

TEPHROSTRATIGRAPHY AND POTASSIUM - ARGON AGE
DETERMINATIONS OF SEVEN VOLCANIC ASH LAYERS IN THE
MUDDY CREEK FORMATION OF SOUTHERN NEVADA

by

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PREFACE

The effective characterization of a site for the long-term management of low-level radioactive waste requires detailed knowledge of the geologic strata through which the waste might conceivably be transported should a worst case leak scenario occur, as well as a knowledge of the way in which the geologic strata encountered at the site relate to the surrounding geologic formations. An important part of the stratigraphic characterization is a knowledge of the depositional environment (geologic and paleoclimatic environment at the time the strata were originally formed); a knowledge of the paleoclimatology requires the identification, in the field, characterization, and dating of as many stratigraphic time-marker horizons as can be located in the area surrounding the site to be characterized. The stratigraphic marker horizons identified and studied in this report will aid considerably in the correlations between sediments in the depositional basins surrounding the area 5 low level defense waste management site at NTS. In turn, this will allow more accurate projections of likely future changes in water table and downward percolation of water in the vadose zone.

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ABSTRACT

Seven silicic tephra layers occur in alluvial deposits of the Muddy Creek and equivalent formations at three localities in southern Nevada. Chemical and petrographic characterization indicate the tephra were derived from seven different volcanic eruptions and do not represent any previously known tephra layers.

K-Ar age determinations on minerals or glass from each layer yielded 6 to 12 m.y. ages. Discordant ages were obtained on multiple mineral phases due to incorporation of detrital contaminants.

The tephra are sufficiently distinctive to constitute stratigraphic marker horizons in the Muddy Creek and equivalent formations. Derivation from the southwestern Nevada volcanic field, active 16 to 6 m.y., is highly likely for some of the tephra. The K-Ar results suggest substantial parts of the Muddy Creek Formation and equivalent basin-fill are 6 to 12 m.y., indicating basin-range faulting began prior to 12 m.y. Little tectonic deformation or physiographic change has occurred in the past 6 m.y.

DISCUSSION

POTASSIUM-ARGON AGE DETERMINATIONS

THE PROBLEM OF K-AR DATING OF SYNCLASTIC MATERIAL

THEORY OF POTASSIUM-ARGON DATING

Argon Analysis

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INTRODUCTION

Volcanic ash layers preserved in the geologic record potentially can be of great value in establishing stratigraphic correlations. Morrison (1968) states that time-stratigraphic correlations can be greatly facilitated by a stratigraphic marker unit which is time parallel and sufficiently widespread to provide a definite time-datum surface. A volcanic ash layer, which mantles the topography upon which it was deposited, is nearly ideal for this purpose.

Volcanic ash, defined by Fisher (1961) as pyroclastic material less than 2 mm in diameter, is included in a more general term "tephra" which collectively refers to all airborne pyroclastic material from a volcanic eruption, regardless of size (Thorarinsson, 1954; 1969; 1974). Tephrostratigraphy involves the definition, description, and age of tephra layers, either in outcrop or from the subsurface (Westgate and Fulton, 1975) and is directly related to tephrochronology, which is the application of the results of tephrostratigraphic studies to the establishment of a chronologic sequence of geologic events (Westgate and Gold, 1974; Westgate and Fulton, 1975). The terms "ash" and "tephra" will be used interchangeably in this report.

The basic criteria for the usefulness of an ash layer in a tephrostratigraphic study are that it be distinctive

in its petrographic and chemical characteristics and it be extensive enough for correlation. Although tephra research is a relatively new discipline, recent advances in chemical and petrographic techniques allow for precise analyses of a variety of characteristics of the components of an ash so that it may be distinguished from other ash layers. Wilcox and Izett (1973) emphasize that reliable correlations among remnants of an ash-fall require not only a match of essential characteristics, but also characteristics by which the ash-fall may be distinguished from other ash falls of the area. This requires that all ash layers in an area be carefully characterized and distinguished before correlations are attempted. Most silicic ash layers younger than Oligocene display a variety of recognizable characteristics and lend themselves readily to such correlation (Steen-McIntyre, 1977).

There are currently a variety of methods employed in the characterization of an ash layer; use of multiple methods to characterize ashes has been repeatedly advocated (Wilcox, 1965; Borchardt and others, 1971; Wilcox and Izett, 1973; Westgate and Fulton, 1975). These are primarily the major and minor element chemistry and the morphology of the glass shards, and characteristics of the phenocryst assemblage. An ash layer may also be dated, by correlation with either an equivalent dated ash layer or with the eruption which produced the layer, or by radiometric means.

A radiometrically dated ash layer is a particularly valuable stratigraphic marker, as it has a determined absolute age (Morrison, 1968).

Despite its potential as a stratigraphic tool, tephrostratigraphy has limitations, due primarily to the restricted extent of most volcanic eruptions, the discontinuous preservation and exposure which make correlation difficult, and the careful, time-consuming research required to definitively distinguish and correlate tephra. Morrison (1968) stated that few ash falls in the United States are sufficiently widespread and adequately studied to allow reliable correlations. Although this was true in 1968, the situation is rapidly changing due to continued research.

PURPOSE

The purpose of this research is to conduct a tephrostratigraphic study of several volcanic ash layers in the vicinity of the Nevada Test Site (NTS) in southern Nevada. The tephra layers were discovered during a purposeful search directed at locating tephra layers in the late Cenozoic alluvial deposits of this area which might serve as stratigraphic marker units.

Characterization of the tephra serves two purposes. First, it will establish the tephra as stratigraphic markers with distinguishing characteristics which may be compared

with subsequently discovered tephra, providing a basis for geologic correlation. The characterization also serves the second purpose of providing data which are used in an attempt to identify the tephra layers by comparative chemical and petrographic studies with tephra from known late Cenozoic eruptions in the western United States, possibly establishing a direct correlation. Possible correlation with ash-flow tuffs erupted from volcanic centers on and adjacent to the Nevada Test Site (southwestern Nevada volcanic field) are also discussed. Such correlations are difficult to assess due to differences in chemistry and mineralogy which exist between the early erupted air-fall ash and subsequently erupted ash-flows from a differentiated magma body (Hildreth, 1979; Smith, 1979).

This study is part of a U.S. Department of Energy research project which is assessing the potential movement of radioactive waste in the unsaturated zone of alluvium on the Nevada Test Site. The paleoclimatological portion of this research requires a stratigraphic study of the late Cenozoic alluvial deposits in the vicinity of the NTS. The deposits which comprise the unsaturated zone of the NTS alluvium are probably, in large part, equivalents of the Tertiary Muddy Creek Formation, which have limited exposure on the NTS. The stratigraphic study would be greatly aided by time-correlative marker horizons which will allow correlations between sediments in widespread depositional

basins. The tephra layers studied here provide distinctive and reliable dated stratigraphic marker horizons in the Muddy Creek and its correlative formations.

This research includes chemical and petrographic characterization of the tephra layers and radiometric age determinations by the potassium-argon method. The methods and results of each investigation will be discussed separately.

GEOLOGIC SETTING

The Nevada Test Site (NTS) is located in southern Nevada, approximately 60 miles (~95 km) northwest of Las Vegas. The seven tephra layers described in this study were collected from three localities (Figure 1), south, east, and northeast of the NTS, in Nye, Clark and Lincoln counties, respectively. (See Appendix I for detailed descriptions of sample localities). The localities to the south and east of the NTS each have two tephra layers, in stratigraphic succession, while the third locality, to the northeast of the NTS, has three tephra layers in stratigraphic succession.

The study area is characterized by Basin and Range topography; elongate, fault-bounded mountain ranges alternate with intervening alluvial filled valleys. The mountain ranges, generally north-trending in this area, except for a more irregular pattern to the south, average

Figure 1. Locality map of the study area.

From 2000-3000 m (6000-9000 feet) in elevation, while the valleys usually range from 1300-1600 m (4000-5000 feet). The valley floors are commonly playas which are periodically

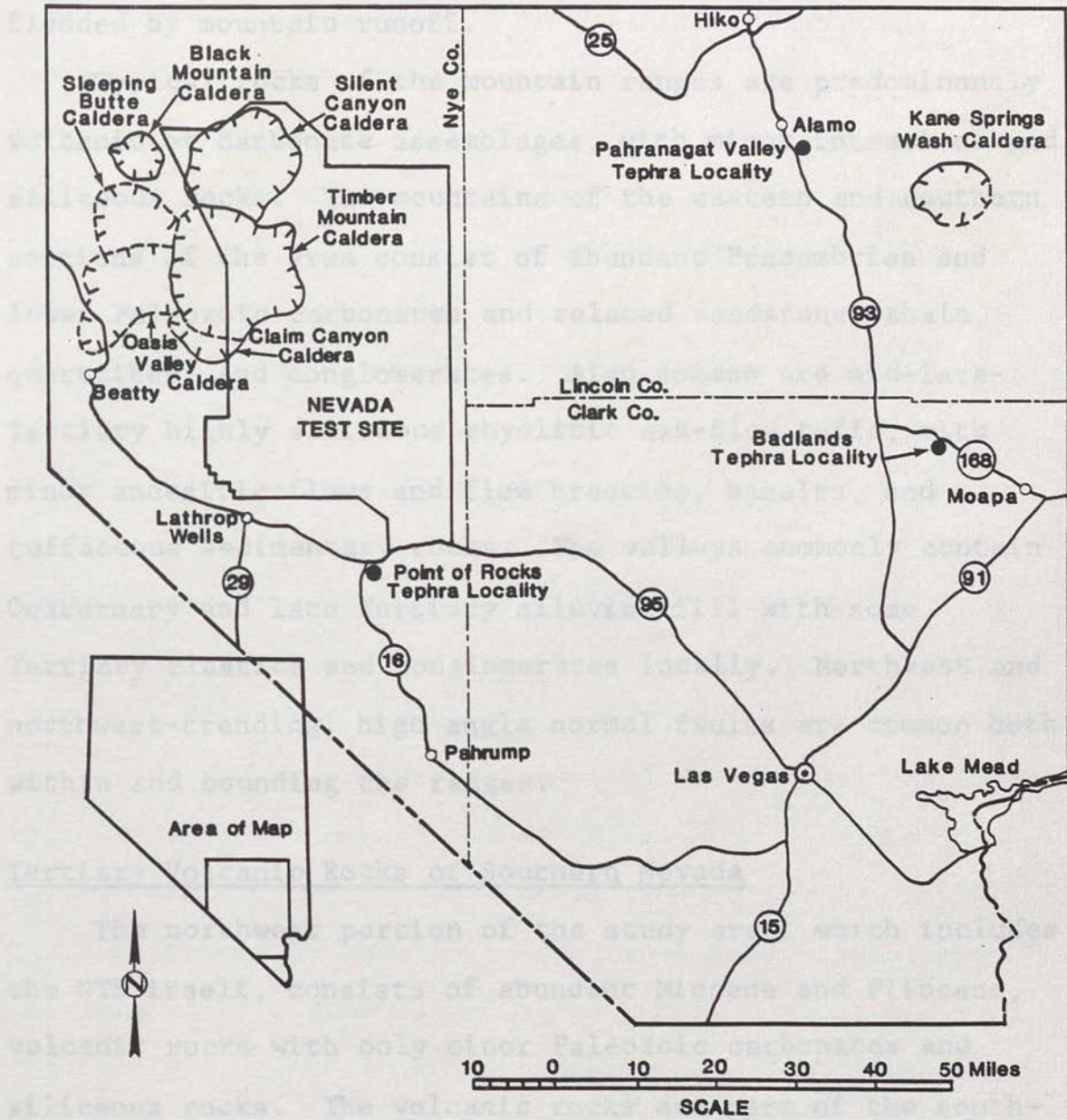


Figure 1. Locality map of the study area.

from 2000-3000 m (6000-9000 feet) in elevation, while the valleys usually range from 1300-1600 m (4000-5000 feet). The valley floors are commonly playas which are periodically flooded by mountain runoff.

Typical rocks of the mountain ranges are predominantly volcanic or carbonate assemblages, with minor intrusives and siliceous rocks. The mountains of the eastern and southern portions of the area consist of abundant Precambrian and lower Paleozoic carbonates and related sandstone, shale, quartzites, and conglomerates. Also common are mid-late-Tertiary highly siliceous rhyolitic ash-flow tuffs, with minor andesitic flows and flow breccias, basalts, and tuffaceous sedimentary rocks. The valleys commonly contain Quaternary and late Tertiary alluvial fill with some Tertiary clastics and conglomerates locally. Northeast and northwest-trending, high angle normal faults are common both within and bounding the ranges.

Tertiary Volcanic Rocks of Southern Nevada

The northwest portion of the study area, which includes the NTS itself, consists of abundant Miocene and Pliocene, volcanic rocks with only minor Paleozoic carbonates and siliceous rocks. The volcanic rocks are part of the southwestern Nevada volcanic field which produced ash-flow tuffs that once covered an area of more than 11,000 km². The field is centered around a complex of six collapse

calderas, five of which overlap one another (Figure 1). The volcanic rocks erupted from the field are predominantly rhyolites with some basalts, trachytes, trachyandesites and other differentiates related to basaltic and rhyolitic parent magmas (Christiansen and others, 1977). The calderas, ranging in age from 16 to 6 million years, are, from oldest to youngest, the Sleeping Butte, Silent Canyon, Claim Canyon, Oasis Valley, Timber Mountain, and Black Mountain calderas (Noble and others, 1964; Christiansen and Noble, 1965; Noble, 1965; Byers and others, 1976; Christiansen and others, 1977). The Sleeping Butte Caldera, active from 16 to 14 million years ago, is the probable source of three rhyolitic ash-flow sequences. Collapse of the Sleeping Butte caldera was followed by eruption of the Belted Range Tuff, 15 to 13 million years ago, from the Silent Canyon Caldera. This tuff consists of two rhyolitic members, the Tub Spring and Grouse Canyon, both of peralkaline composition (alkalis > alumina). The Claim Canyon - Oasis Valley caldera complex was active from 13 to 12.5 million years ago, producing the rhyolitic Paintbrush Tuff. This tuff consists of five members which are petrographically and chemically distinct from one another. The Timber Mountain Tuff, erupted from the Timber Mountain Caldera between 11 and 9.5 million years ago, consists of two rhyolitic members. The lower Rainier Mesa Member is distinguished from the upper Ammonia Tanks Member on the basis of chemistry and

petrography. The youngest caldera of the field, the Black Mountain Caldera, was active between 7.5 and 6 million years ago. This caldera, which is located northwest of the other five overlapping calderas, produced the Thirsty Canyon Tuff consisting of five distinct peralkaline members.

Other volcanic centers in the vicinity of the study area include the Mt. Helen Caldera to the northwest of the NTS, the Cathedral Peak Caldera to the north, the Bald Mountain Caldera to the northeast, and the Kane Spring Wash (Noble, 1968) and Caliente calderas to the east.

Late Cenozoic Alluvial Deposits

The late Tertiary and Quaternary stratigraphy of southern Nevada is complex and not well studied or understood. Detailed studies are in restricted localities (Stock, 1921b; Longwell, 1928; 1939; 1949; Westgate and Knopf, 1932; Phoenix, 1948; Tschanz, 1960; Anderson and others, 1972; Lucchitta, 1972; 1979; Blair and others, 1977; Blair, 1978), so that much of the knowledge of the late Tertiary and Quaternary stratigraphy is on a very broad and general level, mostly gathered from reconnaissance work (Longwell and others, 1965; Tschanz and Pampeyan, 1970; Cornwall, 1972). Much of the following geologic descriptions are summarized from these references.

