclase; Pe, perrierite; Q, quartz; S, sanidine; Sp, sphene; Z, zircon.

[3] A, small radius bubble-wall shards and bubble-junction shards;
B, large radius, then bubble-wall shards and flat platelike shards;
C, fibrous to equant frothy shards;
D, equant chunks of dark-brown glass.

[4] Perrierite found only in DW5-23 and 71.

* Rare.

** Extremely rare.

TABLE 3.--Chemical analyses of glass shards of selected Miocene ash beds from Colorado, Nebraska, and Wyoming

[Analysts: G. T. Burrow, W. D. Goss, C. Huffman, Jr., H. H. Lipp, J. D. Mensik, W. Mountjoy, Vertie Smith, all of U.S. Geological Survey.]

Age	Ash type	Sample No.	SiO_2	Al_2O_3	Fe_2O_3[1]	MgO	CaO	K_2O	Na_2O	SrO	Rb_2O	MnO	TiO_2	Zn (ppm)	Cl (ppm)	F (ppm)	U (ppm)
MIOCENE; Sheep Creek-lower Snake Creek-Box Butte	DGG	80	61.3	15.1	5.61	2.06	4.30	2.79	2.49	.046	.008	.12	.90	110	600	1200	2
		LW-506[2]	62.3	14.2	4.8	1.0	2.2	3.60	2.60			.10	.86				
	SG	66G43	72.0	11.3	1.69	.15	.59	6.59	1.65			.03	.25	40		1000	
		DN5-46	73.5	12.1	1.8	.13	.68	6.86	1.29	.008	.023	.03	.30	43	400	1000	
		DW9-8	73.6	11.9	2.1	.40	.85	5.00	2.13	.013	.020	.03	.35	49			
		66G17	73.2	12.3	1.5	.10	.63	6.91	1.32	.003	.021	.04	.20	40	300	1000	
	OG	65G57	71.1	11.0	2.2	.14	.72	6.40	1.70	.012	.021	.04	.33	76	400	1100	5.3
		66G92	70.3	10.4	2.51	.07	.80	6.17	1.77	.006	.021	.04	.27	112	300	1000	
		66G91	68.8	10.9	2.92	.06	.75	6.29	1.77			.06	.24	130	300	900	
		66G90	69.0	10.5	2.80	.03	.79	6.28	1.69			.06	.24	120	200	900	
		66G75	71.7	13.4	2.80	.03	.71	5.69	1.94	.003	.019	.06	.22	120	300	800	
		66G74	68.6	10.1	2.80	.05	.74	5.55	1.69			.06	.26	120	200	800	
		66G76	70.5	11.3	3.38	.04	.84	5.45	2.06			.07	.25	130	200	900	
		65G48	71.1	12.0	3.0	.13	.82	5.43	1.78	.008	.021	.06	.28	110			
		73	70.6	11.7	3.02	.04	.78	5.06	2.30	.005	.017	.06	.25	130	300	1000	5
		DW4-10	71.5	10.6	3.0	.18	.26	5.47	2.28	.006	.022	.06	.27	150			
		66G23	73.5	11.6	2.75	.09	.84	5.40	1.99	.005	.017	.06	.20	110			
		66G46	71.2	14.2	2.74	.08	.80	5.92	1.70	.004	.019	.06	.22	110			
	UW	66G85	70.8	10.3	.71	.09	.49	6.50	2.35			.05	.10	40	1200	700	
		66G89	71.1	10.7	.78	.06	.53	7.08	1.70			.05	.10	40	1100	600	
		66G39	72.0	10.7	.78	.05	.59	6.76	1.81			.05	.09	50	1100	700	
		66G62	72.5	11.3	.69	.37	.41	6.06	2.04			.06	.10	40	1100	800	
		DW4-11	74.3	12.9	.58	.47	1.9	5.79	2.02	.003	.036	.05	.06	52	500	900	
		78	74.9	11.8	.55	.05	.42	6.90	1.48	<.002	.018	.07	.07	54	800	600	4
		66G52	72.4	13.6	.76	.07	.95	7.26	1.27	.004	.021	.08	.07	50			
		66G66	74.4	13.4	.69	.16	.60	6.70	2.02	.003	.024	.08	.10	50			
	GB	66G95	71.7	11.0	1.8	.08	.54	6.65	1.39	.003	.022	.03	.22	60	900		
		66G94	70.3	9.6	2.6	.21	.30	6.58	1.36			.07	.15	190			
		65G17	71.1	10.8	2.6	.08	.41	6.44	1.27	.007	.022	.07	.25	170		400	
		66G110	71.2	11.2	1.62	.07	.19	6.16	2.23	.001	.025	.10	.10	100			
		66G109	73.2	14.1	1.75	.08	.23	6.18	2.11	.002	.020	.10	.14	110			
Harrison-Marsland	CW	66G69	71.5	11.3	.52	.05	.51	6.37	1.94			.06	.07	30	700	300	
		65G34	76.0	12.5	.45	.14	.58	6.26	1.92	.004	.023	.07	.13	33	600	500	
		66G135	71.7	10.8	.62	.11	.71	5.56	2.41			.04	.10	20	700	300	
		66G36	73.4	11.6	.61	.07	.61	5.71	2.28			.04	.11	20	600	400	
		65G35	73.8	11.9	.58	.07	.62	5.46	2.41	.009	.026	.05	.08	29	700	300	
		66G165	70.4	12.0	.52	.05	.59	6.02	2.37	.005	.020	.07	.06	28			
		66G164	74.0	12.9	.57	.07	.64	5.84	2.34	.005	.024	.04	.14	32			
	MG	79	70.4	13.5	2.10	.44	1.22	5.18	2.16	.016	.007	.07	.32	56			2
	MW	74	74.2	12.3	.66	.37	.70	6.77	1.33	.010	.020	.04	.09	44	1200	500	8
		75	74.6	12.1	.60	.55	.69	6.30	1.32	.009	.019	.04	.09	37	1200	800	7
Gering	G	DN9-23	72.2	11.8	1.5	.12	.73	6.79	1.26	.005	.020	.05	.10	72	1000	400	
	LW	DW6-39	71.8	13.7	.76	.14	1.04	5.88	1.82	.018	.021	.03	.12	24	1000	200	
		65	73.6	12.3	.82	.16	,95	5.31	2.27	.022	.021	.04	.14	41	900	400	7
		72	73.8	12.5	.74	.14	.79	5.06	1.74	.024	.016	.03	.11	20			8
		67	73.3	12.8	.98	.12	.50	5.92	2.61	<.002	.048	.05	.05	88			8
		DW5-23	74.8	11.8	.85	.16	.30	5.92	2.63	.001	.031	.07	.10	99	1700	1100	
		71	75.8	12.1	.88	.06	.29	6.34	.94	<.002	.030	.07	.12	82			8

O L I G O C E N E

[1] Total iron as Fe_2O_3.

[2] After Love (1961, p. 23).

Ash Beds of Tables 2 and 3

Sample No.	Ash	Thickness	Location	Collectors
80	Dark-gray, sooty; crossbedded, sooty, pisolitic in lower 1 in.; locally in two beds, the upper of which is probably reworked lower bed.	3-4 ft.	About 40 ft above base of type section of Sand Canyon Mbr of Sheep Creek Fm of Elias (1942, p. 130), in NE¼NE¼ sec. 14, T. 29 N., R. 47 W., Dawes County, Nebr.	G. A. Izett, N. M. Denson, R. E. Wilcox
LW-506	Dark-gray.	About 1 ft.	In type section of Moonstone Fm of Love (1961, p. 23, 28), in NW¼SE¼ sec. 19, T. 30 N., R. 89 W., Natrona County, Wyo.	J. D. Love
66G43	Silver-gray.	About 2 ft.	In upper part of Troublesome Fm, in NE¼NW¼ sec. 30, T. 1 N., R. 79 W., Grand County, Colo.	G. A. Izett
DN5-46	Silver-gray.	2-3 ft.	About 130 ft above base of Box Butte Mbr of Sheep Creek Fm, at Shimek Farm in NE¼SW¼ sec. 26, T. 27 N., R. 52 W., Box Butte County, Nebr.	G. A. Izett, N. M. Denson
DW9-8	Silver-gray.	About 3 ft.	In Ogallala Fm of N. M. Denson, in NE¼NW¼ sec. 36, T. 28 N., R. 86 W., Carbon County, Wyo.	N. M. Denson
66G17	Silver-gray.	About 3 ft.	In lower part of Ogallala Fm, at Porcupine Butte in SW¼NW¼ sec. 17, T. 37 N., R. 42 W., Shannon County, S. Dak.	G. A. Izett, N. M. Denson
65G57	Olive-gray.	About 3 ft.	In upper part of Troublesome Fm, 120 ft below 66G43 in SW¼SW¼ sec. 19, T. 1 N., R. 79 W., Grand County, Colo.	G. A. Izett
66G92	Olive-gray.	About 2 ft.	In upper part of Troublesome Fm, in NE¼NE¼ sec. 33, T. 2 N., R. 80 W., Grand County, Colo.	Do.