Muddy Creek Formation

The Muddy Creek Formation, first described by Stock (1921 a,b), lies unconformably above the Horse Spring

Horse Spring Formation

The oldest Tertiary sedimentary rocks that will be discussed here is the Horse Spring Formation (Longwell, 1921), which is exposed at scattered localities in northern Clark County and at a few isolated localities in adjacent parts of Nye and Lincoln counties. The Horse Spring Formation consists of much lacustrine limestone, dolomite, silt, sandstone and conglomerate, intermixed with gypsum, borate minerals, and numerous lenses and thin beds of water-laid volcanic ash (Longwell, 1928; 1949; Longwell and others 1965; Anderson and others, 1972). It was deposited in shallow, local basins under conditions which are believed to have persisted or recurred for long periods of time, so that the sediments are not everywhere of identical age or source (Longwell and others, 1965; Anderson and others, 1972). Fossils in the Horse Spring Formation are sparse, but isotopic ages from the interspersed volcanic tuffs and lavas indicate that it spans most of the Miocene, and locally, part of the Oligocene (Tschanz, 1960; Marvin and others, 1970a; Anderson and others, 1972). Most of the Horse Spring Formation is tilted, folded and faulted, indicating that it predates Basin and Range faulting.

Muddy Creek Formation

The Muddy Creek Formation, first described by Stock (1921 a,b), lies unconformably above the Horse Spring

Formation, and is usually conformable with younger, overlying deposits. It is extensively exposed in interior basins in southern Nevada, northwestern Arizona, and southwestern Utah. The beds consist of subaqueous, fine-grained sands, silts and clays in the basins, grading into coarser-grained conglomerates of cemented pebbles and angular fragments of bedrock near the mountain fronts (Longwell, 1928; Longwell and others, 1965; Tschanz and Pampeyan, 1970; Blair, 1978). The deposits are essentially flat-lying, usually yellow, buff, gray or pink in color, and contain abundant tuffaceous material and beds of gypsum, carbonate and caliche. Although the total thickness of the Muddy Creek is not known, several thousand feet (~1000 m) is considered reasonable. Erosional dissection of the fine-grained beds has created typical badlands topography of mesas and buttes. In the Lake Mead area of southern Nevada and northwestern Arizona, the Muddy Creek Formation, exposed in the Grand Wash Cliffs, contains an uppermost member of limestone (the Hualapai Limestone) more than 1000 m thick in places.

Much controversy and contradiction has arisen regarding the age of the Muddy Creek Formation. Stock (1921a,b) originally assigned the formation to the Miocene (the Miocene/Pliocene boundary was then considered to be about 13 m.y.) on the basis of mammalian fossils, but these were

later considered to have no diagnostic value (Longwell, 1963). Longwell (1928) tentatively referred the formation to the Pliocene (then considered to range from 13 to 1 m.y.) due to the close resemblance to the deposits of the Pliocene Panaca Formation, which is exposed further north in Lincoln County, Nevada. More recent investigations, which will be discussed in detail in a later section, indicate a late Miocene to early Pliocene age (~17-~5 m.y.)

Panaca Formation

The Panaca Formation, named by Stock in 1921, is exposed in the upper part of the Meadow Valley Wash drainage system in the vicinity of Panaca and Caliente. It is similar in lithology to the Muddy Creek Formation, and consists primarily of white, buff, light brown to terra cotta, fine-grained lake sediments and wind deposits containing much tuffaceous material and diatoms, and some carbonate and chalcedony (Westgate and Knopf, 1932; Phoenix, 1948; Tschanz and Pampeyan, 1970). The deposits, which have been dissected to form typical badlands topography, are generally flat-lying, although dips of two to three degrees are common near basin margins. The deposits are coarser near the basin margins. Although the full thickness of these valley fill deposits is not known, Phoenix (1948) estimates at least 1400 feet (~430 m) and probably more. Due to the lack of deformation and only slight faulting, the

mountain ranges are assumed to have been in their present position at the time of deposition of the Panaca Formation.

Stock (1921b) considered the Panaca to be probably Pliocene in age, based on mammalian fossils. Stirton (in Phoenix, 1948) indicates an age of lower or middle Pliocene (the Pliocene was then considered to be from 13 to 1 m.y.), based on fossil horse remains. Mann (in Westgate and Knopf, 1932) states that diatoms taken from the Panaca Formation resemble some Pleistocene types found in Alabama, but may belong to the Pliocene. Although no direct correlation has been proven, the Panaca Formation is considered equivalent to the Muddy Creek Formation (Phoenix, 1948; Longwell and others, 1965; Tschanz and Pampeyan, 1970).

Younger Deposits

Unconsolidated, later Tertiary and Quaternary deposits of the study area have been generally described by Longwell and others (1965), Denny and Drewes (1965), Tschanz and Pampeyan (1970), and Cornwall (1972). Gravel and alluvium fanglomerates, deposited in fans and aprons along mountain fronts, cover large portions of the area. These dissected fans commonly contain poorly sorted, angular boulders and cobbles derived from the adjacent hills and mountains, and grade basinward into finer detritus. Locally the gravels are cemented with calcium carbonate. Although no fossil evidence is available, the fanglomerates are considered

younger than basin-range faulting and the Muddy Creek Formation, and older than Pleistocene lake beds of the region. Pleistocene lakes were present throughout much of the area and included lakes which are broadly correlated with Lahontan and Bonneville. Locally (i.e., in the Las Vegas Formation), there is evidence of a very shallow, marshy environment, rather than true lacustrine deposition (Longwell and others, 1965; M. Mifflin, personal commun.) Deposits from the Pleistocene lakes are predominantly silt and clay, locally containing mammalian and fresh water fossils.

Other Quaternary deposits include younger alluvial fans with surface pavements of angular rocks and networks of shallow arroyos. Recent surficial deposits are composed of alluvium in drainage channels and on flood plains, playa strata, dune sands and talus (Longwell and others, 1965; Tschanz and Pampeyan, 1970; Cornwall, 1972).

The distinction between Tertiary and Quaternary deposits is difficult and unclear due to their often similar appearance and also to the lack of detailed stratigraphic investigations of Cenozoic alluvium in this region.

PREVIOUS STUDIES

Tephrostratigraphic and tephrochronologic studies are relatively new, and although research in this field is rapidly expanding, there are few areas in the United States

where tephrochronologic sequences have been established or even attempted. Previous research in southern Nevada is minimal and sporadic. The earliest report is by Callaghan (Hewitt and others, 1936) of a nine foot thick ash layer in the Panaca Formation northwest of Panaca in Lincoln County. A partial chemical analysis is included with the report. Later, Phoenix (1948) indicated that this thick ash unit, clearly water-laid, supports lacustrine deposition of some of the Panaca Formation. *was obtained by Longwell (1951).*

The first radiometric dating of air-fall tuff in southern Nevada was reported by Tschanz (1960). The tuff, interbedded with the Horse Spring Formation near Glendale in Clark County, yielded a K-Ar age on biotite of approximately 24 m.y. Armstrong (1970) correlated the Horse Spring tuff from this same area with the Harmony Hills tuff of southwestern Utah (Mackin, 1960) on the basis of petrography and identical K-Ar ages of 21.3 ± 0.4 m.y. Marvin and others (1970a) obtained a K-Ar age of 29.4 ± 1.4 on biotite from an ash-fall bedded tuff in the Horse Spring Formation on the Nevada Test Site. Due to discrepancies with the previously determined ages of Horse Spring tuff, they postulated that the 29.4 m.y. date was anomalous or perhaps the Horse Spring Formation on the NTS was not time-correlative with the Horse Spring Formation exposed in Clark County. Anderson and others (1972), however, indicate that many beds of volcanic ash are interlayered with the Horse Spring Formation, and

Marvin and others (1970a) dated just one of these. Their (Anderson and others) K-Ar dates on Horse Spring Formation tuffs and lavas from Clark County range from 13.2-21.3 m.y. They report ages of 21.3 ± 0.4 m.y. and 19.6 ± 0.8 m.y. on biotite from a tuff near Glendale from about the same horizon as the tuff with the 24 m.y. date which was reported by Tschanz (1960). The base of the Horse Spring Formation in this area lies conformably on an ash layer for which a K-Ar biotite age of 23 m.y. was obtained by Longwell (1963).

There have been no reports of volcanic ash layers in the Muddy Creek deposits except for one air-fall tuff in the Hualapai Limestone Member of the upper Muddy Creek Formation at Lake Mead, dated at 8.44 ± 2.2 m.y. (Blair, 1978).

Two ash layers have been discovered in young alluvium in the Amargosa Desert southwest of the NTS. One layer, exposed in a discontinuous lens in a clay pit southwest of the NTS, has since been removed during mining excavations in the pit. The ash was one to two meters below the surface and yielded a K-Ar age of 3 m.y. (D.L. Hoover, personal commun.). The other layer is the 0.7 m.y. Bishop Ash (see following section), which has been found in a shallow wash in an alluvial fan northeast of Lathrop Wells (A.M. Sarna-Wojcicki, personal commun.) and in dune sands between Lathrop Wells and the NTS (Hoover and others, 1981). Correlation of these remnants with the Bishop Ash is made on

Point of Rocks Local (Pal) tephra layer (C.J. Carr, personal

the basis of major and minor element chemistry of glass shards, and petrography.

Two major tephrochronologic studies have recently been conducted in areas to the north and west of the present study area. The first of these was the tephrochronology of the Lake Lahontan area by Davis (1978), in which 20 different tephra layers were recognized, including the Mazama Ash (Crater Lake), the Bishop Ash, a St. Helens ash, and possibly one of the Pearlette Ashes (Yellowstone area). The tephra layers are characterized on the basis of petrography, major element chemistry of the glass shards by means of electron microprobe analysis, and glass shard morphology and refractive index. The second study is an ongoing research project, by Sarna-Wojcicki and others (1980), of Pliocene and Pleistocene tephra units in east-central and southern California, which are characterized primarily on the basis of minor and trace elements of the glass. In the lake beds of Pleistocene Lake Tecopa, near the California-Nevada border in southern Inyo county, California, they have identified the Pearlette type 0 ash (0.6 m.y.), the Bishop Ash (0.7 m.y.), and an ash chemically very similar to Pearlette type B ash (2.0 m.y.).

A single radiometric age determination already exists from one of the tephra layers in the present study. This is a fission track age of 11.5 ± 1.3 m.y. on zircon from the Point of Rocks Lower (PRL) tephra layer (W.J. Carr, personal

commun.). Carr indicates that the fanglomerate which contains the Point of Rocks tephra layers is similar to the 4 m.y. old Funeral Formation of southern Nevada (Hunt and Mabey, 1966) and the Osborn Wash Formation of southeastern California and northwestern Arizona (Dickey and others, 1980). Both formations are considered correlative with the Muddy Creek Formation discussed previously. The fanglomerate rests unconformably on tuffaceous and fine-grained sediments similar to the Pavit Spring Formation on the Nevada Test Site (Orkild, 1965).

Pleistocene Ash Layers in the Western United States

There are few sufficiently widespread ash falls in the United States which have been adequately studied to allow reliable correlations. Only two widely distributed ashes of Pleistocene age have been recognized in the western United States, the Bishop and the Pearlette ashes, and as a result they have received much attention and have been the object of much research. A third Pleistocene ash layer, from the Vallez Caldera in northern New Mexico, is not as widespread nor as thoroughly studied.

The Bishop Ash is a rhyolitic ash which has been recognized at numerous localities from California to Nebraska, and is correlated, on the basis of chemistry and petrography, with the 0.7 million year old Bishop Tuff from the Long Valley Caldera in eastern California (Izett and

others, 1970). Bailey and others (1976) estimate the volume of Bishop Ash distributed over the western United States was on the order of 300 km^3 . Air-fall pumice from the Bishop Tuff has been dated by both the potassium-argon and fission-track methods. Early attempts to date the Bishop Tuff (Evernden and others, 1959; 1964) gave erroneous ages due to the incorporation of vent material in the air-fall. Dalrymple and others (1965) obtained the currently accepted K-Ar age of 0.7 m.y., using sanidine separated from primary pumice fragments in the air-fall at the base of the Bishop Tuff. The 0.7 m.y. age was later supported by fission-track ages on zircons separated from pumice fragments in the Bishop Tuff air-fall (Izett and Naeser, 1976). Correlations between the Bishop Tuff of eastern California and the Bishop Ash bed from various localities in the western United States have been made using neutron activation analysis of the minor and trace element chemistry of the glass (Borchardt and others, 1972; Sarna-Wojcicki and others, 1980) and electron microprobe analyses of the major element chemistry of the glass (Izett and others, 1970). Sarna-Wojcicki and others (1980) determined, on the basis of minor element chemistry of the glass, that there are three very similar chemical types of Bishop Ash. They consider the three to be members of a single eruptive episode of short duration. In addition, there are other ash layers in the western United States which chemically resemble the Bishop Ash, but for

which a source area is not known (Izett and others, 1970; Izett and Naeser, 1976; Sarna-Wojcicki and others, 1980; Sarna-Wojcicki, personal commun.). The Bishop Ash bed has been found, among other places, in the Tecopa lake beds in eastern California (Sarna-Wojcicki and others, 1980), in alluvial fan sediment and sand dunes southwest of the Nevada Test Site (Hoover and others, 1981) and at several places in central and eastern Utah (Izett and others, 1970; 1972). The ash is generally chalky white and contains dominant biotite with lesser hornblende, quartz, sanidine, plagioclase and sparse zircon, apatite, allanite, sphene, ilmenite and magnetite (Izett and others, 1970). The glass shards are mostly pumiceous and have a refractive index which ranges from 1.492-1.499.

The Pearlette ashes were first described at localities in Kansas, by Swineford and Frye (1946), and thought to be a single ash fall, possibly from the Vallez Caldera in northern New Mexico (Swineford, 1949). Subsequent discoveries of the Pearlette ashes at localities as far west as California, and significant differences in mineralogy and chemistry from Vallez volcanic ejecta, later ruled out the Vallez Caldera as the source area (Izett and others, 1970). It has since been shown, on the basis of chemical and petrographic studies, that there are three Pearlette ash layers which closely correlate with three tuffs from the Yellowstone Park area in Wyoming and Idaho (Izett and others, 1971). The

three tuffs have been K-Ar dated at 1.96 m.y., 1.20 m.y., and 0.60 m.y., and correspond to the Pearlette type B, Pearlette type S, and Pearlette type O ashes, respectively (Naeser and others, 1973). The Pearlette ashes, from localities in Kansas, have also been dated by the fission-track method on zircons, and the resulting ages support their correlation with the three Yellowstone tuffs (Naeser and others, 1973). The Pearlette ashes occur at localities from California to Iowa, and have been correlated by neutron activation and electron microprobe analyses on the glass shards (Izett and others, 1970; 1971; 1972; Borchardt and others, 1972; Sarna-Wojcicki and others, 1980). Some localities of the Pearlette type O ash (0.6 m.y.) include the Tecopa lake beds in eastern California (Sarna-Wojcicki and others, 1980) and several exposures in central and eastern Utah (Izett and others 1970; 1972; Borchardt and others, 1972); where it is commonly found above the Bishop Ash. The Pearlette ash from the Lake Tecopa area varies slightly in chemistry between several samples, probably due to zonation in the magma chamber or to several closely spaced eruptions from the same chamber (Sarna-Wojcicki and others, 1980). Pearlette O ash is found near Rye Patch on the Humboldt River of northwestern Nevada (Davis, 1978; personal commun.). The Pearlette ashes are silver-gray and contain sparse phenocrysts of quartz, plagioclase, sanidine, clinopyroxene and hornblende

falls apart from many other late Cenozoic rhyolitic tuffs.

with minor chevkinite, allanite, zircon, apatite, magnetite, ilmenite, and rare fayalite. The glass shards are platy, nonvesicular, bubble-wall fragments with smooth, gently curved or straight edges, and have a refractive index which ranges from 1.498-1.500.