Ash Beds of Tables 2 and 3--continued

Sample No.	Ash	Thickness	Location	Collectors
66G91	Olive-gray.	About 2 ft.	In upper part of Troublesome Fm, in SE¼NE¼ sec. 33, T. 2 N., R. 80 W., Grand County, Colo.; 70 ft below 66G92.	G. A. Izett
66G90	Olive-gray.	About 2 ft.	In upper part of Troublesome Fm, in SE¼NE¼ sec. 33, T. 2 N., R. 80 W., Grand County, Colo.; 6 ft below 66G91.	Do.
66G75	Olive-gray.	About 2 ft.	In upper part of Troublesome Fm, in SW¼SE¼ sec. 24, T. 1 N., R. 80 W., Grand County, Colo.	Do.
66G74	Olive-gray.	About 2 ft.	In upper part of Troublesome Fm, in SW¼SE¼ sec. 24, T. 1 N., R. 80 W., Grand County, Colo.; 9 ft below 66G75.	Do.
66G76	Olive-gray.	About 2 ft.	In upper part of Troublesome Fm, in SW¼SE¼ sec. 24, T. 1 N., R. 80 W., Grand County, Colo.; 8 ft below 66G74.	Do.
65G48	Olive-gray. May be same ash as 66G76.	2 ft.	In upper part of Troublesome Fm, in NE¼SW¼ sec. 24, T. 1 N., R. 80 W., Grand County, Colo.	Do.
73	Olive-gray.	3-4 ft.	At head of Merychippus Draw about 150 ft above base of type section of Sheep Creek Fm, in NE¼SE¼ sec. 30, T. 26 N., R. 55 W., Sioux County, Nebr.; locality of Evernden and others (1964, KA 891).	G. A. Izett, N. M. Denson, R. E. Wilcox
DW4-10	Olive-gray.	3-4 ft.	In uppermost part of Arikaree Fm of Denson (1965) and Split Rock Fm of Love (1961), in NE¼NW¼ sec. 31, T. 29 N., R. 89 W., Natrona County, Wyo.	N. M. Denson, G. A. Izett
66G23	Olive-gray	About 2 ft.	About 14 ft above base of Sheep Creek Fm, in SW¼NE¼ sec. 32, T. 26 N., R. 55 W., Sioux County, Nebr.	G. A. Izett, N. M. Denson

Ash Beds of Tables 2 and 3--continued

Sample No.	Ash	Thickness	Location	Collectors
66G46	Olive-gray.	About 3 ft.	In upper part of Troublesome Fm about 70 ft below 65G57, in SE¼SE¼ sec. 24, T. 1 N., R. 80 W., Grand County, Colo.	G. A. Izett
66G85	White.	About 1 ft.	In upper part of Troublesome Fm, along Back Troublesome Road at head of Horse Gulch in NE¼NW¼ sec. 3, T. 1 N., R. 80 W., Grand County, Colo.	Do.
66G89	White. Probably same ash bed as 66G85.	About 1 ft.	In upper part of Troublesome Fm 6 ft below 66G90 and about 180 ft above 66G95, in SE¼NE¼ sec. 33, T. 2 N., R. 80 W., Grand County, Colo.	Do.
66G39	White.	About 6 in.	About 10 ft below 65G57 in upper part of Troublesome Fm, in SW¼SW¼ sec. 19, T. 1 N., R. 79 W., Grand County, Colo.	Do.
66G62	White.	About 2 in.	About 270 ft above base of Miocene rocks, along Piney Creek west of road near Rick-strew Ranch in SE¼ sec. 1, T. 3 S., R. 83 W., Eagle County, Colo.	Do.
DW4-11	White.	About 1 ft.	In Arikaree Fm of Denson (1965) at "Split Rock local fauna" locality of Love (1961, p. 16).	N. M. Denson, G. A. Izett
78	White.	About 1 ft.	In Miocene rocks, in first main draw W. of Nebr. Hwy 2, SE¼SE¼ sec. 19, T. 28 N., R. 51 W., Box Butte County, Nebr.	G. A. Izett, N. M. Denson, R. E. Wilcox
66G52	White.	About 2 ft.	In upper part of Troublesome Fm, in SW¼ sec. 22, T. 2 N., R. 80 W., Grand County, Colo.	G. A. Izett
66G66	White.	About 1 ft.	In Miocene rocks, along Piney Creek about 75 ft above 66G62, in SE¼ sec. 1, T. 3 S., R. 83 W., Eagle County, Colo.	Do.

Ash Beds of Tables 2 and 3--continued

Sample No.	Ash	Thickness	Location	Collectors
65G17	Grayish-blue.	2 ft.	In upper part of Troublesome Fm in center sec. 34, T. 2 N., R. 80 W., Grand County, Colo.; about 190 ft below 66G90.	G. A. Izett
66G94	Grayish-blue. May be same bed as 65G17.	2 ft.	In upper part of Troublesome Fm in center sec. 34, T. 2 N., R. 80 W., Grand County, Colo.	Do.
66G95	Grayish-blue.	About 2 ft.	In upper part of Troublesome Fm in center sec. 34, T. 2 N., R. 80 W., Grand County, Colo.; 8 ft above 66G94.	Do.
66G110	Grayish-blue.	1 ft.	In middle part of Troublesome Fm about 125 ft below 66G85, along Horse Gulch in NW¼ sec. 3, T. 1 N., R. 80 W., Grand County, Colo.	Do.
66G109	Grayish-blue.	About 1 ft.	In middle part of Troublesome Fm about 136 ft below 66G85, along Horse Gulch in NW¼ sec. 3, T. 1 N., R. 80 W., Grand County, Colo.	Do.
66G69	White.	About 1 ft.	At top of lower part of Troublesome Fm on sec. line between 24 and 25, T. 1 N., R. 80 W., Grand County, Colo.; about 2,000 ft W. of E. line.	Do.
65G34	White.	About 2 ft.	Near sec. line between 24 and 25, T. 1 N., R. 80 W., Grand County, Colo.; about 9 ft below 66G69.	Do.
66G135	White.	About 1 ft.	About 225 ft above base of Troublesome Fm, in SW¼SW¼ sec. 24, T. 1 N., R. 80 W., Grand County, Colo.	Do.
66G36	White.	About 2 ft.	In lowermost part of Troublesome Fm, in NW¼NE¼ sec. 25, T. 1 N., R. 80 W., Grand County, Colo.	Do.
66G35	White. Could be same bed as 66G36.	About 5 ft.	In lower part of Troublesome Fm, about 100 ft above base of fm.	Do.