The Vallez-Toledo caldera complex of north-central New Mexico, once thought to be the source of the Pearlette ashes of the Great Plains, has produced two major rhyolitic ash flow units, which together comprise the Bandelier Tuff (Smith and Bailey, 1968). Air-fall pumice layers associated with the ash flow units are the Guaje Pumice Bed, K-Ar dated at 1.4 m.y., and the Tsankawi Pumice Bed, K-Ar dated at 1.1 m.y. (Doell and others, 1968). The ash which accompanied the two eruptions was presumably carried downwind and deposited in New Mexico and Texas (Izett and others, 1972). The Guaje ash bed has been discovered in northwestern Texas (Izett and others, 1972; Izett, 1977) and is correlated with the Guaje Pumice Bed on the basis of chemical analysis of the glass and petrography. The Guaje ash is light gray and contains phenocrysts of quartz, sanidine and clinopyroxene with minor chevkinite, allanite, magnetite, and ilmenite. It is similar in petrography to the Tsankawi Pumice Bed, except that the Tsankawi Pumice Bed contains hornblende. None of the units of the Bandelier Tuff contain plagioclase, a characteristic which sets the Bandelier ash-flows and ash falls apart from many other late Cenozoic rhyolitic tuffs.

The glass shards of the Guaje ash bed are platy bubble-wall and bubble-junction types, with some pumiceous shards, and range in refractive index from 1.497-1.499. Although the Guaje and Tsankawi pumice beds are petrographically similar, they can be distinguished by chemical analyses of the glass with the electron microprobe and neutron activation.

others, 1971; 1972; Sarna-Wojcicki, 1976; Sarna-Wojcicki and others, 1980), phenocryst assemblages (Wilcox, 1965; Trett and others, 1970; 1972; Bandle and others, 1971), glass shard morphology (Baiken, 1972; 1974), refractive index of the glass (Steen and Fryxell, 1965; Trett and others, 1970; 1972; Bandle and others, 1971; Hodder, 1978) and radiometric age determinations on glass and phenocryst components (Dalrymple and others, 1953; Dalrymple, 1967; Armstrong and others, 1970; Marvin and others, 1970a; Anderson and others, 1972; Nasser and others, 1973; Trett and Nasser, 1974).

Chemical analysis of the glass shards, as opposed to a bulk chemical analysis of the tephra, is preferred due to possible post-depositional changes in bulk chemistry, contamination due to addition of detrital material, or possible sorting effects during transport and deposition. i.e., one mineral phase may be preferentially concentrated relative to another (Wilcox, 1968; Smith and Westgate, 1969). A combination of methods is usually required to identify a volcanic

METHODS

There are several current methods of characterizing pyroclastic deposits; some are more effective than others. These include major, minor, and trace element chemistry of the glass (Izett and others, 1970; 1972; Borchardt and others, 1971; 1972; Sarna-Wojcicki, 1976; Sarna-Wojcicki and others, 1980), phenocryst assemblages (Wilcox, 1965; Izett and others, 1970; 1972; Randle and others, 1971), glass shard morphology (Heiken, 1972; 1974), refractive index of the glass (Steen and Fryxell, 1965; Izett and others, 1970; 1972; Randle and others, 1971; Hodder, 1978) and radiometric age determinations on glass and phenocryst components (Dalrymple and others, 1965; Dalrymple, 1967; Armstrong and others, 1970; Marvin and others, 1970a; Anderson and others, 1972; Naeser and others, 1973; Izett and Naeser, 1976).

Chemical analysis of the glass shards, as opposed to a bulk chemical analysis of the tephra, is preferred due to possible post-depositional changes in bulk chemistry, contamination due to addition of detrital material, or possible sorting effects during transport and deposition, i.e., one mineral phase may be preferentially concentrated relative to another (Wilcox, 1968; Smith and Westgate, 1969). A combination of methods is usually required to identify a volcanic

ash layer. (Wilcox, 1968; Borchardt and others, 1971; Wilcox and Izett, 1973).

The methods chosen for this study include

- (1) major element chemistry of the glass shards by electron microprobe analysis,
- (2) minor and trace element chemistry of the glass shards by X-ray fluorescence analysis,
- (3) petrographic examination,
- (4) refractive index determination of the glass shards,
- (5) isotopic age determination by the potassium-argon method.

The choice of methods was based primarily on two factors: the usefulness of the method in characterizing and correlating volcanic ash layers in previous studies, and the availability of the resources required for the analyses. Each of the procedures will be described here, except for the potassium-argon analysis, which is included in a later section.

FIELD PROCEDURE

The ash layers were located by first finding sediments reflecting geologic environments where conditions would have been favorable for the preservation of an ash blanket, such as a lake or an alluvial fan in which deposition was stable or continuous (Wilcox, 1968; Steen-McIntyre, 1977). Once such an area was found, erosional or man-made features which

would expose a buried ash layer, such as a stream channel or a roadcut, were sought. Primary air-fall or water-laid ash are considered to be most favorable for characterizing an ash layer (Steen-McIntyre, 1977), but most of the ash layers discovered were reworked to varying degrees. As Wilcox (1968) indicates, these reworked ashes are also suitable for characterization, as reworking takes place during the first few seasons after deposition and the secondary ash blanket can be considered the same as the original ash mantle, except for the addition of detrital contaminants.

Each ash layer was sampled, in the manner described below, photographed, and the stratigraphic relations and geologic detail recorded. Each layer was sampled at only one locality, although for some of the layers more than one sample was taken at a locality. No attempt was made to sample at multiple intervals along a layer. The exposures were not continuous enough to trace the layers for any considerable distance, a problem which Wilcox (1968) realized would be encountered in many areas. The layers could occasionally be traced for up to several hundred meters in either direction, but more often were observed to lens out abruptly. Due to this restricted exposure and/or preservation, additional sampling of the same layer would only have served to document variation within a layer due to depositional processes and reworking. It would be of considerable interest to try to follow a single distal ash

layer and to observe the range of chemical and petrographic parameters which might be produced due to the affects of transport and depositional mechanisms. Such extensive sampling and analyses were beyond the scope of this study.

Sampling Procedure

Samples were taken at two different times from each locality. Initially, small samples of 50 gm or less, for the microprobe and petrographic analyses, were taken from each layer by breaking out small chunks or scraping material from each layer, being careful to avoid surrounding sediment. Material was always taken from the basal few centimeters to take advantage of sorting effects during deposition which tend to concentrate a crystal-rich fraction at the base of the deposit, and also because primary air-fall ash may be at the base of a reworked deposit and would be expected to have less erosional contamination than the reworked material above it. The samples were placed in plastic ziplock bags and labeled.

Each layer was later re-sampled at the same localities to obtain bulk samples for potassium-argon dating and X-ray fluorescence analyses. Approximately 5-7 kg of sample were collected from each layer by breaking out large chunks and scraping away any sediment or rock fragments from the surfaces. Chunks were often broken open in the field and the laboratory to check for secondary lithic fragments. The

samples were placed in canvas or plastic sample bags and labeled.

ELECTRON MICROPROBE PROCEDURE

A few key major elements in volcanic glass may serve to distinguish volcanic ashes (Smith and Westgate, 1969). The electron microprobe is ideal for the determination of major element chemistry, as it allows analysis of single shards to the exclusion of any contaminants, thereby avoiding the necessity of preparing a glass concentrate from each sample. In addition, the probe allows for the avoidance of inclusions and bubbles within shards so that more accurate results may be obtained (Smith and Westgate, 1969; Westgate and Fulton, 1975), and it is also able to detect heterogeneity within a sample, indicating the possible presence of shards from two or more eruptions.

Sample Preparation

Approximately 2-3 cc (thumb size portion) of each tephra sample was placed in dilute HCl (to remove carbonate), followed by chlorine bleach (to remove organic material), and finally citrate-dithionite (to remove iron coatings); each step was followed by several rinses in distilled water and ultrasonic cleaning. The clean dry samples were sieved through brass U.S.D.A. 2-inch soil sieves and the size fractions, ranging from coarse silt (<300-mesh) to coarse sand (>16-mesh), were placed in separate vials. Most

samples were composed predominantly of coarse silt, very fine sand, and fine sand. Clean sample from this preparation was later used in the refractive index and petrographic procedures.

A small portion of the fine sand fraction from each sample was embedded in petrographic epoxy in an electron microprobe mount made of Buehler petrographic epoxy. The sample was ground on 400 and 600 grit silicon carbide papers to expose the grains and polished with diamond abrasives to smooth the surface. The polished surface was coated with a thin film of carbon to provide conductivity during analysis.

Microprobe Analysis

The samples were analyzed by J.O. Davis and myself at the U.S. Geological Survey in Menlo Park, California, using an Applied Research Laboratories EMX electron microanalyzer fitted with three crystal channels. The method used is similar to that of Smith and Westgate (1969), except that glass was not separated from the bulk sample before mounting. The instrumental conditions are listed in Table 1. Eleven elements were determined - Si, Al, Fe, Mg, Mn, Ca, Ba, Ti, Na, K, and Cl - during four separate runs on the three channel system (i.e., one element per channel was determined during each run). Twenty 10-second counts, with a stationary beam (except for Na and K, for which the beam

TABLE 1
Electron Microprobe Operating Conditions and Procedures

Instrument	Applied Research Laboratories EMX
Accelerating potential	15 kV
Beam current	0.1 microamperes
Sample current	0.01 microamperes
Spot Size	1 micron (focussed, stationary) Si, Al, Fe, Mg, Mn, Ca, Ba, Ti, Cl ~10 micron (focussed, scanning) Na, K
Crystal Channels	3, detecting simultaneously
Crystals	(LiF) lithium fluoride - Fe, Mn, Ba, Ti (ADP) ammonium dihydrogen phosphate - Si, Ca, K, Cl (TAP) thallium acid phthalate - Al, Mg, Na
Counting times	Within 4% of 10 seconds for each analysis; determined by current digitizer reading reference beam current relative to Faraday Cup.
Pulse-height discrimination	used to reduce background.

procedures are identical to those used by Sato-Majumdar and others (1980); the procedure was developed by Charles Meyer, USGS, Menlo Park, California.

The standard deviation for the atomic weight percent was calculated for each element analyzed, using the equation:

was scanned in a raster pattern about 10 μ on a side) were made on each sample for each element determined; four shards were analyzed three times and eight other shards analyzed once, for a total of 20 counts per sample per element.

(Smith and Westgate (1969) made 20 5-second counts on 20 grains, but this technique was later improved (Westgate and Fulton, 1975) by increasing the counts to 20 seconds.)

Mineral grains and detrital or lithic material were easily avoided during analysis due to differing cathodoluminescence and chemical composition, as well as shape. Glass shards were distinguished on the basis of morphology (shape, fracture, vesicles, etc.) and reflectivity. Inclusions were avoided by observing cathodoluminescence and also by listening for changes in the count rate (Westgate and Fulton, 1975).

Analysis were corrected for background, using USGS standards. The data was reduced using a PDP 11 computer and the FRAME 60 program. The microprobe, standards, and procedures are identical to those used by Sarna-Wojcicki and others (1980); the procedure was developed by Charles Meyer, USGS, Menlo Park, California.

The standard deviation for the atomic weight percent was calculated for each element analyzed, using the equation:

$$\sigma = (K \text{ Std. Dev.}/K\text{-value}) \times \text{At. Wt. } \%$$

where σ is the standard deviation of the measured concentration of the element, the K-value is the ratio of 10-second counts on the glass to 10-second counts on the USGS standards used, and K Std. Dev. is the standard deviation of the K-value (calculated by the computer). The standard deviations for each element are represented by the \pm figures with the values in the microprobe results (Table 4). These are the one sigma errors inherent in the analyses themselves.

Additional microprobe analyses were performed by Charles Meyer of the U.S. Geological Survey, Menlo Park, California. The glass was taken from the pure glass samples which were prepared for the X-ray fluorescence analyses (see X-ray Fluorescence Procedure). He analyzed one sample from each ash layer, using the same microprobe, standards, data reduction program, and similar operating conditions to those previously described, except his counts were 15 seconds instead of 10 seconds. The samples are labeled T25-1 through T25-7. Standard deviations were not calculated.

X-RAY FLUORESCENCE PROCEDURE

Minor and trace element chemistry has been successful in chemically "fingerprinting" volcanic glass from several areas (Theisen and others, 1968; Jack and Carmichael, 1968; Borchardt and others, 1971; Randle and others, 1971; Sarna-

Wojcicki, 1976; Sarna-Wojcicki and others, 1979; 1980). Neutron activation is probably the most definitive method of correlation, as it provides the most accurate data on concentrations of a large number of elements, but it is expensive, slow, and hard to obtain (Sarna-Wojcicki, written commun.). X-ray fluorescence has also proved to be very useful and accurate (Jack and Carmichael, 1968; Sarna-Wojcicki, 1976; written commun.; Sarna-Wojcicki and others, 1979), and analyses by this method were readily obtainable.

Sample Preparation

X-ray fluorescence analysis requires the use of very pure glass concentrates, as individual shards cannot be analyzed. Phenocrysts, microlites or lithic fragments can change the trace element compositions by addition or dilution of elements relative to pure glass (Sarna-Wojcicki and others, 1979). Groundwater contamination may have a similar effect. For this reason the glass must be relatively fresh and the glass concentration must be very pure.

The samples were crushed using an iron pestle and buckboard (it is assumed that any metal contamination the samples may have received from the pestle was later removed in the HCl, HF, and heavy liquid procedures). The crushed material was then sieved through nylon screens in a set of plastic sieves specially constructed out of 8-inch PVC pipe

(see K-Ar preparation for details). The nylon screens were changed after each sample so as to avoid contamination from other samples. The 100-170-mesh size fraction was chosen (rather than the 60-100-mesh fraction) as this reduces the number of glass shards containing microlites or phenocrysts (Sarna-Wojcicki and others, 1979). This fraction was placed in a methylene iodide-acetone or bromoform-neothene mixture in a separatory funnel and the crystal and glass fractions tapped off separately using a filter-funnel-vacuum flask arrangement. The glass fraction was rinsed several times in acetone, dried under a heat lamp, treated in a 10% reagent grade HCl solution, rinsed several times, etched in 5% reagent grade HF, rinsed several times, wet-sieved through the 100-170-mesh nylon screen, and dried in an oven. The sample was placed in an electromagnetic separator and run through repeatedly at varying currents to further remove any remaining phenocrysts or glass which was altered, devitrified or contained microlites; the purity was monitored regularly with a petrographic microscope. For one sample (PVL), the heavy liquid separation and following steps had to be repeated, as this sample contained a high proportion of altered and microlitic glass shards. All separations were 98-99% pure.

Analytical Procedure

Further preparation of the samples and the X-ray

fluorescence analyses were performed at the U.S. Geological Survey, Menlo Park, California, by M.J. Woodward. Approximately 0.5 grams of the glass from each sample was packed into plastic holders and analyzed in a Kevex Energy Dispersive X-ray Fluorescence Spectrometer. The glass was analyzed for K, Ca, Ti, Mn, Fe, Cu, Zn, Rb, Sr, Y, Zr, and Nb.