Ash Beds of Tables 2 and 3--continued

Sample No.	Ash	Thickness	Location	Collectors
66G165	White.	About 1 ft.	In middle part of Troublesome Fm about 200 ft below 66G109, along Horse Gulch in NW¼NW¼ sec. 3, T. 1 N., R. 80 W., Grand County, Colo.	Peter Robinson
66G164	White.	About 1 ft.	30 ft below 66G165 in middle part of Troublesome Fm, along Horse Gulch in NW¼NW¼ sec. 3, T. 1 N., R. 80 W., Grand County, Colo.	Do.
79	Light-gray.	About 3 ft.	Marsland Fm, 30 ft above Dry Creek in large meander scar, in SE¼NW¼ sec. 13, T. 28 N., R. 49 W., Box Butte County, Nebr.	G. A. Izett, N. M. Denson, R. E. Wilcox
74	White.	About 6 ft.	About 200± ft above base of Harrison Fm, just N. of Agate-Marsland road along Niobrara River about 0.3 mi. W. of ranch road in SW¼SW¼ sec. 4, T. 28 N., R. 55 W., Sioux County, Nebr.; elev. 4,480± ft. Locality of Evernden and others (1964, KA 481).	Do.
75	White. Same ash bed as 74.	About 2 ft.	In Harrison Fm about 1 mi. E. of ranch house, in SE¼NW¼ sec. 10, T. 28 N., R. 55 W., Sioux County, Nebr. On a small knoll N. of two quarry hills at Agate Springs fossil loc.; about 30± ft below level of Agate quarries.	Do.
DN9-23	Gray.	About 2 ft.	About 55 ft above base of Arikaree Fm, in Monroe Creek Canyon in NW¼NW¼ sec. 8, T. 32 N., R. 56 W., Sioux County, Nebr.	N. M. Denson
DW6-39	White.	About 1 ft.	In lowest part of Arikaree Fm, in NW¼NE¼ sec. 28, T. 34 N., R. 65 W., Niobrara County, Wyo.	Do.

Ash Beds of Tables 2 and 3--continued

Sample No.	Ash	Thickness	Location	Collectors
65	White. Contains concentrations of mafic minerals in bottom 1 in. of ash layer.	3-4 ft.	40 ft above base of Gering age rocks at prominent point in NW¼NW¼ sec. 6, T. 20 N., R. 55 W., Scotts Bluff County, Nebr.; about 6 mi. S-SW of Gering, Nebr. Presumably Darton's (1903, p. 33) illustrated sec. of Gering Sandstone.	G. A. Izett, N. M. Denson, R. E. Wilcox
72	Light-gray.	1.5 ft.	38 ft above base of Arikaree Fm and 36 ft above white ash bed 71 at same exposures; near Chimney Rock in SW¼ sec. 17, T. 20 N., R. 52 W., Morrill County, Nebr. At exposures S. and SE. of Chimney Rock on main butte at least four superposed ash beds in lower Arikaree can be seen.	Do.
67	White.	3 in.	14 ft above base of Gering Fm on road to top of Scottsbluff Nat. Monument; at foot of third tunnel; in NE¼SW¼ sec. 33, T. 22 N., R. 55 W., Scotts Bluff County, Nebr.	Do.
DW5-23	White.	About 1 ft.	About 13 ft above base of Arikaree Fm, in SE¼NW¼ sec. 4, T. 21 N., R. 64 W., along Goshen Hole Rim, Goshen County, Wyo.	N. M. Denson
71	Light-gray. Cross-stratified indicating reworking. Appears clean and fluffy.	18 in.	18 in. above base of Arikaree Fm about 1/3 mi. due S. of Chimney Rock in SW¼ sec. 17, T. 20 N., R. 52 W., Morrill County, Nebr.; at site of Evernden and others (1964, KA 981).	G. A. Izett, N. M. Denson, R. E. Wilcox

Chlorine and fluorine contents of the hydrated glass shards are shown in table 3, and several of the ash types seemingly have characteristic average values for chlorine and fluorine. Powers (1961) reported chlorine and fluorine contents of 120 samples of silicic volcanic glasses and his data suggest that certain ash beds such as the Pearlette-like ash beds have characteristic chlorine and fluorine contents. Friedman and Harris (1961) showed that fluorine is not leached in significant amounts during simple hydration of obsidian to perlite.

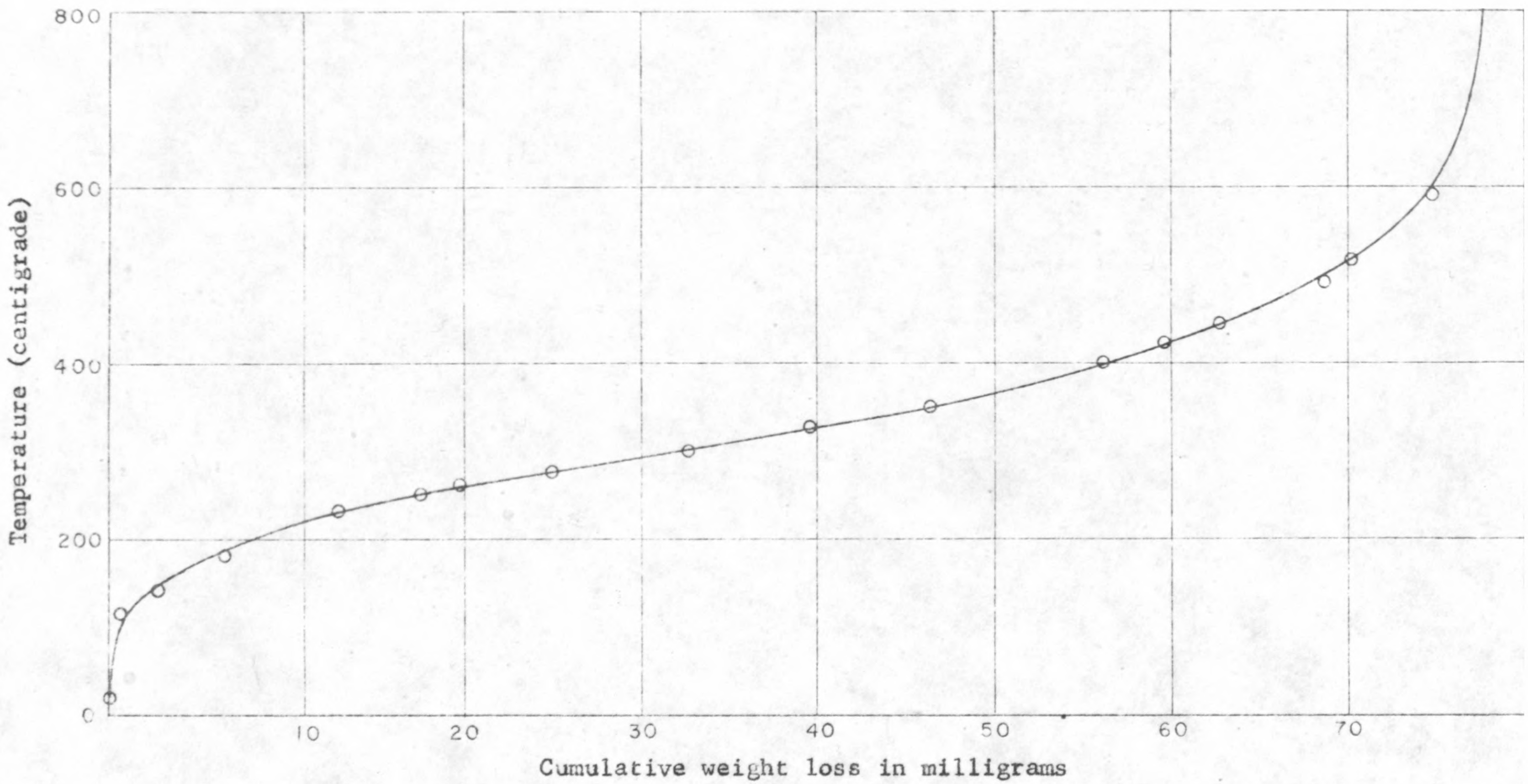
The chemical analyses of table 3 are not corrected volatile-free inasmuch as the volatile content of the ash beds was not directly determined in most cases. The volatile content of a few of the samples of tables 2 and 3 are shown below and were determined by heating the sample at 950°C for 1 hour. The data show that the glass of the ash beds is hydrated and that the glass of many of the ash beds contains about 5-6 percent volatiles.

Sample No.	Ash type of tables 2 and 3	Percent volatile
66G43	SG	5.4
DN5-46	SG	5.2
66G94	GB	6.2
66G135	CW	5.7
66G36	CW	5.5

To determine the best temperature to drive the volatiles completely from the glass, one sample (66G36, table 2) was heated about 2 hours in a thermogravimetric balance and a cumulative weight-loss curve made from the data is shown in figure 6. Most of the volatiles are lost between 200° and 600°C and the total volatile loss was about 5.5 percent.

The Miocene ash beds are generally lenticular, range in thickness from 0 to 5 feet, and can be traced for only short distances along the outcrop. Some of the ash beds are fluffy and fresh appearing, whereas others are contaminated and well indurated owing to alteration and case hardening. The ash is composed chiefly of glass shards of various shapes; some ash beds contain exclusively nearly flat, thin plates that are fragments of large radius bubble walls, others contain a mixed assemblage of Y-shaped bubble-junction shards, small radius bubble-wall shards, and pumiceous fibrous shards.

The air-fall ash beds were probably deposited as thin blankets less than 1 foot thick, but subsequently were concentrated as lenses in swales or in ponds. Even the freshest and cleanest appearing ash beds, when studied in detail, are found to be contaminated with a few grains per thousand of older mineral fragments.



Sample No. 66G36.
Starting weight 1.483 gms.
End weight 1.355 gms.
Percent weight loss 5.5.

FIGURE 6.--Cumulative volatile weight loss of a white biotitic ash bed of Miocene age heated in a thermogravimetric balance.

Conventional heavy-mineral studies are made with the minerals mounted in balsam or other suitable media so that determinations of the relative abundances of the mineral species can be made. However, ash-bed studies chiefly are oriented toward establishing the precise mineral assemblage for a particular ash bed and the optical properties of the nonopaque phenocrysts. The relative amount of each constituent or the amount of detrital minerals that contaminate the ash are so influenced by depositional factors that abundance is generally of secondary importance. The obvious disadvantages of working with fixed mounts in which diagnostic optical properties generally cannot be made are known to all workers studying heavy minerals. These problems are avoided if the minerals are studied under a good high-power stereomicroscope and optical measurements are made with the spindle stage of Wilcox (1959) on a polarizing microscope; when necessary, mineral identifications are confirmed using X-ray powder films.

The ash beds were studied using petrographic techniques developed by R. E. Wilcox of the U.S. Geological Survey, and his guidance during the study is greatly appreciated by the writer. Measurements of the refractive index of the glass shards and phenocrysts were made using the focal masking method; a description of the focal masking method was given by Cherkasov (1957) and Wilcox (1962).

Samples of the ash beds were pulverized to about 100 mesh and cleaned ultrasonically for about 10 minutes. The clay-size material was decanted and the samples were treated briefly with cold dilute hydrochloric acid to remove possible carbonate cement. Heavy minerals were separated with bromoform (sp. G.=2.86) in centrifuge tubes or in separatory funnels. Feldspars and quartz were separated from the glass shards with bromoform cut with acetone (Sp. G.=2.42). The glass was further cleaned in a magnetic separator and again ultrasonically cleaned.

White Ash Beds

Biotitic white ash beds occur in zones from the base of the Miocene sequence upward into rocks that contain a vertebrate fauna as young as the "lower Snake Creek fauna" of the Sheep Creek Formation of western Nebraska. The stratigraphic relations among certain white ash beds in the Troublesome Formation and selected white ash beds from Nebraska, Colorado, and Wyoming are shown in figure 7. It is evident from figure 7 and tables 2 and 3 that the white ash beds are stratigraphically widely separated and that petrographic and chemical features unite the ash beds into a distinct petrogenetic group clearly separable from other Miocene ash beds. The white ash beds shown in tables 2 and 3 are divided into several types based chiefly on their stratigraphic position and are letter-designated LW (lower whites), MW (middle whites), CW (chalky whites), and UW (upper whites). A few of the ash beds may not be assigned

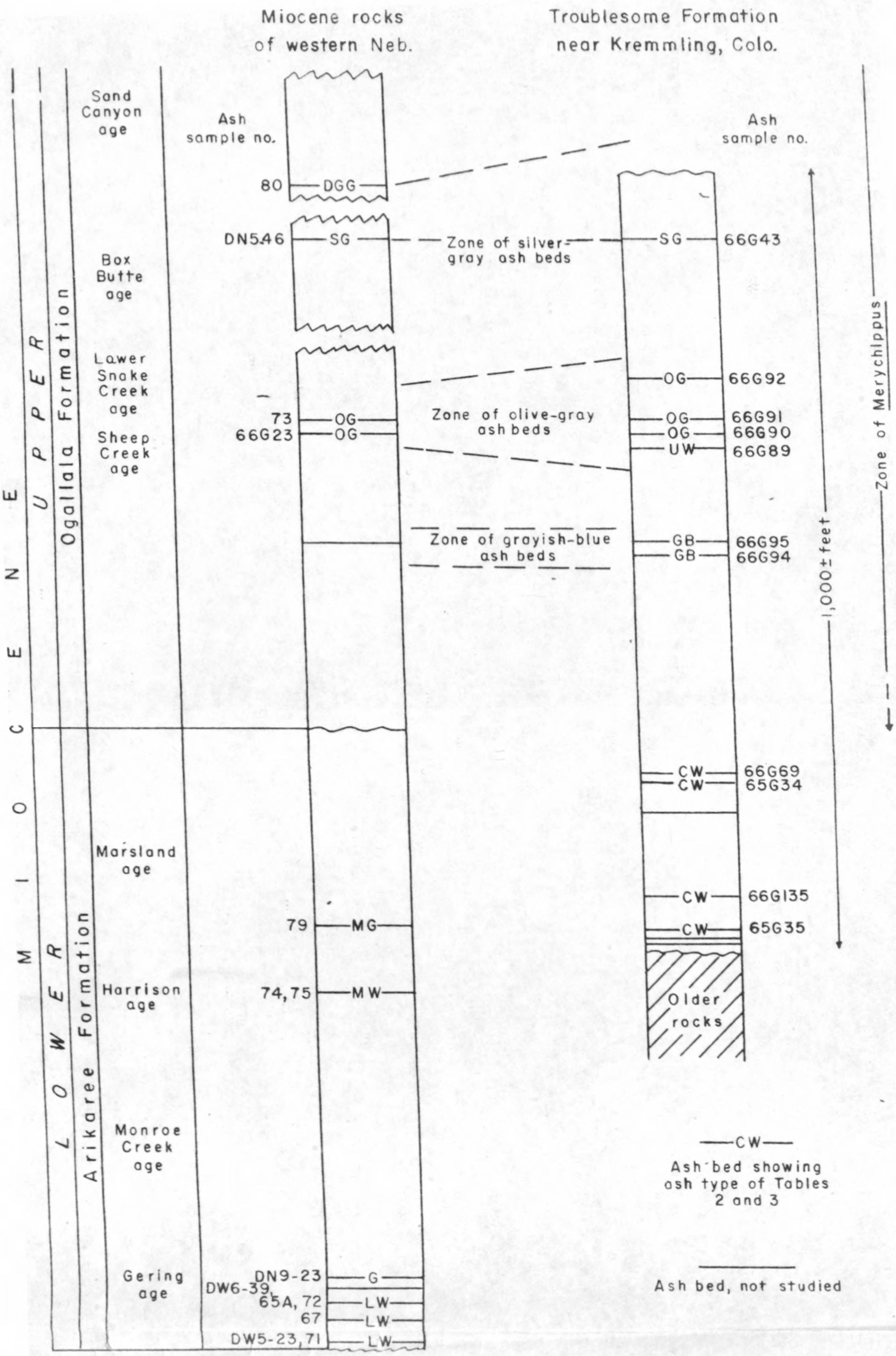


FIGURE 7.--Generalized stratigraphic sections of Miocene rocks in western Nebraska and near Kremmling, Colo., showing positions of ash beds.

to their proper stratigraphic position, owing to correlation problems. In particular, sample DW4-11 from the Split Rock area, Wyoming, could be in the stratigraphic position of the CW rather than the UW ash beds as shown in tables 2 and 3.

The petrography of the white ash beds (table 2) shows that all contain nearly a similar nonopaque phenocryst assemblage including quartz, sanidine, plagioclase (oligoclase), biotite, hornblende, rare augite, zircon, apatite, sphene, and allanite. Because the white ash beds have similar petrographic and chemical characteristics, distinction among the white ash beds in most cases is difficult.