REFRACTIVE INDEX DETERMINATION

Although the glass from a single ash sample may have a range of composition (and therefore a range of refractive index), it is to be expected that most of this range will be present in almost every sample of the ash (Wilcox, 1968). In addition, Steen and Fryxell (1965) have shown that weathering has little effect on the modal refractive indices of glass from the eruptions of Mount Mazama and Glacier Peak, increasing confidence that this is a reliable characteristic by which to distinguish volcanic glasses. Smith and Westgate (1969) indicate this method may not be very useful in cases where there are only minor variations in glass chemistry because the distribution of indices of the various glasses overlap.

Sample Preparation

A small amount of clean glass from the X-ray fluorescence preparation was used for the refractive index determination. If enough sample was not available, approximately

0.5 gm of the very fine sand fraction (140-300-mesh) from the electron microprobe preparation was etched in HF and then run through an electromagnetic separator at various currents to concentrate the glass fraction.

Determination of Refractive Index

The refractive index determinations were made with a petrographic microscope using sodium light (wavelength=590 nanometers) from a Bausch and Lomb High Intensity Monochromator with a tungsten light source. Room temperature and the microscope stage temperature were closely monitored and found to remain essentially constant and to differ from each other by less than 1°C. The glass shards were examined on a microscope slide, under a cover slip, using Cargille immersion oils at 0.002 intervals. The refractive index was determined by the Becke line method and the mode and range for each sample was recorded. If a shard's index was between two oils, it was assumed that the index was exactly halfway between the two. Temperature corrections for the refractive index determinations for each sample were made to account for temperature dispersion effects. Accuracy of the oils was checked with an Abbe refractometer. The measurements for each sample are accurate to 0.001, except in sample PVL, which contained two distinct populations of

glass shards, each of which exhibited an unusually wide range in refractive index.

PETROGRAPHIC PROCEDURE

The characterization of the phenocryst assemblage of an ash layer has been used in numerous studies as an aid in distinguishing different ash falls and ash-flows. (Allison, 1945; Izett and others, 1970; Randle and others, 1971; Mullineaux and others, 1975; Westgate and Fulton, 1975; Ekren and others, 1980). The main problems with this method are 1) sorting may take place during transport and deposition, so that mineral phases may become concentrated or depleted relative to their original proportions, 2) post-depositional reworking may add detrital contaminants (Smith and Westgate, 1969). However, as Wilcox (1968) states, it is not likely that an ash fall will have one set of primary phenocrysts at one locality and another set at a different locality, and although the proportions may vary from place to place, rarely will a primary phenocryst be entirely lacking in a sample. It should be stressed, therefore, that importance is not placed so much on the overall percentages of phenocrysts, but rather on relative abundances of phenocrysts and the presence or absence of a phenocryst species, except in the case of minor and trace quantities where a certain species may not be observed, despite the fact that it is a constituent.

Microscope Analysis

Mineral identification in ash samples was found to be more difficult than standard thin-section identification. This was primarily due to the small size of the phenocrysts, variations in thickness among grains, and difficulty in discerning internal cleavages and in obtaining interference figures on each grain. Relief, habit, color, and interference figures, when satisfactory, were found to be most useful in identification, whereas birefringence and cleavage were of little help. The very fine sand fraction (140-300-mesh), from the electron microprobe preparation procedure, was used due to the higher proportion of phenocrysts in this size fraction than in the fine sand fraction (60-140-mesh).

Epoxy grain mounts were originally prepared for the microscopic examination by mixing a small amount of sample into petrographic epoxy on a microscope slide and applying a cover slip. Difficulties were then encountered in distinguishing among the feldspars and quartz, especially when plagioclase lacked twinning. Clove oil as an immersion medium was found to greatly facilitate identification due to its high dispersion. In clove oil (R.I.= 1.54) sanidine exhibits an orange dispersion rim (index slightly lower than oil) and plagioclase exhibits a blue dispersion rim (index slightly higher than oil). Quartz is distinguished on the basis of its slightly positive relief, common conchoidal

fracture, frequent "bull's-eye" birefringence pattern, and uniaxial positive figure. In addition to its favorable optical properties, clove oil is inexpensive, readily obtainable (from any drugstore), and nontoxic.

The oil immersion mounts were made by mixing a small amount of sample into a few drops of clove oil on a microscope slide. Grain counts were made, using a petrographic microscope with a mechanical stage. After a preliminary examination to determine percent phenocrysts in the sample, 100 mineral grains were counted and tallied on the basis of mineral species. A second and third slide were also prepared and 100 grains counted; the three counts were averaged together to give the primary phenocryst percentages of each tephra sample. If the phenocryst percentage of a sample was so sparse that a slide contained less than 100 mineral grains, then additional slides were counted until a total of 100 grains were counted, rather than having three separate counts of 100. Only those grains with adhering glass or which appeared to be fresh, angular cleavage fragments were counted. Obvious rounded, altered or otherwise detrital-looking grains were not included, but their presence was noted (Appendix II). Although, as stated previously, the presence and relative abundances of species are the important parameters in the petrographic examination, this method

of recording serves as a means of documenting the phenocryst assemblage of each specimen. ~~romeror. The samples were~~

Glass shard morphology was also recorded by counting 100 grains and tallying according to type. The shards are divided into six categories on the basis of vesicularity or shape and fracture pattern. Vesicular shards are categorized on the basis of containing pipe-like (pipes), elongate (spindles), or spherical (vesicles) vesicles or a mixture of these types (mix). Nonvesicular shards are categorized on the basis of shape and fracture; blocky shards are termed chunks and thin, platy shards or Y-shaped bubble-junction types are termed shatter.

Scanning Electron Microscope Analysis

As a means of verifying the microscopic identification of minerals present, several samples were also analyzed using a scanning electron microscope which identifies mineral species by a semi-quantitative analysis of their chemical composition.

Approximately 0.5 gm of very fine sand (140-300-mesh), from the electron microprobe preparation, was embedded in a Buehler petrographic epoxy ring mold and then ground and polished using silicon carbide paper and diamond abrasives.

The surface was coated with a thin film of carbon to provide conductivity. The samples were analyzed on an International Scientific Instruments Super III A Scanning

Electron Microscope equipped with a Princeton Gamma Tech energy-dispersive X-ray spectrometer. The samples were analyzed by scanning the polished surface and probing any phenocrysts encountered. The species were identified by observing their major element spectrums. In addition, scanning electron photomicrographs of tephra from each sample were taken utilizing back scatter electrons as the imaging medium due to their sensitivity to differences in average atomic weight (i.e., heavy minerals will be brighter than light minerals).

to a locality of that name on the state and county maps of Nevada, is to the south of the N75, along U.S. Highway 95 (see Figure 1). Two fine grained, pale gray tephra layers are exposed, in stratigraphic succession, in an alluvial fan consisting of Proterozoic and Paleozoic clasts derived from the nearby mountain ranges. Figure 2 (a,b) shows the tephra and the fan in which they occur. The Point of Rocks Lower (PRL) ash layer, varying in thickness from 20-45 cm, is discontinuous in exposure and occurs approximately five meters below the Point of Rocks Upper (PUL) ash layer, which is 10-20 cm thick and also discontinuous in exposure.

The second locality, to the east of the N75, is here called the Badlands due to its distinctive topography. It is located approximately 13 miles (~21 km) northwest of Moapa, Nevada (see Figure 1), just south of State Highway 168 (old Highway 7). Two tephra layers are exposed here in

FIELD RELATIONS

Seven tephra layers were discovered in areas to the south, east and northeast of the Nevada Test Site (see Appendix I for detailed sample locality and geologic descriptions). All of the tephra layers occur in alluvial deposits which are considered to be part of either the Muddy Creek Formation or its time-correlative equivalents.

The first locality, here named the Point of Rocks due to its proximity to a locality of that name on the state and county maps of Nevada, is to the south of the NTS, along U.S. Highway 95 (see Figure 1). Two fine-grained, pale gray tephra layers are exposed, in stratigraphic succession, in an alluvial fan consisting of PreCambrian and Paleozoic clasts derived from the nearby mountain ranges. Figure 2 (a,b) shows the tephra and the fan in which they occur. The Point of Rocks Lower (PRL) ash layer, varying in thickness from 20-45 cm, is discontinuous in exposure and occurs approximately five meters below the Point of Rocks Upper (PRU) ash layer, which is 10-20 cm thick and also discontinuous in exposure.

The second locality, to the east of the NTS, is here called the Badlands due to its distinctive topography. It is located approximately 13 miles (~21 km) northwest of Moapa, Nevada (see Figure 1), just south of State Highway 168 (old Highway 7). Two tephra layers are exposed here in



Figure 2a. Upper tephra layer at the Point of Rocks locality (PRU).



Figure 2b. Lower tephra layer at the Point of Rocks locality (PRL), several hundred meters east of location shown in Figure 2a. The ash fills a channel.

stratigraphic succession in a sequence of lake sediments that have been dissected to form badlands topography (Figure 3a,b). Both of the water-laid tephra layers are fine-grained and fairly uniform in thickness. The Badlands Lower (BL) layer is silvery gray and approximately 30-40 cm thick; it is distinctly different in appearance from the dark, greenish gray 30 cm thick Badlands Upper (BU) layer approximately five meters above it.

The third locality, here named Pahrnagat Valley for its occurrence in this valley, is northeast of the NTS along State Highway 93, several miles (~6 km) south of Alamo, Nevada (see Figure 1). Three tephra layers are exposed; two in the wall of a gully cut into an alluvial fan composed of poorly sorted volcanic clasts in a tuffaceous matrix, and a third layer in the roadcut above and just south of the gully (Figure 4a,b). All three ash layers are fine-grained, have limited exposure of 10-20 m or less, and dip gently westward with the tilt of the alluvial fan. The Pahrnagat Valley Lower (PVL) layer is light gray, approximately 10 cm thick, and occurs three meters below the buff-colored Pahrnagat Valley Upper (PVU) layer which varies in thickness from 5-15 cm. Both layers contain abundant foreign lithic clasts. The Pahrnagat Valley Roadcut (PVR) layer, approximately 13 meters above the highway, is pale gray, 10-12 cm thick, and moist from groundwater.



Figure 3a. The Badlands tephra locality; a sequence of lake sediments north of Moapa, Nevada.

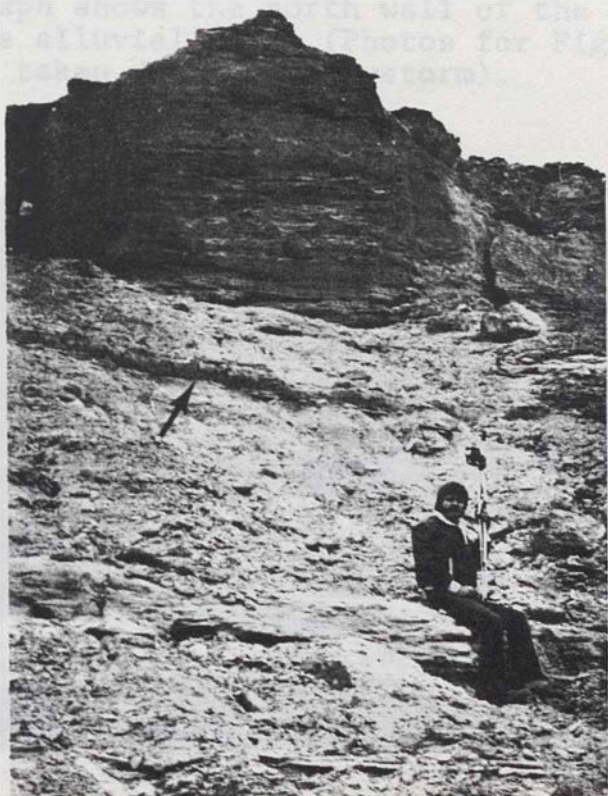


Figure 3b. The Badlands Lower (BL; man sits upon) and Badlands Upper (BU; dark, thin layer above) tephra layers, below a thick, dark carbonate layer capping the lake sediments.



Figure 4a. The Pahrnagat Valley tephra locality. Photograph shows the north wall of the gully cut in the alluvial fan. (Photos for Figures 4a and 4b taken during a snowstorm).



Figure 4b. The Pahrnagat Valley Lower (PVL) and Upper (PVU) tephra layers. The Roadcut layer (PVR) occurs approximately 100 meters south of the gully exposure.

CHEMICAL AND PETROGRAPHIC RESULTS

One sample from each of the seven tephra layers was characterized petrographically according to mineralogy, glass shard morphology, and glass refractive index. The data is presented in Tables 2 and 3 and in Appendix II.

Electron microprobe analyses of the major element chemistry of the glass shards were performed on two or three samples from each tephra layer so as to indicate chemical homogeneity within a single layer. The results are shown in Table 4. X-ray fluorescence analyses of the minor and trace element chemistry of the glass was performed on one sample from each tephra layer. The results, given in Table 5, represent normalized peak intensity for each of the elements analyzed, rather than element concentrations.

PETROGRAPHY OF THE TEPHRA LAYERS

Mineralogy

The phenocryst assemblages of all the tephra layers exhibit detrital contamination to varying degrees. This is apparent from the presence of subrounded to rounded, altered and/or corroded phenocrysts in the crystal fraction of each tephra sample. These phenocrysts were excluded from the grain counts, but their presence and estimated percentages were recorded (see Appendix II).

Table 2. Petrography of the tephra layers. See Appendix II for detailed descriptions and explanation of categories. Values represent percentages.

Minerals	Pt of Rocks		Badlands		Pahranagat Valley		
	Lower (PRL)	Upper (PRU)	Lower (BL)	Upper (BU)	Lower (PVL)	Upper (PVU)	Roadcut (PVR)
Plagioclase	64	36	25	46	25	38	53
Sanidine	11	9	10	-	6	19	33
Quartz	9	14	45	26	10	22	8
Biotite	1	25	8	3	28	5	-
Hornblende	-	5	1	2	27	6	1
Clinopyroxene	4	-	4	7	-	4	2
Orthopyroxene	4	-	-	5	-	-	-
Apatite	-	1	-	-	-	-	-
Zircon	2	4	4	4	1	1	-
Opagues	5	6	3	7	3	5	3
GLASS SHARDS							
Pipes	20	30	4	32	8	40	38
Spindles	10	30	4	3	-	7	-
Vesicles	8	8	-	5	72	19	7
Mix	9	7	-	3	6	7	2
Chunks	38	22	-	-	12	22	6
Shatter	15	3	92	57	2	5	47

Table 3. Refractive index of the glass

	<u>Mode</u>	<u>Range</u>
Point of Rocks Lower (PRL)	1.497	1.496-1.498
Point of Rocks Upper (PRU)	1.497	1.494-1.498
Badlands Lower (BL)	1.499	1.498-1.501
Badlands Upper (BU)	1.521	1.519-1.522
Pahranagat Valley Lower (PVL)	(a) 1.498	1.496-1.502
	(b) 1.510	1.507-1.512
Pahranagat Valley Upper (PVU)	1.498	1.495-1.500
Pahranagat Valley Roadcut (PVR)	1.503	1.501-1.504

Table 4. Electron microprobe analyses of glass from the southern Nevada tephra layers