Biotite is the chief ferromagnesian mineral in the white ash beds and generally occurs as hexagonal thin books. Biotite from certain lower white ash beds is a darker variety, whereas the biotite from most other white ash beds is light yellowish brown. Hornblende is not as common as biotite in the white ash beds, and it occurs mainly as prismatic glass-mantled cleavage fragments and sparingly as euhedral prisms. Preliminary data on the optical properties of the hornblendes (table 4) suggest that they may be useful in characterizing certain white ash beds. Because hornblende is a scavenger-type ferromagnesian mineral and its optical properties are sensitive to the thermal and chemical history of the parent magma, the mineral may be of use in characterizing certain white ash beds. Although the lower refractive index (N_x) of the hornblendes (table 4) generally have narrow ranges, the lower refractive index of several of the hornblendes overlap or are duplicated. This duplication and overlap makes correlation based on the hornblende optical properties in some cases permissive but not definitive. The optical properties of the hornblende from samples 71 and DW5-23 (table 4) are different than others studied; in particular, the refractive index (N_x) is much lower and the extinction angle $Z \wedge C$ is higher than other Miocene hornblendes. The hornblende from samples DW6-39, 65, and 72 characteristically occurs in fairly large amounts with large amounts of biotite, but the lower refractive index (N_x) of the hornblende is similar to other hornblendes in white ash beds. The hornblendes from samples 66G85 and 66G89 are unusual in that two different kinds of glass-mantled hornblende occur in both samples, and this may be an important characteristic of these ash beds.

Clinopyroxene occurs sparingly in the white ash beds as broken crystals and small euhedral stubby prisms whose optical properties suggest that the clinopyroxenes are diopsidic to salitic (N_y= 1.693-1.695; $2V_z$= 54-60). The clinopyroxenes are not enriched in iron as much as clinopyroxenes (ferroaugite) from certain upper Cenozoic ash and tuffs such as the Pearlette Ash and the Bandelier Tuff. Why certain rhyolitic magmas give rise to rocks whose ferromagnesian minerals are iron-rich and characterized by ferroaugite and fayalite, yet other rhyolite magmas produce comparatively iron-poor ferromagnesian minerals is not understood. Observations suggest that those rhyolitic rocks of

TABLE 4.--Preliminary optical properties of glass-mantled hornblendes from white biotitic ash beds of Miocene age.

Ash type	Sample No.	N_x	Z∧C
UW	66G85	1.646-1.648 1.658-1.664 } bimodal	16 14
	66G89	1.646-1.648 1.660-1.664 } bimodal	16 14
CW	66G36	1.654-1.658	14-16
	65G35	1.653-1.659	14-16
MW	74	1.650-1.652	14-16
	75	1.650-1.652	14-16
LW	DW6-39	1.652-1.658	14-17
	65	1.652-1.658	14-16
	72	1.652-1.658	14-16
	DW5-23	1.639-1.642	20-22
	71	1.639-1.642	20-22

about the same SiO_2 content that contain biotite have ferromagnesian minerals which are lower in iron but that those that do not contain biotite commonly contain iron-rich mafic minerals such as ferroaugite and fayalite.

Two white ash beds from near the base of the Arikaree Formation, one from near Chimney Rock, Nebr. (sample 71, tables 2 and 3), and the other from along Goshen Hole Rim, Wyo. (DW5-23, tables 2 and 3), are unusual in that they contain small euhedral phenocrysts of perrierite (rare-earth titanosilicate). Perrierite has not been reported previously from volcanic rocks in North America, and its occurrence in the ash beds may be of considerable use for correlation. The two ash beds have hornblendes with similar optical properties (table 4) and have glass shards whose refractive index is similar. Correlation of these two ash beds on the basis of their petrography and chemistry (tables 2, 3) is permissive.

Mention should be made that many of the biotitic white Miocene ash beds have petrographic and chemical characteristics similar to some of the white ash beds in the Oligocene White River Formation, and before Miocene and Oligocene white ash beds can be separated with certainty, detailed studies of all Oligocene and Miocene ash beds should be made. White ash beds in the upper part of the White River Formation in the Dilts Ranch quadrangle, Wyoming, in NW¼SW¼ sec. 5, T. 33 N., R. 70 W., and in the Orin quadrangle, Wyoming, in NE¼SE¼ sec. 12, T. 31 N., R. 70 W., contain phenocrysts of glass-mantled monazite. Monazite previously has not been reported in volcanic ash to the writer's knowledge, and the mineral may characterize some of the upper Oligocene ash beds. The Rockyford ash of Nicknish and Macdonald (1962) in the White River Badlands of South Dakota was assigned a Miocene age, and the ash was tentatively correlated with one of several known Miocene Gering ash beds in southwestern Nebraska. Analyses of the ash presented by Nicknish and Macdonald (1962, p. 689) were apparently made on raw ash and, accordingly, their correlation of the Rockyford ash and a thin white Gering ash bed at Scottsbluff National Monument (Swineford and others, 1955) on the basis of chemical similarity is not convincing. The writer believes that the Rockyford ash of Nicknish and Macdonald more closely resembles white ash beds in the upper Oligocene in the Scotts Bluff area of Nebraska than the several known Gering ash beds.

Inspection of the chemical analyses of the white ash beds (table 3) shows that they form a petrogenetic group and are silicic inasmuch as they average about 73 percent SiO_2 and range from 70 to 76 percent SiO_2. The volatile content of the ash beds was not determined in all cases, but the ash beds certainly must contain about 5-6 percent water of hydration, as shown above. If the SiO_2 contents of the white ash beds are recast volatile-free, the average SiO_2 content is perhaps 76-77 percent. The high SiO_2 content and appreciable content of alkalis certainly indicate that the white ash beds are the product of rhyolitic volcanism. The ratio of K_2O to Na_2O of most white ash beds is from near 2 to as much as 6. This ratio is high for calc-alkaline or peralkaline rhyolites (compare Nockolds, 1954, p. 1012-1013) and suggests that some Na_2O was leached and some K_2O was added to the glass during hydration. Other evidence that suggests that K_2O and Na_2O have either been leached or added from the glass shards during hydration is that the amount of K_2O varies directly with the amount of Na_2O. In general, the ash beds within a particular ash type that have the highest K_2O have the lowest Na_2O. The white ash beds contain less than 1 percent Fe_2O_3 which clearly separates them from all other Miocene ash beds studied. From the data in table 3 it seems obvious that it is difficult to distinguish among most of the white ash beds on the basis of the chemical analyses at hand. Perhaps trace-element studies may reveal important differences between certain white ash beds, but preliminary results of spectrographic analyses show that the trace-element content of most white ash beds is similar. The chemical analyses (table 3) suggest that the iron and SiO_2 content of the lower white ash beds is slightly higher than that of the other white ash beds of table 3, but more analyses are needed to confirm this suggestion. The rubidium-strontium ratio of three of the LW ash beds (DW6-39, 65, 72) is near 1 and is significantly different from that of other Miocene ash beds studied. The petrography of the three ash beds is also similar and correlation of the ash beds is permissive.

Gray Ash Beds

Several gray ash beds occur in lower Miocene rocks, and some petrographic and chemical data are given in tables 2 and 3. Other gray to dark-gray ash beds are known in Miocene rocks, but much more detailed work is needed to determine stratigraphic relations among these ash beds. One ash bed, here designated as the lower gray ash type (LG) occurs in the lower part of the Arikaree Formation in Monroe Creek Canyon. The petrography of the ash bed is shown in table 2. The ash bed is characterized by a low index of refraction of the glass shards for a gray ash bed and by its content of small euhedral hornblende phenocrysts (N_x= 1.654; $Z \wedge C$ 15°).

Gray ash beds, here designated MG (middle gray) in tables 2 and 3, occur in rocks of Marsland age in western Nebraska, Jay Em area, Wyoming (Love, 1961, p. 23), and in the Troublesome Formation. Only the ash from along Dry Creek in Nebraska is included in tables 2 and 3 inasmuch as the ash beds from the Troublesome and from the Jay Em areas are too contaminated to give reliable petrographic and chemical information. Whether these gray ash beds are the same bed or several petrographically related ash falls is not known.