Lab No. At. Wt. %	Point of Rocks Tephra						Badlands Tephra				Pahrangat Valley Tephra					
	Lower (PRL)			Upper (PRU)			Lower (BL)		Upper (BU)		Lower (PVL)		Upper (PVU)		Roadcut (PVR)	
	LM1	LM4	T25-2	LM-2	LM-5	T25-6	LM3	T25-7	LM11	T25-3	LM7	T25-4	LM10	T25-1	LM6	T25-5
Si	34.350 ± .485	33.845 ± .612	32.835	34.205 ± .850	34.988 ± .482	33.504	33.928 ± .540	33.101	30.723 ± .561	29.552	32.136 ± .857	33.476	34.739 ± .715	33.129	33.690 ± .499	32.249
Al	6.371 ± .221	6.274 ± .178	6.250	6.206 ± .177	6.279 ± .171	6.287	6.287 ± .185	6.227	7.525 ± .256	7.281	7.452 ± .295	6.305	6.458 ± .268	6.409	6.862 ± .202	6.782
Fe	0.888 ± .055	0.820 ± .071	0.861	0.507 ± .036	0.534 ± .055	0.519	0.935 ± .050	0.907	3.229 ± .208	3.210	1.055 ± .109	0.501	0.686 ± .151	0.810	1.059 ± .059	1.031
Mg	0.022 ± .006	0.013 ± .007	0.021	0.033 ± .012	0.030 ± .010	0.033	0.033 ± .009	0.037	0.270 ± .030	0.303	0.113 ± .025	0.032	0.031 ± .015	0.043	0.081 ± .009	0.090
Mn	0.021 ± .017	0.025 ± .021	0.027	0.022 ± .019	0.033 ± .016	0.041	0.021 ± .020	0.027	0.103 ± .027	0.121	0.042 ± .018	0.051	0.038 ± .024	0.024	0.025 ± .024	0.048
Ca	0.371 ± .049	0.329 ± .058	0.311	0.379 ± .046	0.387 ± .049	0.378	0.373 ± .052	0.346	1.241 ± .109	1.306	0.896 ± .156	0.404	0.355 ± .062	0.388	0.558 ± .045	0.536
Ba	0.060 ± .045	0.059 ± .044	0.038	0.049 ± .039	0.056 ± .041	0.044	0.046 ± .036	0.030	0.07 ± .035	0.062	0.126 ± .047	0.001	0.032 ± .040	0.045	0.045 ± .032	0.039
Ti	0.057 ± .019	0.057 ± .018	0.051	0.056 ± .017	0.072 ± .019	0.056	0.080 ± .015	0.070	0.318 ± .040	0.349	0.145 ± .036	0.075	0.087 ± .021	0.069	0.109 ± .021	0.106
Na	2.238 ± .158	2.109 ± .134	2.319	1.950 ± .067	1.910 ± .071	2.179	2.173 ± .106	2.378	3.839 ± .276	4.556	1.474 ± .279	2.227	2.066 ± .238	2.436	2.486 ± .617	2.818
K	4.378 ± .285	4.425 ± .247	4.264	4.038 ± .279	4.713 ± .166	4.201	4.376 ± .232	4.305	1.700 ± .128	1.682	4.842 ± .241	4.405	4.702 ± .298	4.193	3.731 ± .938	3.557
Cl	0.103 ± .035	0.119 ± .032	0.108	0.052 ± .027	0.067 ± .044	0.054	0.132 ± .026	0.117	0.116 ± .027	0.070	0.164 ± .031	0.126	0.080 ± .036	0.065	0.062 ± .023	0.034
Wt. % Oxide																
SiO ₂	73.481	72.399	70.238	73.169	74.845	71.669	72.578	70.807	65.721	63.217	69.385	71.611	74.313	70.868	72.068	68.985
Al ₂ O ₃	12.037	11.855	11.810	12.663	11.864	11.880	11.879	11.766	14.218	13.757	14.080	11.914	12.202	12.110	12.966	12.814
FeO	1.270	1.172	1.167	0.723	0.764	0.743	1.337	1.297	4.617	4.592	1.509	0.717	0.980	1.158	1.515	1.443
MgO	0.036	0.022	0.035	0.055	0.049	0.054	0.055	0.061	0.448	0.502	0.187	0.054	0.052	0.071	0.135	0.148
MnO	0.027	0.032	0.035	0.028	0.042	0.053	0.027	0.035	0.133	0.156	0.054	0.065	0.049	0.031	0.032	0.062
CaO	0.519	0.461	0.435	0.531	0.541	0.530	0.522	0.484	1.737	1.828	1.253	0.565	0.497	0.543	0.781	0.749
BaO	0.067	0.066	0.042	0.055	0.062	0.049	0.052	0.033	0.079	0.070	0.141	0.001	0.036	0.050	0.050	0.043
TiO ₂	0.094	0.095	0.085	0.093	0.119	0.093	0.133	0.177	0.531	0.582	0.242	0.125	0.145	0.115	0.182	0.177
Na ₂ O	3.016	2.842	3.126	2.629	2.574	2.938	2.929	3.205	5.175	6.141	1.987	3.002	2.785	3.283	3.351	3.798
K ₂ O	5.274	5.331	5.136	4.865	5.678	5.061	5.272	5.186	2.048	2.026	5.833	5.306	5.664	5.050	4.494	4.285
Cl	0.103	0.119	0.108	0.052	0.067	0.054	0.132	0.117	0.116	0.070	0.164	0.126	0.080	0.065	0.062	0.034

Table 5. X-ray fluorescence analyses of glass from the southern Nevada tephra layers [Values represent relative peak intensities]

	SAMPLES						
	PRL	PRU	BL	BU	PVL	PVU	PVR
K	1165	1602	1039	194	1420	1229	986
Ca (K α)	265	366	231	192	325	278	283
Ca (K β)	38	55	36	36	48	42	44
Ti	106	144	112	152	124	122	143
Mn	87	193	120	176	261	98	93
Fe (K α)	5281	4525	5301	6411	4568	5175	5511
Fe (K β)	859	739	874	1033	743	846	896
Cu	65	74	54	20	171	65	56
Zn	132	125	188	80	219	114	92
Rb	1958	1735	1630	357	2130	1923	1719
Sr	487	1191	318	1716	873	538	641
Y	1114	716	1184	639	872	872	758
Zr	2358	1925	2510	3904	1899	2635	3016
Nb	535	633	1113	466	738	551	514

The percentage of phenocrysts in each tephra sample ranges from 2-25%. The tephra layers composed predominantly of platy, nonvesicular bubble-wall shards, such as the Badlands layers (see Figure 5a,b) contain very low percentages of phenocrysts, whereas the tephra layers composed predominantly of pumiceous shards contain higher percentages of phenocrysts.

Plagioclase, sanidine and quartz are ubiquitous in the samples and are therefore undiagnostic. One exception is in the Badlands Upper layer (BU) where sanidine is completely absent, providing a unique petrographic distinction. Biotite is also present in all except one sample (Pahranagat Valley Roadcut-PVR), but it varies considerably in abundance among the different layers. It is generally present in only trace or minor amounts, although in two samples, Point of Rocks Lower and Pahranagat Valley Lower, it is a major constituent of the phenocryst assemblages. This wide range in variation makes biotite one of the more diagnostic phases. Although most of the biotite is green (in plane polarized light), several samples contain some reddish brown biotite. Hornblende exhibits a range in variation similar to biotite, generally being sparse to absent, except for a striking abundance in Pahranagat Valley Lower. At the Point of Rocks locality the presence of hornblende in the upper layer (PRU) and not the lower (PRL) serves to distinguish the two layers. Small amounts of clinopyroxene

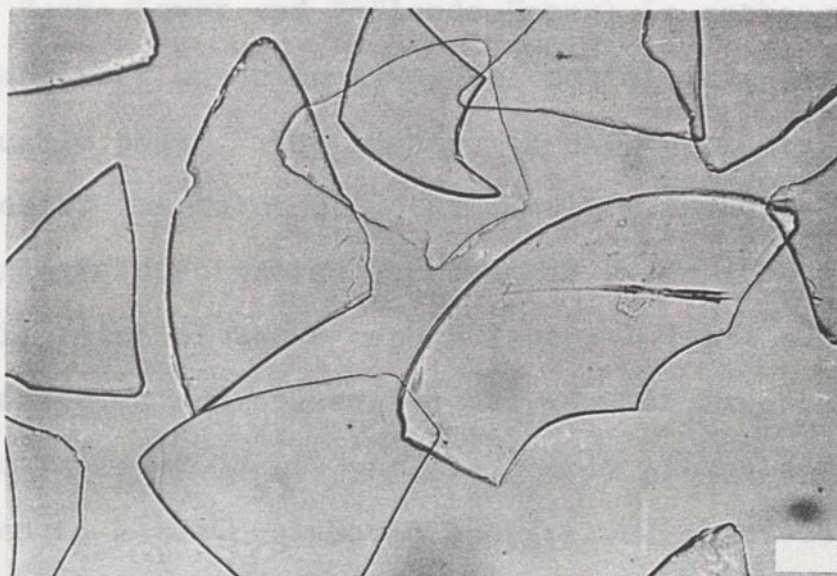


Figure 5a. Platy glass shards from the Badlands Lower tephra. Scale bar = 50 μm .

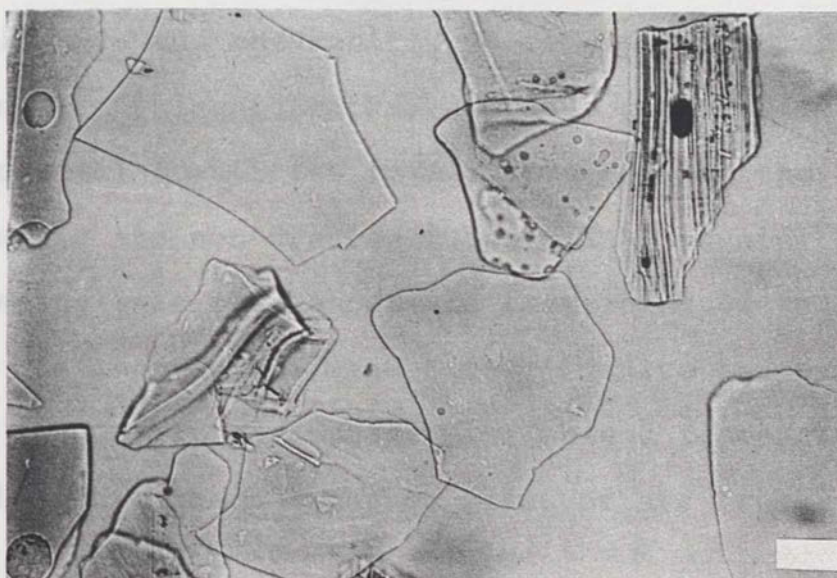


Figure 5b. Platy and vesicular glass shards from the Badlands Upper tephra. Scale bar = 50 μm .

are common in most of the layers, but in only two layers (Point of Rocks Lower and Badlands Upper) is orthopyroxene also present with the clinopyroxene, making it a particularly valuable phase. The absence of any pyroxenes in the upper layer at the Point of Rocks locality further supports the mineralogic distinction between the Upper (PRU) and Lower (PRL) Point of Rocks tephra layers. Trace to small amounts of zircon are present in all samples except Pahranaagat Valley Roadcut, and are nearly always euhedral and encased in glass. Although apatite was observed only in Point of Rocks Upper, it is probably a trace constituent in several if not all of the samples, having been missed in the grain counts due to its scarcity. Other trace phenocrysts may also have been missed in some of the samples. (For example allanite and chevkenite, which are common trace constituents in volcanic rocks). Opaque phenocrysts are present in small quantities in all samples, but the individual species are not distinguished. The Scanning Electron Microscope analysis of phenocrysts from Point of Rocks Lower indicates the opaques are magnetite, ilmenite and pyrrhotite (?). The phenocryst percentages in Table 2 represent only those grains which have adhering glass or are fresh, angular fragments (Figure 6).

Glass Shard Morphology

The glass shards consist of two very distinct types: pumiceous (vesicular) shards and dense (non-vesicular) shards. The pumiceous shards differ in the shape and quantity of vesicles and the dense shards differ in shape, being either chunky or glassy fragments. All of the samples contain both types of shards, although not necessarily in equal proportions.

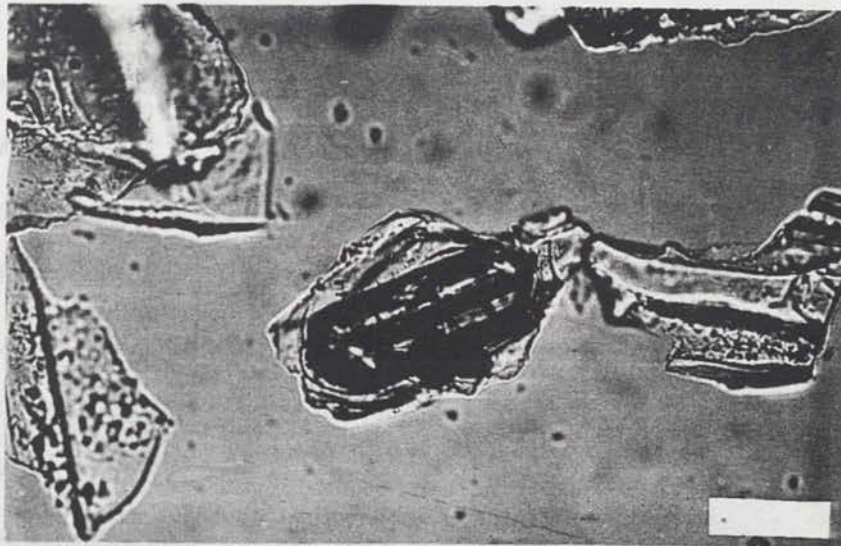


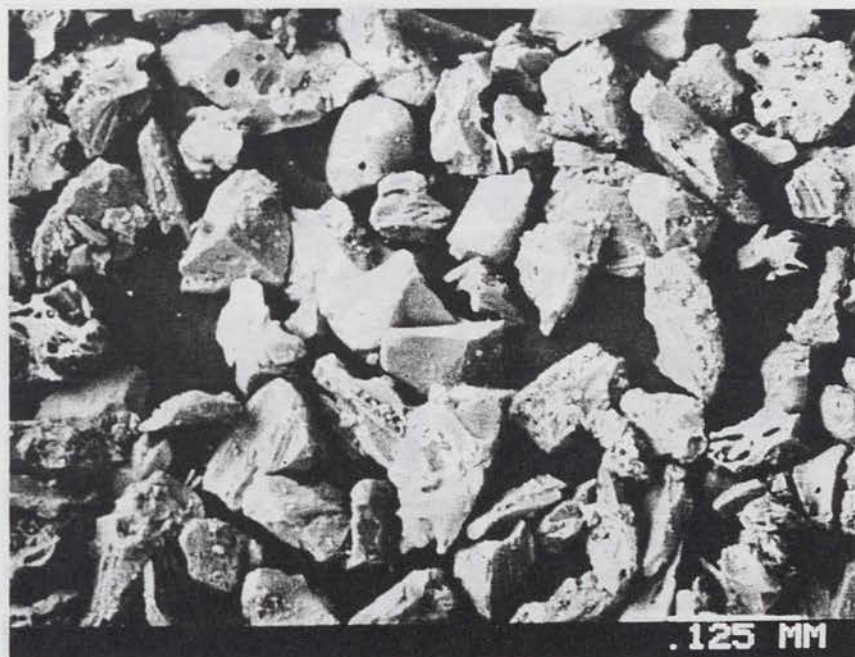
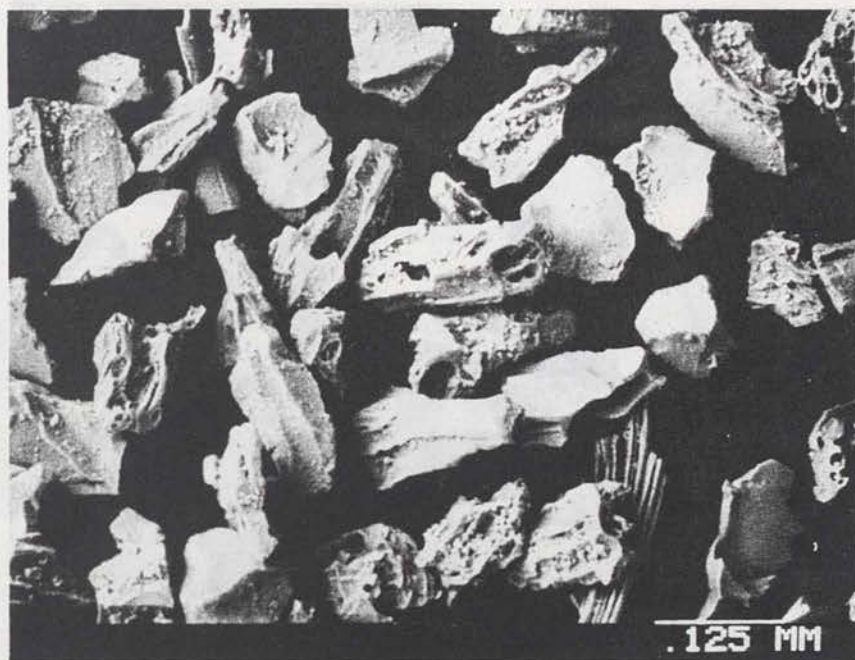
Figure 6. Zircon crystal encased in glass, from the Point of Rocks Lower tephra. Scale bar = 50 μm .