Grayish-Blue Ash Beds

Grayish-blue ash beds designated GB in tables 2 and 3 occur in the upper Miocene part of the Troublesome Formation. The ash beds occur stratigraphically about 200 feet below olive-gray ash beds (fig. 7) in association with merychippine fossil horse remains. Another locality where grayish-blue ash beds occur is about 300 feet below olive-gray ash beds along Piney Creek, Eagle County, Colo. Grayish-blue ash beds have not yet been collected from Wyoming or Nebraska, but it seems likely that they will be found.

Petrographic characteristics of the grayish-blue ash beds are shown in table 2. The ash beds can be distinguished from other gray ash beds because of their shard characteristic, average refractive index, shape, and color.

Chemical analyses of the grayish-blue ash beds are shown in table 3. More samples of this ash-bed type need to be analyzed before the chemical characteristics are well documented. The ash beds are rhyolitic and chemically similar to the olive-gray and middle gray ash beds.

Olive-Gray Ash Beds

Olive-gray ash beds, designated OG in tables 2 and 3, occur in Miocene rocks in the Troublesome Formation and in Miocene rocks in many other areas in the Western Interior. The ash beds form a distinctive petrogenetic group and characteristically occur in upper Miocene rocks in association with merychippine fossil horse remains. A classic occurrence of olive-gray ash beds is in the upper part of the Sheep Creek Formation of western Nebraska, and one of several olive-gray ash beds (sample 73, tables 2 and 3) marks the top of an interval of rock containing a succession of fossil merychippi described by Osborn (1918, p. 17). Evernden and others (1964, KA 891) reported a potassium-argon isotope age of the glass fraction of the ash to be about 15 million years. McKenna (1965, p. 12) stated that the ash "* * * has yielded an anomalously young absolute date of 14.7 million years." Examination of the ash shows that in the main most shards are optically isotropic, but the hydrated shards show thin birefringent edges and mineral separations reveal that the ash is contaminated with older minerals. It seems that argon loss from hydration and incipient devitrification of the shards would give an anomalously young age. The age cannot be considered absolute even if the glass shards were not hydrated, and until the isotope age can be checked by other methods, the precise age of the ash is uncertain.

Certain petrographic features of the olive-gray Miocene ash beds are shown in table 2. Typically, the glass shards in each sample of olive-gray ash have a moderately large refractive index range

(1.502-1.528), and the average refractive index is near 1.505. The frequency distribution of shards with a particular refractive index was not determined by statistical methods but was estimated using focal masking methods, and this estimate is shown by the small Gaussian curve (table 2).

The olive-gray ash beds are characterized by a small assemblage of nonopaque phenocrysts other than quartz and feldspars, generally only including zircon, apatite, and in some ash beds chevkinite. In one olive-gray ash bed from the Troublesome Formation, a few grains of clinopyroxene (ferroaugite) were found. The olive-gray ash beds generally are made up of relatively coarse bubble-wall shards that contrast sharply with the paucity of phenocryst minerals.

Chemical analyses of the olive-gray ash beds (table 3) show that they form a distinctive family of ash beds united by common chemical characteristics. They contain about 67-72 percent SiO_2 (not corrected volatile-free) and from 2 to 3 percent iron oxide computed as Fe_2O_3. The glass contains appreciable amounts of zinc (76-150 ppm). Zinc content of all the Miocene ash beds seems to correlate well with (1) changes in iron content and (2) changes in the refractive indices of the glass shards. The olive-gray ash beds are products of rhyolitic volcanism as shown by their petrography, SiO_2 content (corrected volatile-free of about 72-74 percent), and the considerable amount of K_2O and Na_2O. The chemistry and petrography of the olive-gray ash beds suggest that they have calc-alkaline magmatic affinity.

At places in the Troublesome Formation, a stratigraphic sequence of several olive-gray ash beds is found in an interval of as much as 100 feet. Samples of two such sequences, 66G90, 66G91, 66G92 and 66G75, 66G74, and 66G76, are shown in tables 2 and 3. It is obvious from table 3 that chemically the ash beds are nearly identical and that the ash beds probably represent products of recurrent volcanism from one volcanic center. This stratigraphic repetition of chemically and mineralogically similar ash beds makes bed-to-bed correlations in many cases only permissive.

Silver-Gray Ash Beds

Silver-gray ash beds, designated SG in tables 2 and 3, occur in upper Miocene rocks generally stratigraphically higher than the olive-gray ash beds (fig. 7). In the Troublesome Formation, one silver-gray ash (66G43, tables 2 and 3) bed occurs about 100 feet stratigraphically above the highest olive-gray ash bed. At another place in Barger Gulch, a second dirty silver-gray ash bed is in the uppermost part of the olive-gray zone of ash beds.

Ash beds grouped with the silver-gray ash beds of the Troublesome occur in the Box Butte Member of the Sheep Creek Formation (DN5-46, tables 2 and 3) about 6 miles south of Marsland, Nebr., in the Ogallala Formation of N. M. Denson in the Split Rock, Wyo., area (DW9-8), and in the Ogallala Formation at Porcupine Butte, Shannon County, S. Dak. (66G17). Other silver-gray ash beds whose petrographic and chemical features are similar to the silver-gray ash-bed type, but not shown in tables 2 and 3, occur near the base of the Ogallala Formation north of Cheyenne, Wyo., at the site of the Trail Creek fauna (Voorhies, 1965), and in the Ogallala Formation of N. M. Denson in the Buzzard Ranch quadrangle, Split Rock area, Wyoming.

Petrographic features common to the silver-gray ash beds include their thin colorless nearly flat large-radius bubble-wall shards, their paucity of nonopaque phenocrysts, and their characteristic average index of refraction of the glass shards (table 2). The silver-gray ash beds seemingly are easily separated from other gray ash beds of Miocene age by the shard shape and the refractive index of the shards.

Chemical analyses show the silver-gray ash beds to be rhyolitic and to contain less iron oxide as Fe_2O_3 (1.5-2.1 percent) and less zinc (40-49 ppm) than the olive-gray ash beds. The silver-gray ash beds are chemically similar to the gray ash beds in the lower Miocene rocks and cannot be separated from them with confidence on the basis of chemical data at hand.

Dark-Greenish-Gray Ash Beds

Only two dark-greenish-gray ash beds, designated DGG on tables 2 and 3, were studied. One ash bed (sample 80, tables 2 and 3) occurs near the base of the Sand Canyon Member of the Sheep Creek Formation of Elias (1942) and was correlated by Elias with the prominent olive-gray ash bed (sample 73, tables 2 and 3) in Merychippus Draw at the type section of the Sheep Creek Formation. It is obvious from the petrographic (table 2) and chemical (table 3) data that the two ash beds are markedly different and cannot be the same ash bed. The ash at Sand Canyon contains numerous glass-mantled phenocrysts of augite (N_y= 1.692-1.696; $2V_z$= 54-57) and hypersthene (N_x= 1.686-1.696), whereas the ash at Merychippus Draw is barren of these phenocryst minerals. In addition, chemical analyses show marked differences between the ash beds (table 3). The Sand Canyon ash contains significantly more Fe_2O_3, CaO, TiO_2, and SrO and less SiO_2 than the olive-gray ash at Merychippus Draw.

The second dark-greenish-gray ash bed studied occurs in the Moonstone Formation of Love (1961, p. 28, unit 18). The formation was assigned a Pliocene age by Love on the basis of diatom assemblages and fragmentary vertebrate remains (Love, 1961, p. 34). Concerning the age of the Moonstone, Love (1961, p. 35) reported a fossil rodent from the Moonstone which was identified by R. W. Wilson as an entoptychine rodent. According to Simpson (1945, p. 80), the entoptychine rodents are found in rocks of Miocene age. The ash at Sand Canyon (sample 80) occurs in association with merychippine horse remains and the oreodont Brachychrus (Pronomotherium) of late Miocene age (Elias, 1942, p. 129-130). If the Sand Canyon ash and the Moonstone ash (LW-506) are the same ash bed, and the data seem to suggest the correlation (table 2), then seemingly part of the Moonstone Formation of Love could be of Miocene age.

The petrography of the two dark-greenish-gray ash beds is shown in table 2. The refractive index of the glass shards shows an extremely large range, 1.506-1.575, and a meaningful average value for the shards cannot be determined without detailed statistical analysis. The refractive index of the shards is markedly different from that of other Miocene ash beds.