The glass shards in all samples except Subaqueous Valley Lower (SVL) are fresh and unhydrated, but they are hydrated as evident from their fluid-filled vesicles. The SVL shards exhibit partial devitrification, which appears to be clay. Colored glass is rare to absent in all samples.

Glass Shard Morphology

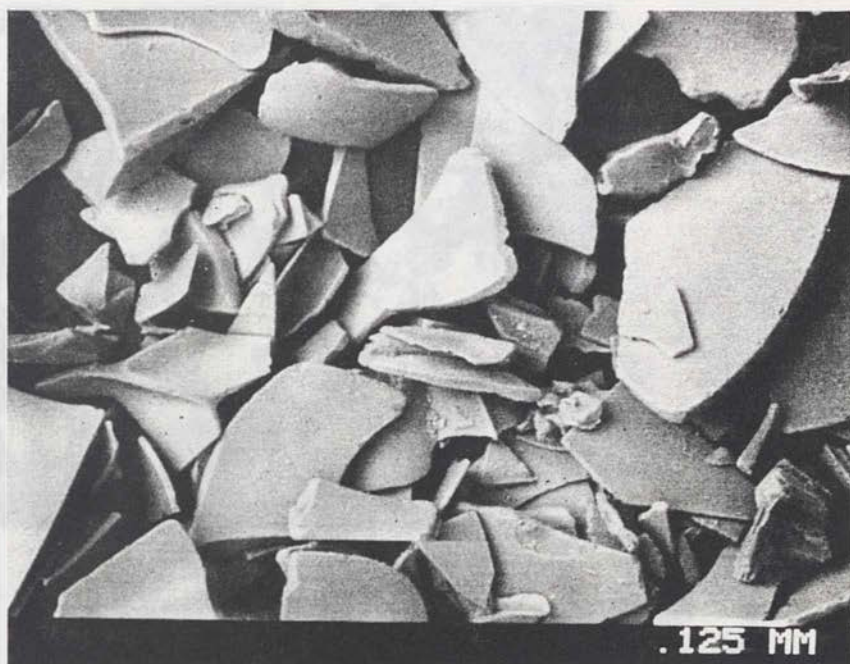
The glass shards consist of two very distinct types: pumiceous (vesicular) shards and dense (nonvesicular) shards. The pumiceous shards differ in the shape and quantity of vesicles and the dense shards differ in shape, being either chunky or platy fragments. All of the samples contain both types of shards, although most commonly one type is dominant. Figures 7-9 show scanning electron photomicrographs of each tephra sample. Three of the samples have a high percentage of platy, bubble-wall shards (shatter), a morphology which is associated with a low phenocryst content. Badlands Lower is composed almost entirely of this type of platy shard (Figure 8a) and Badlands Upper (BU) and Pahranaagat Valley Roadcut (PVR) contain nearly equal proportions of platy and pipe-like vesicle shards. Despite the similar morphologies of BU and PVR, which can be seen in Figure 7b and 9c, these two samples differ markedly in their glass chemistry and refractive index, precluding correlation between them. The remainder of the samples consist predominantly of pumiceous or chunky, nonvesicular shards, as seen in Figures 7-9.

The glass shards in all samples except Pahranaagat Valley Lower (PVL) are fresh and undevitrified, but they are hydrated as evident from their fluid-filled vesicles. The PVL shards exhibit partial devitrification, which appears to be clay. Colored glass is rare to absent in all samples



b.

Figure 7. Scanning Electron Photomicrographs of the Point of Rocks tephra; a: Point of Rocks Lower (PRL); b: Point of Rocks Upper (PRU).



a.



b.

Figure 8. Scanning Electron Photomicrographs of the Badlands tephra; a: Badlands Lower (BL); b: Badlands Upper (BU).

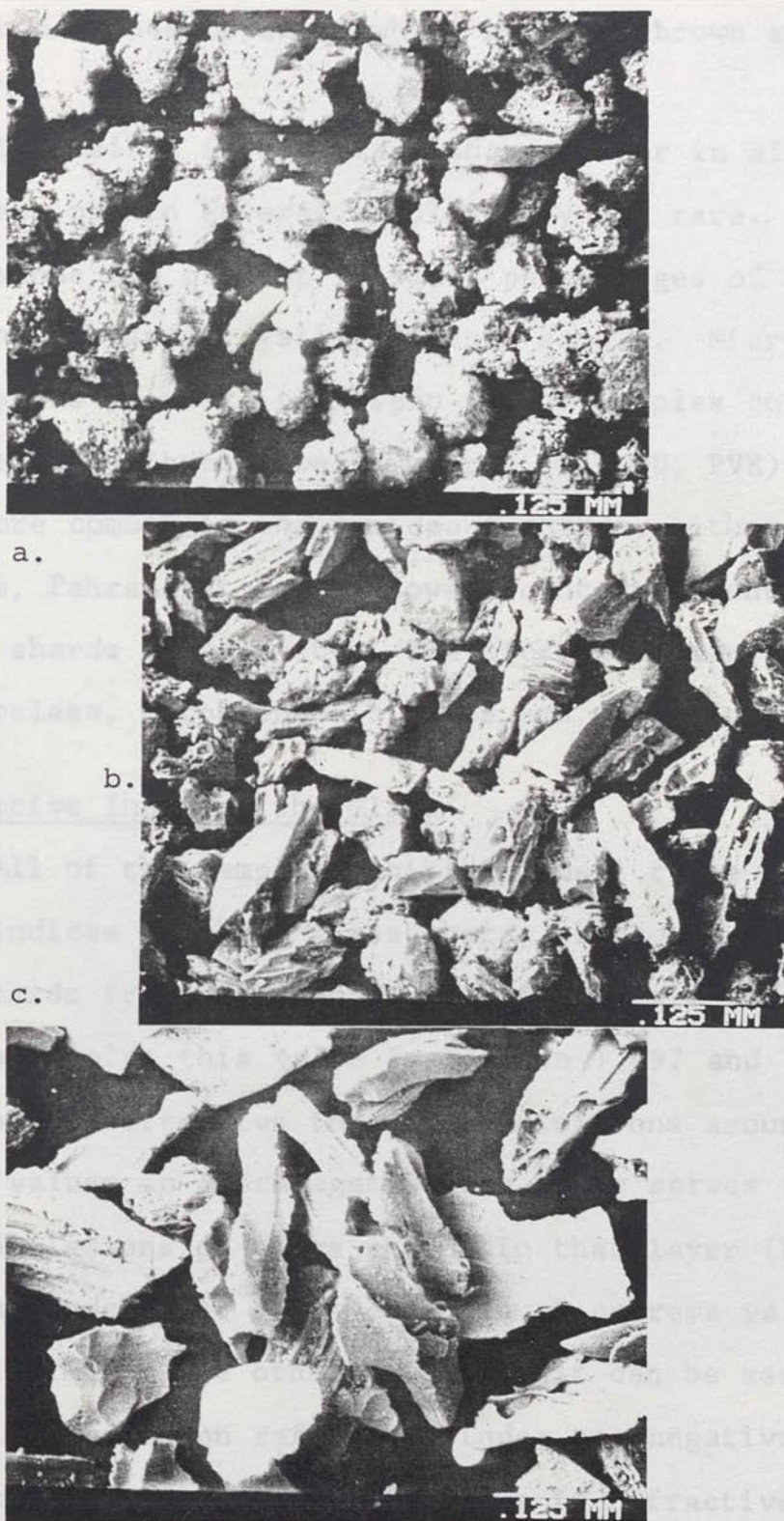


Figure 9. Scanning Electron Photomicrographs of the Pahrana-gat Valley tephra; a: Pahrana-gat Valley Lower (PVL); b: Pahrana-gat Valley Upper (PVU); c: Pahrana-gat Valley Roadcut (PVR).

except Badlands Upper in which purplish brown shards are common.

Inclusions in the glass shards occur in all of the samples, but in several samples they are rare. Phenocrystic inclusions are present in small percentages of shards in all but the Pahrnagat Valley Roadcut sample. Microlitic inclusions are rare to absent in the samples consisting of shatter-type (bubble-wall) shards (BL, BU, PVR). Microlites are more common in the pumiceous shards, although only one sample, Pahrnagat Valley Lower, contains abundant microlitic shards (Figure 10). The microlites are most commonly plagioclase, hornblende, biotite and occasionally pyroxene.

Refractive Index of the Glass

All of the samples exhibit a small range in the refractive indices of their glass shards, although the majority of the shards from each sample are of a single value. For most of the samples this value is between 1.497 and 1.503. The cluster of refractive index determinations around two distinct values in Pahrnagat Valley Lower serves to delineate two populations of glass shards in that layer (Figure 11). The Badlands Upper glass exhibits an extreme value (1.521) in relation to the other samples. It can be seen that correlations based on refractive index are negative in character; significant differences in refractive index indicates two tephra layers are not correlative, but similar

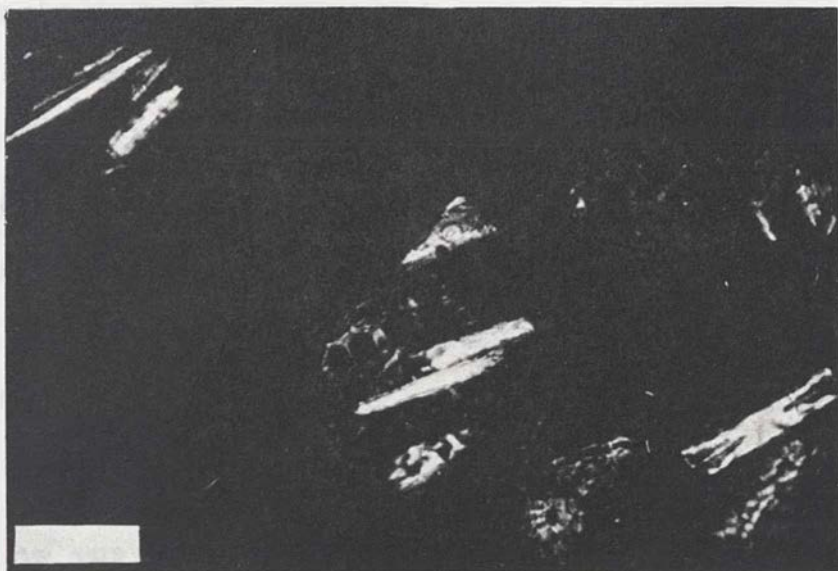


Figure 10. Abundant microlites in vesicular glass shards from the Pahrnagat Valley Lower tephra. Scale bar = 50 μ m.

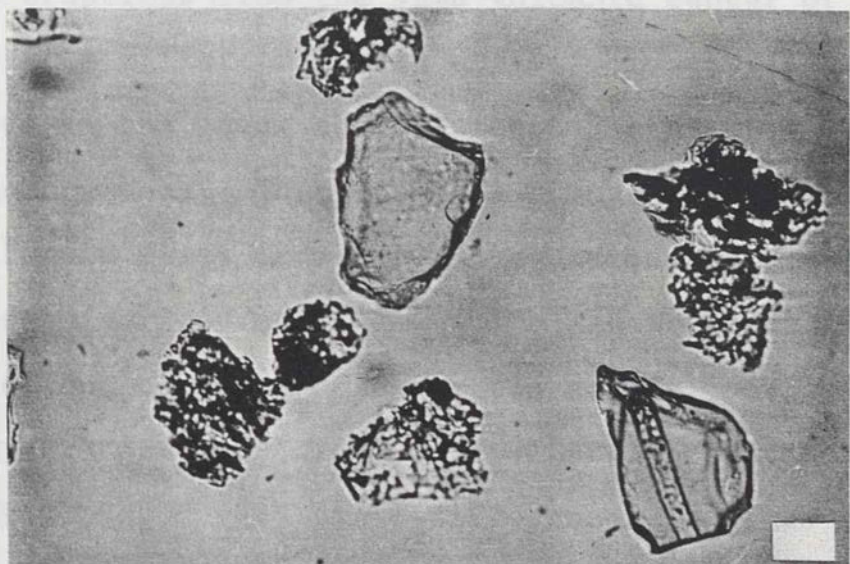


Figure 11. Two populations of glass shards in the Pahrnagat Valley Lower tephra; vesicular shards contain abundant microlites (Figure 10); nonvesicular, chunky shards are non-microlitic. Scale bar = 50 μ m.

refractive indices from two tephra layers is not evidence that they are correlative. This is because the restricted composition of the predominantly rhyolitic, late Cenozoic tephra layers do not allow for significant differences in refractive index. In addition, refractive index comparisons are based on a single parameter rather than multiple parameters, as in the mineralogic and chemical characterizations.

CHEMISTRY OF THE TEPHRA LAYERS

The characterization of volcanic ash by means of chemical composition requires that the variation within an individual eruptive unit is less than the variation among different eruptions from the same volcanic center or among eruptions from different source areas. In other words, the composition of the glass shards within a single ash layer must be homogeneous. That chemical homogeneity is achieved in the volcanic glass from plinian eruptions has been substantiated by various studies. Smith and Westgate (1969) found excellent consistency among the shards from a single tephra layer. Sarna-Wojcicki (1976; Sarna-Wojcicki and others, 1979) found very small differences in glass from single tephra layers, while differences between tephra from the same volcanic field were larger and differences between tephra from different volcanic provinces were even greater. This not only verifies chemical homogeneity of individual

tephra layers but also establishes the validity of characterizing and correlating tephra layers on the basis of chemical composition. In addition, it has also been shown that while a few major elements may be very diagnostic in distinguishing between tephra layers (Smith and Westgate, 1969), it is the minor and trace element concentrations which exhibit the greatest degree of variation among tephra layers and are therefore the most distinctive for chemical characterization (Jack and Carmichael, 1968; Sarna-Wojcicki and others, 1980).