Chemical analyses of the two ash beds suggest that they are probably the product of rhyodacitic volcanism as shown by the SiO_2 content (about 65 percent volatile-free), the iron-oxide content (about 5.6 percent), and the moderate K_2O and Na_2O content. The DGG ash beds are the most mafic ash beds studied as shown by their high Fe_2O_3, TiO_2, CaO, MgO, and SrO content, and are easily separated from other Miocene ash beds.

Source of Ash Beds

The source of the Miocene ash beds may never be known with absolute assurance, but certain evidence points to western sources in the Great Basin, perhaps in Nevada or western Utah. Figure 5 shows that Miocene ash beds occur practically wherever Miocene rocks are found in the Western Interior. Had Miocene rocks been preserved everywhere in the area of figure 5, ash-bed occurrences would probably extend in a great north-trending belt at least from Montana to New Mexico. A western source for the ash beds seems probable because ash beds coarsen westward and increase in number and thickness. One of the westernmost occurrences of Miocene ash beds is in the type area of the Browns Park Formation where Hansen (1965, p. 120-127) reported many thick ash beds. Ash beds in Nebraska and South Dakota are thin and fine grained compared to ash beds farther west. Assuming that the planetary westerly winds were active in Miocene time, they would spread ash eastward from known Miocene volcanic centers in Nevada and western Utah.

The petrography and chemistry of most Miocene ash beds in figure 5 are silicic and must have had volcanic sources that extruded extremely large amounts of silicic tuffs throughout Miocene time. Recent work in southern and central Nevada by many U.S. Geological Survey geologists (Hinrichs and Orkild, 1961; Byers and others, 1964; E. B. Ekren, written commun., 1966) has shown the existence of numerous silicic volcanic centers of several Miocene ages. Associated with these centers are thick piles of silicic tuffs whose chemistry and petrography are similar to the air-fall Miocene ash beds. Another area of Miocene silicic volcanism includes the Thomas and Dugway Ranges in western Utah (Staatz and Carr, 1964). Other areas of Miocene silicic volcanism as yet undocumented doubtless exist in the Great Basin and could have contributed to the air-fall Miocene ash beds of figure 5.

Other sources for the Miocene ash beds, including well-known volcanic centers in Colorado where thick piles of silicic tuffs are associated with upper Cenozoic volcanic centers, have been suggested. Most of these are now known to be of late Oligocene age and, accordingly, too old to provide ash in the bulk of the Miocene rocks. For example, the San Juan Mountains of southwestern Colorado might be considered possible source areas for Miocene ash beds, but recent isotope age determinations (Steven and others, 1967, p. 53) show that the bulk of the intermediate to silicic tuffs were probably extruded near the end of Oligocene time. Specimen Mountain in Rocky Mountain National Park, Colo., has been suggested as a source, but silicic tuffs in the Mount Richthofen-Iron Mountain area which probably have the same age as Specimen Mountain Volcanics were dated as late Oligocene by Corbett (1965). Miocene Tertiary stocks are known to occur elsewhere in Colorado, but they lack associated thick piles of silicic tuffs.

In summary, the writer believes that the Miocene ash beds may have been derived from volcanic centers in Nevada or western Utah, but other areas of upper Cenozoic volcanism farther west or north of Nevada might have contributed ash beds to the Miocene rocks.

REFERENCES CITED

Aramaki, Shigeo, and Lipman, Peter, 1965, Possible leaching of Na_2O during hydration of volcanic glasses: Japan Acad. Proceedings, v. 41, no. 6, p. 467-470.

Buffler, R. T., 1967, The Browns Park Formation and its relationship to the late Tertiary geologic history of the Elkhead region, northwestern Colorado-south central Wyoming: Calif. Univ. doctoral thesis.

Burbank, W. S., Lovering, T. S., Goddard, E. N., and Eckel, E. B., 1935, Geologic map of Colorado: U.S. Geological Survey.

Byers, F. M., Jr., Orkild, P. P., Carr, W. J., and Christiansen, R. L., 1964, Timber Mountain caldera, Nevada Test Site and Vicinity--a preliminary report [abs.], in Abstracts for 1963: Geol. Soc. America Spec. Paper 76, p. 267.

Cady, R. C., and Scherer, O. J., 1946, Geology and ground-water resources of Box Butte County, Nebraska: U.S. Geol. Survey Water-Supply Paper 969, 102 p.

Cherkasov, Yu. A., 1957, O primenenii "fokalnogo ekranirovaniia" pri izmereniiakh pokazatelei prelomleniia immersionnym metodom (Application of "focal screening" to measurement of indices of refraction by the immersion method), in Rozhkova, E. V., ed., Sovremennye metody mineralogicheskogo issledovaniia gornykh porod, rud i mineralov (Modern methods of mineralogic investigation of rocks, ores and minerals): Moscow, Gosudarstvennoe Nauchno-Tekhnicheskoe Izdatel'stvo Literatury po Geologii i Okhrane Nedr., p. 184-207 (translated by Ivan Mittin in Internat. Geology Review, v. 2, 1960, p. 218-235).

Cockerell, T. D. A., 1908, A new locality for Miocene mammals: Science, new ser., v. 28, p. 683.

Cook, H. J., 1915, Notes on the geology of Sioux County, Nebraska, and vicinity: Nebraska Geol. Survey, v. 7, pt. 11, p. 59-75.

Corbett, M. K., 1965, Tertiary igneous petrology of the Mount Richthofen-Iron Mountain area, north-central Colorado [abs.], in Abstracts for 1964: Geol. Soc. America Spec. Paper 82, p. 324-325.

Darton, N. H., 1903, Preliminary report on the geology and water resources of Nebraska west of the one hundred and third meridian: U.S. Geol. Survey Prof. Paper 17, 69 p.

_____1906, Geology of the Bighorn Mountains: U.S. Geol. Survey Prof. Paper 51, 129 p.

Denny, C. S., 1940, Santa Fe formation in the Espanola valley, New Mexico: Geol. Soc. America Bull., v. 51, no. 5, p. 677-693.

Denson, N. M., 1965, Miocene and Pliocene rocks of central Wyoming, in Cohee, G. V., and West, W. S., 1965, Changes in stratigraphic nomenclature by the U.S. Geological Survey, 1964: U.S. Geol. Survey Bull. 1224-A, p. 70-74.

Denson, N. M., and Gill, J. R., 1965, Chemical, semiquantitative, spectrographic, heavy-mineral analyses of rock and water samples and a table of selected dry holes and producing wells from the Williston basin: U.S. Geol. Survey open-file report.

Elias, M. K., 1942, Tertiary prairie grasses and other herbs from the High Plains: Geol. Soc. America Spec. Paper 41, 176 p.

Evernden, J. F., Savage, D. E., Curtis, G. H., and James, G. T., 1964, Potassium-argon dates and the Cenozoic mammalian chronology of North America: Am. Jour. Sci., v. 262, no. 2, p. 145-198.

Fleischer, R. L., and Price, P. B., 1964, Techniques for geological dating of minerals by chemical etching of fission fragment tracks: Geochim. et Cosmochim. Acta, v. 28, no. 11, p. 1705-1714.

Friedman, Irving, and Harris, Joseph, 1961, Fluorine during hydration of rhyolitic glass, Art. 258: U.S. Geol. Survey Prof. Paper 424-C, p. C304-C305.

Galbreath, E. C., 1953, A contribution to the Tertiary geology and paleontology of northeastern Colorado: Kansas Univ. Paleont. Contr., no. 13, Vertebrata, art. 4, 119 p.

Hail, W. J., Jr., 1965, Geology of northwestern North Park, Colorado: U.S. Geol. Survey Bull. 1188, 133 p.

Hail, W. J., Jr., and Lewis, G. E., 1960, Probable late Miocene age of the North Park formation in the North Park area, Colorado, in Short papers in the geological sciences: U.S. Geol. Survey Prof. Paper 400-B, p. B259-B260.

Hansen, W. R., 1965, Geology of the Flaming Gorge area, Utah-Colorado-Wyoming: U.S. Geol. Survey Prof. Paper 490, 196 p.