Similarity Coefficient

Chemical analyses were compared by calculating similarity coefficients. The similarity coefficient is a means of comparing two samples; it is the average of the ratios of element concentrations. The ratio of each element is calculated by dividing the lower concentration by the higher concentration of the two samples. In this way the ratio will always be between zero and one. For example, in calculating the iron ratio of two glass samples, if the iron concentration is 1% in the first sample and 2% in the second, then the first concentration is divided by the second, giving a ratio of $1/2$ or .5. The ratios for all the elements in the sample comparison are averaged. This average is the similarity coefficient of two glass samples, providing a measure of how closely they resemble one

another. Borchardt and others (1972) first developed this technique and derived the following equation:

$$d(A,B) = \frac{\sum_{i=1}^n R_i}{n}$$

where

$d(A,B) = d(B,A)$ = similarity coefficient for comparison
between sample A and sample B

i = element number

n = number of elements

$R_i = X_{iA}/X_{iB}$ if $X_{iB} > X_{iA}$

or $R_i = X_{iB}/X_{iA}$ if $X_{iA} > X_{iB}$

X_{iA} = concentration of element i in
sample A

X_{iB} = concentration of element i in
sample B

The closer the similarity coefficient is to unity the more similar the two glass samples are. Borchardt and others (1972) found that the similarity coefficients calculated using both major and minor element concentrations were .88 or higher for two samples from the same ash layer. Sarna-Wojcicki and others (1980) report that for similarity coefficients calculated using only minor and trace element concentrations, values greater than .95 indicate that two glass samples are correlative with one another (i.e., they

represent ejecta from the same volcanic eruption). The range from .93 to .95 represents an interval of uncertainty and requires other means of correlation between two samples. Davis (personal commun.) claims that for microprobe results as well, coefficients of .95 or more indicate correlation.

Major Elements

The results of the analyses of duplicate and triplicate samples from the same tephra layer are almost entirely consistent within the range of analytical error, indicating the chemically homogeneous nature of the individual tephra layers. Exceptions to this internal consistency are the major differences in the Pahranaagat Valley Lower (PVL) glass analyses. Samples LM-7 and T25-4 yielded radically different values for nearly every element analyzed. This is attributed to, and also provides further evidence for, the mixture of two populations of glass shards in this tephra layer, which was discussed in the petrographic results (Figure 11). Sample LM-7 contains abundant microlite-rich shards, while the nonmicrolitic shard population has been concentrated in T25-4 due to its preparation by density separation techniques (for the X-ray fluorescence procedure). Such abundant microlites in LM-7, predominantly feldspars with some amphibole and pyroxene, are very difficult to avoid in the microprobe analysis and almost cer-

tainly account for the high concentration of Fe, Mg, Ca, Ba, and Ti in LM-7 as compared to T25-4.

The major element concentrations of the glasses indicate that all of the tephra layers except for the Badlands Upper are rhyolitic, evident primarily from their high Si contents of 32 to 35 percent, and also their high K content. The Badlands Upper layer with 30% Si tends more toward a dacitic composition. It is distinguished from the other tephra layers not only by its low Si content, but also by the fact that it exhibits higher concentrations than any of the rhyolitic glasses for every other element except K and Cl; its K content is lower than any of the rhyolitic glasses.

In characterizing the rhyolitic glasses by means of their major element concentrations, some of the constituents often do not show enough variation to be particularly distinctive. The Al values, for example, do not vary significantly among the samples except for a slightly higher concentration in Pahranaagat Valley Roadcut. The Na and K values, similarly, do not exhibit much variation. It should be recognized, though, that the Na and K values probably do not represent the original concentrations, but rather are the result of secondary chemical changes, specifically, leaching of Na and gain of K by ion exchange. Such secondary alteration is to be expected during hydration of silicic glasses (Noble, 1967). For this reason the Na and K

values are not considered reliable for characterization purposes. The relatively high analytical errors associated with Na and K values, as well as their apparent discrepancies in internal consistency in some tephra layers (Point of Rocks Upper for example) is due to mobilization during analysis.

Among the more diagnostic elements in the rhyolitic samples are Fe and Ca, and often Ti and Cl. These elements vary considerably among the layers and often, especially in the case of Fe, provide a chemical distinction between different layers from the same locality. The Mg, Mn and Ba values also show variation among the layers, but their usefulness in characterization is limited by their low concentration levels. It can be seen from the 50 to 100+% errors associated with the Mg, Mn, and Ba values (and often Ti and Cl) that their concentrations are approaching the detection limit of the microprobe. This limit is generally about 0.02-0.03 atomic weight percent for these analyses.

In calculating the similarity coefficient between two tephra samples, each element used in the calculation will have an equal effect on the coefficient. An element which has been determined with a low degree of accuracy has the same significance as an element whose determination is highly accurate. For this reason, the similarity coefficients for this study were calculated using only those elements which were most accurately determined. As was

previously stated, elements whose concentrations approach the detection limit of the microprobe have high analytical errors and are not considered to be highly accurate. Therefore, elements which are present in concentrations less than 0.100 atomic weight percent were not used in the calculation of the similarity coefficients. Among these elements are Mg, Mn and Ba, which only exceed 0.100 in two tephra layers (Badlands Upper and one of the Pahrnagat Valley Lower samples). Similarly, Ti and Cl are often not included in the comparisons, as their concentrations are commonly below 0.100 percent. The K and Na values have been used in the similarity coefficient calculations despite their occasionally high degree of error. Although the K and Na values probably do not present the original concentrations, they do exhibit a limited range in composition among the rhyolitic tephra layers. This suggests that although the K values are slightly higher and the Na values slightly lower than what might generally be expected from rhyolitic glasses, the glasses appear to have gained and lost the same relative proportions of K and Na, respectively. Even if the K and Na are indeed secondary concentrations, it is likely that they still reflect original concentrations in one tephra layer relative to another and it would seem valid to use them in this comparison procedure.

The similarity coefficients were calculated using a computer program written by J.O. Davis (personal commun.).

Each tephra sample was compared to every other sample from this study to determine if any correlations existed among these seven tephra layers. In addition, the tephra from this study were compared to tephra from many eruptions in the western United States. The chemical data for these known tephra layers was obtained from published data of Sarna-Wojcicki and others (1980) as well as unpublished data of Davis. The resulting similarity coefficients are plotted in the form of two matrices shown in Figures 12 and 13. For the sake of simplicity the matrices include only those coefficients which are .90 or higher. All coefficients less than .90 have been replaced by a zero value since these coefficients are not considered to indicate possible correlations. The matrices will be evaluated in the discussion at the end of this section.

Minor and Trace Elements

The results of the X-ray fluorescence analyses, in Table 5, are not element concentrations but instead represent element peak intensities. These values are obtained, in two spectral regions, by dividing the integrated peak intensity for each element analyzed by the total integrated peak intensities of all the elements plus the background in that spectral region. These values have been multiplied by 10,000 to give whole integers. The two spectral regions represent the spectral energies of potassium through zinc

FIGURE 12. Similarity coefficient matrix for the electron microprobe analyses, comparing every sample pair in this study. The coefficients are calculated using those elements in Table IV which are present in a concentration greater than or equal to 0.100 atomic weight percent, in both samples of each sample pair. Coefficient values are given in hundredths, with decimal points omitted. Values less than .90 are shown as zero (0). Outlined coefficients indicate sample pairs from the same tephra layer.

		PRL			PRU			BL		BU		PVL		PVU		PVR	
		LM1	LM4	T25-2	LM2	LM5	T25-6	LM3	T25-7	LM11	T25-3	LM7	T25-4	LM10	T25-1	LM6	T25-5
Point of Rocks Lower (PRL)	LM1	1	94	94	0	0	91	95	95	0	0	0	0	93	95	0	0
	LM4		1	96	0	0	90	94	95	0	0	0	90	91	93	0	0
	T25-2			1	0	0	0	91	95	0	0	0	0	90	95	0	0
Point of Rocks Upper (PRU)	LM2				1	96	97	0	0	0	0	0	95	90	0	0	0
	LM5					1	95	0	0	0	0	0	94	93	0	0	0
	T25-6						1	91	0	0	0	0	97	91	91	0	0
Badlands Lower (BL)	LM3							1	95	0	0	0	91	92	94	0	0
	T25-7								1	0	0	0	91	95	0	0	0
Badlands Upper (BU)	LM11									1	93	0	0	0	0	0	0
	T25-3										1	0	0	0	0	0	0
Pahranagat Valley Lower (PVL)	LM7											1	0	0	0	0	0
	T25-4												1	90	0	0	0
Pahranagat Valley Upper (PVU)	LM10													1	91	0	0
	T25-1														1	0	0
Pahranagat Valley Roadcut (PVR)	LM6															1	96
	T25-5																1

FIGURE 13. Similarity coefficient matrix for the electron microprobe analyses, comparing tephra in this study to other known late Cenozoic tephra layers in the western U.S. (chemical data from Sarna-Wojcicki and others, 1980). Only those tephra layers which yielded one or more similarity coefficients of 90 or greater, when compared to tephra of this study, are included in the matrix. Values are in hundredths, with the decimal points omitted. Values less than 90 are shown as zero (0).

		PEARLETTE ASH					BISHOP ASH							MONO GLASS MOUNTAIN		GRAY		BAILEY			COSO			
		0	S		B			BISHOP			FRIANT		IAQ	SW17	SW18	SW21	SW22	SW23	SW24	SW25	SW49	SW36		
		0	SW39A	S	SW41	SW43	SW45	B	B1	B3	SW1	SW2	SW3	SW4	SW8									
Point of Rocks Lower (PRL)	LM1	93	93	96	0	0	90	91	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
	LM4	90	0	91	0	0	0	90	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
	T25-2	92	91	92	0	0	0	90	0	91	90	0	0	0	91	0	0	91	0	0	0	0		
Point of Rocks Upper (PRU)	LM2	0	0	0	0	0	0	0	0	92	92	0	91	90	93	91	0	90	91	90	90	0	0	
	LM5	0	0	0	0	0	0	0	90	93	92	91	92	91	94	91	90	92	93	91	91	91	0	0
	T25-6	0	0	90	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Badlands Lower (BL)	LM3	92	91	94	0	90	0	93	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	T25-7	94	93	94	0	90	91	93	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Badlands Upper (BU)	LM11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	T25-3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Pahranagat Valley Lower (PVL)	LM7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	T25-4	0	0	0	0	0	0	0	0	92	92	0	90	90	93	90	0	90	91	90	90	0	0	90
Pahranagat Valley Upper (PVU)	LM10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	T25-1	92	0	94	0	91	91	92	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Pahranagat Valley Roadcut (PVR)	LM6	91	92	0	90	90	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	93	0	
	T25-5	0	0	0	93	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	91	0

(includes K, Ca, Ti, Mn, Fe, Cu and Zn) and rubidium through niobium (includes Rb, Sr, Y, Zr, and Nb). These elements have been found to be very useful in chemically distinguishing different tephra layers (Sarna-Wojcicki, 1976). Within each spectral region the values are very roughly proportional to concentration; the Ti and Mn concentrations, for example, are often approximately equal to one another, as can be seen by their similar peak intensities. Between spectral regions, though, there is no relationship between peak intensity and concentration; the high Zr values, from the Rb-Nb spectral region, for example, cannot be compared to the Mn and Ti values from the K-Zn spectral region.

The X-ray fluorescence analyses include some major elements in addition to the minor and trace elements because elements such as Ca and Fe have been found to be particularly diagnostic in late Cenozoic tephra. The two sets of values for Ca and Fe represent the $K\alpha$ and $K\beta$ peaks (corresponding to the L-shell to K-shell and M-shell to K-shell electron transitions, respectively). All other values are $K\alpha$ peak intensities. The X-ray fluorescence data obtained in this study are used strictly for correlation purposes and not for characterizing each tephra layer. In determining correlations between tephra samples, the use of peak intensities rather than concentrations is entirely satisfactory, as it is the relative proportions of elements rather than their absolute amounts which are important. If two tephra

layers have similar peak intensities for each element analyzed, then a correlation may be assumed.

Similarity coefficients will again be used to compare the seven tephra layers of this study. Each layer is compared to each other layer in the form of a matrix shown in Figure 14. The coefficients represent the average of the peak intensity ratios, and are calculated using all the analyzed elements except K. The Ca and Fe values used are the K α peak intensities. All coefficients are shown, regardless of how low they may be.

Similarity coefficients were also calculated for comparison between these tephra layers and all other late Cenozoic tephra layers which are included in the computer data base for a U.S.G.S. tephrochronology project headed by A.M. Sarna-Wojcicki (personal commun.). The results of this comparison are not available in matrix form, but will be discussed below.

DISCUSSION

In examining the similarity coefficient matrix for the microprobe analyses (Figure 12) it can be seen that glass samples from the same tephra layer, such as LM-1, LM-4 and T25-2 from the Point of Rocks Lower and LM-2, LM-5 and T25-6 from the Point of Rocks Upper, generally have similarity coefficients of .93-.97. The two exceptions to this are the Pahrnagat Valley Lower (PVL) and Upper (PVU) glass samples.

FIGURE 14. Similarity coefficient matrix for the x-ray fluorescence analyses. Coefficients are calculated for every sample pair in this study using Ca, Ti, Mn, Fe, Cu, Zn, Rb, Sr, Y, Zr, Nb. Coefficient values are given in hundredths with decimal point omitted.

		Point of Rocks Tephra		Badlands Tephra		Pahranagat Valley Tephra		
		PRL	PRU	BL	BU	PVL	PVU	PVR
Point of Rocks Tephra Layers	Lower (PRL)	1	74	82	58	69	91	83
	Upper (PRU)		1	68	65	79	78	77
Badlands Tephra Layers	Lower (BL)			1	55	67	78	74
	Upper (BU)				1	54	62	68
Pahranagat Valley Tephra Layers	Lower (PVL)					1	73	68
	Upper (PVU)						1	89
	Roadcut (PVR)							1

The lack of correlation in the PVL samples is attributed to a microlite-rich glass sample (LM-7) and a microlite-free glass sample (T25-4), as well as the fact that there appear to be two shard populations. The relatively low (.91) coefficient between the two PVU samples (LM-10 and T25-10) is due to the difference in the Na and K values from each analysis. This is believed to be the result of mobilization during analysis rather than sample inhomogeneity. It can be seen that some samples from tephra at different localities, such as the Point of Rocks Lower (LM-1, LM-4, T25-2) and the Badlands Lower (LM-3, T25-7) have similarity coefficients in the .93-.97 range. In the absence of other data it might seem that these two tephra layers are correlative with one another. Similarly, the matrix also suggests possible correlations between the Point of Rocks Upper and the Pahrnagat Valley Lower (only the microlite-free shard population: T25-4) and Upper layers (.90-.97), between the Badlands Lower and the Pahrnagat Valley Lower (microlite-free shards) and Upper layers (.91-.94), and between and the Point of Rocks Lower and Pahrnagat Valley Upper layers (.90-.95). The similarity coefficient matrix (Figure 14) for the X-ray fluorescence analyses does not support any of these correlations, nor do the petrographic results in most cases. The minor and trace element matrix, in fact, does not indicate correlation between any of the seven tephra layers studied. The highest coefficients

obtained are .89, between Pahrnagat Valley Upper and Roadcut, and .91, between Pahrnagat Valley Upper and Point of Rocks Lower. The Pahrnagat Valley Upper and Roadcut coefficient is not nearly high enough to indicate a correlation, nor do the field relations or petrographic study suggest a correlation. The .91 coefficient between Pahrnagat Valley Upper and Point of Rocks Lower seems more significant. Although .91 is still too low to be considered a correlation, it is interesting to note that the microprobe similarity coefficients (.93-.95), the glass shard morphology and refractive index (1.498 and 1.497), and the mineralogy, to an extent, support such a correlation. The .91 minor and trace element coefficient from the XRF analyses is the only evidence which does not strongly favor the correlation. Although they probably do not represent the same tephra layer (an XRF coefficient of at least .93 would be expected for correlation), the similarities obtained for all of the analytical methods suggest some relationship is highly likely. Perhaps the Pahrnagat Valley Upper and Point of Rocks Lower tephra layers represent eruptions from the same volcanic source area or possible may even be different eruptions from the same volcanic vent.