Hinrichs, E. N., and Orkild, P. P., 1961, Eight members of the Oak Spring formation, Nevada Test Site and Vicinity, Nye and Lincoln Counties, Nevada, Art. 327: U.S. Geol. Survey Prof. Paper 424-D, p. D96-D103.

Izett, G. A., 1966, Tertiary extrusive volcanic rocks in Middle Park, Grand County, Colorado, in Geological Survey research 1966: U.S. Geol. Survey Prof. Paper 550-B, p. B42-B46.

_____1968, Geology of the Hot Sulphur Springs quadrangle, Grand County, Colorado: U.S. Geol. Survey Prof. Paper 586 (in press).

Izett, G. A., and Lewis, G. E., 1963, Miocene vertebrates from Middle Park, Colorado, in Short papers in geology and hydrology: U.S. Geol. Survey Prof. Paper 475-B, p. B120-B122.

Lipman, P. W., 1965, Chemical comparison of glassy and crystalline volcanic rocks: U.S. Geol. Survey Bull. 1201-D, 24 p.

Love, J. D., 1956, New geologic formation names in Jackson Hole, Teton County, northwestern Wyoming: Am. Assoc. Petroleum Geol. Bull., v. 40, no. 8, p. 1899-1914.

_____1961, Split Rock formation (Miocene) and Moonstone formation (Pliocene) in central Wyoming: U.S. Geol. Survey Bull. 1121-I, 36 p.

Love, J. D., Weitz, J. L., and Hose, R. K., 1955, Geologic map of Wyoming: U.S. Geological Survey.

Lovering, T. S., 1930, The Granby anticline, Grand County, Colorado: U.S. Geol. Survey Bull. 822-B, p. 71-76.

Lovering, T. S., and Goddard, E. N., 1950, Geology and ore deposits of the Front Range, Colorado: U.S. Geol. Survey Prof. Paper 223, 319 p.

Lugn, A. L., 1939, Classification of the Tertiary system in Nebraska: Geol. Soc. America Bull., v. 50, no. 8, p. 1245-1275.

Macdonald, J. R., 1963, The Miocene faunas from the Wounded Knee area of western South Dakota: Am. Mus. Nat. History Bull., v. 125, art. 3, 238 p.

Marvine, A. R., 1874, Report [on the Middle Park region, Colo.], in Hayden, F. V., Seventh Annual Report of the U.S. Geological and Geographical Survey of the Territories * * * for the year 1873: Washington, U.S. Govt. Printing Office, p. 83-192.

Masursky, Harold, 1962, Uranium-bearing coal in the eastern part of the Red Desert area, Wyoming: U.S. Geol. Survey Bull. 1099-B, p. B1-B152.

Matthew, W. D., 1901, Fossil mammals of the Tertiary of northeastern Colorado: Am. Mus. Nat. History Mem., v. 1, pt. 7, p. 355-447.

_____1924, Third contribution to the Snake Creek fauna: Am. Mus. Nat. History Bull., v. 50, p. 59-210.

Matthew, W. D., and Cook, H. J., 1909, A Pliocene fauna from western Nebraska: Am. Mus. Nat. History Bull., v. 26, p. 361-414.

McGrew, L. W., 1967, Geologic map of the Casebier Hill quadrangle, Goshen County, Wyoming: U.S. Geol. Survey Geol. Quad. Map GQ-621.

McKenna, M. C., 1965, Stratigraphic nomenclature of the Miocene Hemingford Group, Nebraska: Am. Mus. Novitates, no. 2228, 21 p.

Montagne, J. M. de la, 1955, Cenozoic history of the Saratoga Valley area, Wyoming and Colorado: Wyoming Univ. doctoral thesis; Ann Arbor, Mich., Univ. Microfilms, Inc.

Montagne, J. M. de la, and Barnes, W. C., 1957, Stratigraphy of the North Park Formation in North Park area, Colorado, in Rocky Mtn. Assoc. Geologists Guidebook 9th Ann. Field Conf., North and Middle Park Basins, 1957: p. 55-60.

Nicknish, J. M., and Macdonald, J. R., 1962, Basal Miocene ash in White River Badlands, South Dakota: Am. Assoc. Petroleum Geologists Bull., v. 46, no. 5, p. 685-690.

Nockolds, S. R., 1954, Average chemical compositions of some igneous rocks: Geol. Soc. America Bull., v. 65, no. 10, p. 1007-1032.

Osborn, H. F., 1918, Equidae of the Oligocene, Miocene, and Pliocene of North America, iconographic type revision: Am. Mus. Nat. History Mem., new series, v. 2, pt. 1, p. 1-330.

Powers, H. A., 1961, Chlorine and fluorine in silicic volcanic glass, Art. 111: U.S. Geol. Survey Prof. Paper 424-B, p. B261-B263.

Powers, H. A., Young, E. J., and Barnett, P. R., 1958, Possible extension into Idaho, Nevada, and Utah of the Pearlette ash of Meade County, Kansas [abs.]: Geol. Soc. America Bull., v. 69, no. 12, pt. 2, p. 1631.

Powers, H. A., and Wilcox, R. E., 1964, Volcanic ash from Mount Mazama (Crater Lake) and from Glacier Peak: Science, v. 144, no. 3624, p. 1334-1336.

Richards, Arthur, 1941, Geology of the Kremmling area, Grand County, Colorado: Michigan Univ. doctoral thesis; Ann Arbor, Mich., Univ. Microfilms, Inc.

Robinson, G. D., 1967, Geologic map of the Toston quadrangle, southwestern Montana: U.S. Geol. Survey Misc. Geol. Inv. Map I-486.

Ross, C. S., and Smith, R. L., 1955, Water and other volatiles in volcanic glasses: Am. Mineralogist, v. 40, nos. 11-12, p. 1071-1089.

Sato, Yoshiaki, and Denson, N. M., 1967, Volcanism and tectonism as reflected by the distribution of nonopaque heavy minerals in some Tertiary rocks of Wyoming and adjacent states, in Geological Survey research 1967: U.S. Geol. Survey Prof. Paper 575-C, p. C42-C54.

Schultz, C. B., 1938, The Miocene of western Nebraska: Am. Jour. Sci., 5th ser., v. 35, no. 210, p. 441-444.

Schultz, C. B., and Stout, T. M., 1961, Field conference on the Tertiary and Pleistocene of western Nebraska: Nebraska Univ. State Mus. Spec. Pub. 2, 55 p.

Simpson, G. G., 1945, The principles of classification and a classification of mammals: Am. Mus. Nat. History Bull., v. 85, 350 p.

Staatz, M. H., and Carr, W. J., 1964, Geology and mineral deposits of the Thomas and Dugway Ranges, Juab and Tooele Counties, Utah: U.S. Geol. Survey Prof. Paper 415, 188 p.

Steen, V. C., and Fryxell, Roald, 1965, Mazama and Glacier Peak pumice glass: Uniformity of refractive index after weathering: Science, v. 150, no. 3698, p. 878-880.

Steven, T. A., Mehnert, H. H., and Obradovich, J. D., 1967, Age of volcanic activity in the San Juan Mountains, Colorado, in Geological Survey research 1967: U.S. Geol. Survey Prof. Paper 575-D, p. D47-D55.

Swineford, Ada, Frye, J. C., and Leonard, A. B., 1955, Petrography of the late Tertiary volcanic ash falls in the central Great Plains: Jour. Sed. Petrology, v. 25, no. 4, p. 243-261.

Voorhies, M. R., 1965, The carnivora of the Trail Creek fauna: Wyoming Univ. Contr. to Geology, v. 4, no. 1, p. 21-25.

Wilcox, R. E., 1959, Use of the spindle stage for determination of principal indices of refraction of crystal fragments: Am. Mineralogist, v. 44, nos. 11-12, p. 1272-1293.

_____1962, Cherkasov's "focal screening" for determination of refractive index by the immersion method, in McCrone, W. C., ed., Proceedings of the International Microscopy Symposium, Chicago, 1960 [1962]: Chicago, Ill., McCrone Associates, p. 160-165.

Wood, H. E., and others, 1941, Nomenclature and correlation of the North American continental Tertiary: Geol. Soc. America Bull., v. 52, no. 1, p. 1-48.