On the basis of the low similarity coefficients obtained from the XRF data, it is concluded that each of the seven tephra layers represents a distinct volcanic eruption.

The similarities in the major elements among some layers may be indicative of similar source regions.

The similarity coefficients in the microprobe matrix (Figure 13), which compare tephra from this study with other late Cenozoic tephra layers, indicate some similarities but no definite correlations. For example, the Badlands Lower tephra (LM-3) is similar to the three Pearlette tephra layers (0.6 - 2.0 m.y.) from the Yellowstone Park area in northwest Wyoming and southeast Idaho. The Point of Rocks Upper samples (LM-2 and LM-5) are similar to the Bishop ash from the Long Valley Caldera (0.7 m.y.) and several other tephra layers which are thought to be from the Long Valley area (Glass Mountain, Gray, and Bailey ashes). The similarity coefficients for the X-ray fluorescence analyses (reported by A.M. Sarna-Wojcicki) do not support these or any other correlations with late Cenozoic tephra layers. The minor and trace element compositions of the tephra from this study do not match the composition of any units analyzed by Sarna-Wojcicki and his co-workers on the tephrochronology project. Sarna-Wojcicki (written commun.) indicates that several of the tephra layers (PRL, PRU, PVU, PVR) have a general chemical similarity to Tertiary tephra of early Pliocene to Miocene age in the eastern San Joaquin Valley of California. He suggests the San Joaquin tephra "may be distal air-fall ashes associated with eruptions of voluminous mid-Tertiary ash-flow sheets in the Basin and

Range area." The similar chemistry of the San Joaquin tephra layers and those of this study may be indicative of derivation from the same volcanic region. The closest match which Sarna-Wojcicki reports for the X-ray fluorescence analyses is a .92-.93 similarity coefficient between the Badlands Lower sample and the Pearlette B ash (2.0 m.y.). The microprobe data, as mentioned above, shows a similarity also, but Sarna-Wojcicki (Sarna-Wojcicki and others, 1980; personal commun.) emphasizes that for minor and trace element compositions, similarity coefficients in the .93-.95 range represent an uncertain interval and therefore result in uncertain correlations. In addition, Sarna-Wojcicki also advises that tephra which appear to correlate with Pearlette ashes be viewed with caution, as there are numerous ashes with similar characteristics. The correlation between the Badlands Lower and Pearlette B tephra is possible, on the basis of chemical and petrographic data, but it is not certain. This will be discussed further, in view of the K-Ar age determination on the Badlands Lower tephra, in a later section.

The results of both the chemical and petrographic analyses of the tephra layers from this study emphasize the importance of multiple methods in characterizing and correlating tephra. Although some analyses, such as the microprobe element concentrations and the refractive indices suggest correlations among the seven layers, other analyses,

such as the minor and trace elements and the glass shard morphologies, do not. Furthermore, in characterizing each of the tephra layers, although some characteristics may be similar among the tephra layers, there are usually one or more features of each layer which distinguish it from the rest. For instance, although Point of Rocks Lower and Badlands Lower have similar major element concentrations, their glass shard morphologies are radically different. Similarly, the Point of Rocks Upper is distinguished from the Point of Rocks Lower by its significantly lower Fe content, lack of pyroxene, and presence of hornblende.

allow the precise and accurate determination of argon (Ar) and potassium (K) content of rocks and minerals, even at very low concentration levels.

THE PROBLEM OF K-AR DATING OF PYROCLASTIC MATERIAL

The dating of pyroclastic material by the potassium-argon (K-Ar) method has long presented a problem to geologists. Due to the fragmental and unconsolidated nature of such deposits, contamination from older material is almost certain. Curtis (1966) indicates that contamination becomes increasingly more critical in younger units and discusses its causes and criteria for recognition. The contamination may be derived either from the walls of the conduit during eruption or may be picked up from the ground surface over which the material passes during transport. Since

POTASSIUM-ARGON AGE DETERMINATIONS

During the past two decades, the potassium-argon method has become one of the most useful radioactive dating techniques and has been applied to a wide variety of geochronologic studies (Dalrymple and Lanphere, 1969; Faure, 1977). Two primary advantages of the method are the widespread occurrence of potassium-bearing minerals in nature, and the potassium-40 (^{40}K) half-life of 1.31 billion years, which makes the method applicable to nearly the whole range of geologic time. Analytical procedures are available which allow the precise and accurate determination of argon (Ar) and potassium (K) content of rocks and minerals, even at very low concentration levels.

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fragmental conduit material is more likely to be winnowed out as distance from the vent increases, contamination due to depositional processes presents the greater problem. Both ash-flow and ash fall material are subject to such contamination. Dalrymple and Lanphere (1969) state that inherited contamination is a continual problem with ash-flow tuffs due to their turbulent emplacement and therefore likely incorporation of debris. Silberman and others (1978) encountered various cases of older contamination in ash-flows and indicate it is a common problem with tuffaceous rocks. Air-borne ash would not be expected to contain as much contamination as an ash-flow but, as Curtis (1966) points out, a reworked ash fall will be contaminated to the greatest extent. Although the problem of detrital and eruptive contamination can often be solved by concentrating phenocrysts from primary pumice fragments, coarse pumice is usually absent in reworked air-fall ash.

Five of the seven tephra layers in this study represent reworked ash deposits; two are water-laid. That contamination would be a critical factor in the success of the K-Ar age determinations was acknowledged from the onset of this study. The incorporation of detrital material in these loose, reworked ashes was considered a certainty; indeed, the microscopic examination of the samples revealed rounded, corroded grains. The removal of such contamination would be very difficult if not impossible, short of handpicking the

sample, a highly impractical method to obtain several grams of material. Furthermore, in many cases it is not possible to distinguish foreign material from primary. For instance, older volcanic feldspars are very likely to go unnoticed in an ash unless they are obviously more rounded and altered. It would seem that the easiest way to avoid contaminants in a volcanic ash would be to date the glass shards, but as Naeser and others (1973) indicate, glass may yield unreliable ages. However, in two of the samples, glass shards were selected for dating because the phenocryst assemblages were too sparse for satisfactory concentration. Despite these obstacles in dating pyroclastics, the K-Ar analyses were still undertaken due to the potential value of establishing stratigraphic marker horizons with absolute age determinations.

In order to provide some control on the ages, at least two mineral phases were dated from each tephra layer (except for the glass phases, as noted above). Two different mineral concentrates from the same tephra layer would not be expected to contain the same degree of contamination. Theoretically, therefore, an agreement in age between two phases would be evidence of obtaining the true age of the eruption and deposition. Detrital components in the mineral concentrates would be expected to yield discordant ages, as the different phases will contain differing amounts of contamination. Biotite, for instance, is not as resistant

as the feldspars and therefore exotic biotite would not be expected in large amounts. In ash-flows and other pyroclastic rocks, when such discordances are obtained, it is recommended that the youngest age be accepted as that which most closely approximates the true age, as higher degrees of contamination produce older apparent ages (M.L. Silberman, written commun.). This is opposed to the general procedure in volcanic and plutonic rocks of accepting the oldest age of a suite of minerals, subject of course, to the generally recognized order of argon retention of the various minerals in the suite (Hanson and Gast, 1967; Hart, 1964; Hart and others, 1968; Dalrymple and Lanphere, 1969).

The possible sources and ages of contamination are also an important consideration in the evaluation of the discordances. An estimation of the degree of contamination and its probable age can yield much useful information and help provide a reasonable interpretation of what otherwise might be meaningless results. The evaluation of detrital contamination at the Point of Rocks locality, which will be discussed later, well illustrates this.

Despite the use of multiple phases and the determination of contamination sources, it must be conceded here that the results of this study demonstrate the deleterious effects of even a tiny amount of contamination. Some of the discordances obtained can be explained in terms of detrital components, but others remain puzzling and can only be spec-

ulated upon. These results once again bring into question the already suspect usefulness of K-Ar dating of pyroclastics. Some workers advocate the use of zircon fission-track determinations for dating such material (Naeser and others, 1973), but the highly resistant zircons are also subject to detrital concentration. Perhaps the only solution is the use of multiple, independent dating methods, for this may provide the strongest evidence for a correct age, provided that a concordance is obtained. A second method of dating the ash layers from this study would be most useful. Ideally, the K-Ar determinations should be compared with fission-track determinations on one and preferably two phases, a possible future research project which will require considerable time and effort. The potential value of an absolutely-dated tephra marker seems to justify the effort.

THEORY OF POTASSIUM-ARGON DATING

Potassium consists of three naturally occurring isotopes, one of which (^{40}K) is radioactive. ^{40}K undergoes decay by two processes: beta emission to form ^{40}Ca , and electron capture to form ^{40}Ar . The generation of ^{40}Ar is the basis for K-Ar dating. Due to its abundance in the earth's crust, potassium is a major constituent in many rock-forming minerals and volcanic glass. The ^{40}Ar produced from radioactive decay of ^{40}K may be completely retained,

under certain conditions, in these minerals and in glass. The amount of radiogenic ^{40}Ar which has accumulated is a measure of time since crystallization. From the general age equation for radioactive decay (Dalrymple and Lanphere, 1969, p. 21-22), an age equation is developed for the decay of ^{40}K which relates the content of radiogenic ^{40}Ar to ^{40}K in a rock or mineral:

$$t = \frac{1}{\lambda_{\epsilon} + \lambda_{\beta}} \ln \left[\frac{{}^{40}\text{Ar}_{\text{rad.}}}{{}^{40}\text{K}} \left(\frac{\lambda_{\epsilon} + \lambda_{\beta}}{\lambda_{\epsilon}} \right) + 1 \right]$$

where λ_{ϵ} is the decay constant for ^{40}K to ^{40}Ar and λ_{β} is the decay constant for ^{40}K to ^{40}Ca . These constants have been experimentally determined and are $\lambda_{\epsilon} = 0.581 \times 10^{-10} \text{ yr}^{-1}$ and $\lambda_{\beta} = 4.963 \times 10^{-10} \text{ yr}^{-1}$ (Dalrymple, 1979). Using these values, the above equation reduces to:

$$t = 1804 \times 10^{-9} \ln \left[9.540 \frac{{}^{40}\text{Ar}_{\text{rad.}}}{{}^{40}\text{K}} + 1 \right]$$

Argon Analysis

Argon consists of three naturally occurring isotopes: ^{36}Ar , ^{38}Ar , and ^{40}Ar . The argon present in the earth's atmosphere is composed of a mixture of all three isotopes, whereas that produced by radioactive decay of ^{40}K consists of only ^{40}Ar . The argon present in a rock or mineral is a combination of both atmospheric and radiogenic argon, the

relative abundances of which must be determined in order to calculate an age. Argon is commonly analyzed by the isotope dilution method in which a known amount of argon of known isotopic composition is added to the argon which is extracted from the rock or mineral. This added argon acts as a tracer which is used to measure ratios in the mass spectrometer analysis of total argon. The tracer is nearly pure ^{38}Ar , chosen because it is present in very minute quantities in the earth's atmosphere and therefore has an isotopic composition very different from that of the extracted argon (atmospheric plus radiogenic). The ^{38}Ar present in the mixture of tracer and extracted argon is essentially from the tracer only; the mixture contains ^{40}Ar from the radioactive decay of ^{40}K and from the atmosphere, ^{38}Ar from the tracer (plus the minute quantity from atmosphere), and ^{36}Ar from the atmosphere. The ^{38}Ar tracer allows for the precise determination of the total ^{40}Ar in the sample:

$$^{40}\text{Ar}_{\text{total}} = \frac{^{40}\text{Ar}}{^{38}\text{Ar}} \times ^{38}\text{Ar}_{\text{tracer}}$$

↑
measured by a
mass spectrometer

The correction for atmospheric ^{40}Ar is then made, using the known ratio of $^{40}\text{Ar}/^{36}\text{Ar}$ in the earth's atmosphere, which is 295.5 (Nier, 1950):

$$^{40}\text{Ar}_{\text{radiogenic}} = ^{40}\text{Ar}_{\text{total}} - (295.5) ^{36}\text{Ar}$$

↑
atmospheric ^{40}Ar

It can be seen from this equation that the precision of the radiogenic ^{40}Ar determination depends on the amount of atmospheric ^{40}Ar present relative to radiogenic ^{40}Ar and also on the precision of the atmospheric ^{40}Ar determination. In young rocks this becomes a critical limiting factor, as a large error in the atmospheric ^{40}Ar content, when subtracted from the total ^{40}Ar measured, will give a large error in the calculation of the relatively small amount of radiogenic ^{40}Ar which has accumulated during a short period of geologic time.

POTASSIUM-ARGON ASSUMPTIONS

In determining the age of a rock or mineral by the K-Ar method, there are 5 basic assumptions which are made (Dalrymple, 1968; Dalrymple and Lanphere, 1969).

1. The decay of ^{40}K takes place at a constant rate in all materials, regardless of environment.
2. The proportion of $^{40}\text{K}/\text{K}_{\text{total}}$ in the materials used for K-Ar dating is the same at any given time.
3. The time span of formation of the rock or mineral is short compared to its age.
4. There is no extraneous argon present in the rock or mineral at the time of its formation.
5. There has been no gain or loss of ^{40}K or ^{40}Ar from the rock or mineral since the time of its formation.

The first 3 assumptions have been proven valid by

numerous studies. Radioactive nuclides are characterized by their rate of decay, which is unaffected by chemical or physical conditions, except in a few rare instances. The decay constants of ^{40}K quoted previously have recently been redetermined (Steiger and Jager, 1977) based on new data on the natural abundance of ^{40}K and its decay scheme. It has also been shown that potassium does not exhibit isotopic fractionation, except in rare cases (Verbeek and Schreiner, 1967), and therefore has a constant $^{40}\text{K}/\text{K}_{\text{total}}$ ratio (Burnett, Lippelt, and Wasserburg, 1966) which can be used to calculate ^{40}K total in a sample. Assumption 3 can be considered valid for volcanic rocks due to their quick cooling history and therefore short time span of formation (crystallization).

Assumptions 4 and 5 are not always valid and can cause problems in K-Ar dating. The assumption that no extraneous argon is present in the mineral at the time of formation is only valid if all the ^{40}Ar in a mineral is either the result of radioactive decay of ^{40}K since the time of the mineral's crystallization, or atmospheric argon which has been adsorbed onto the surface of the mineral grain through time. If any extraneous ^{40}Ar is present in the mineral at the time of its crystallization then dating of the mineral will result in an anomalously old age. The extraneous argon may be due to either incorporation of argon gas into the mineral at the

time of its formation or incorporation of older mineral grains in the sample.

The possibility that a mineral may contain excess radiogenic ^{40}Ar at the time of its crystallization is discussed by Damon and Kulp (1958), Everden and Curtis (1965a), Curtis (1966), Dalrymple and Lanphere (1969), Fyfe and others (1969), and Silberman and others (1979). Studies show that excess radiogenic argon may be dissolved in a magma, having been derived by degassing of the crust and mantle, and that under certain conditions this argon can be incorporated into the crystal lattice during a mineral's growth. This would require that the magma be under sufficient confining pressure to maintain a high enough gas pressure to keep the argon in solution, a condition which Curtis (1966) and Dalrymple (1969) indicate rarely occurs in volcanic or plutonic rocks. Most reports of excess ^{40}Ar in various minerals, including biotite and the feldspars, have been from pegmatites, dikes or kimberlite pipes. Zartman and others (1967) reported excess ^{40}Ar in biotites from kimberlite and peridotite dikes. Pegmatitic and basaltic plagioclase have also been reported to contain excess ^{40}Ar (Damon and Kulp, 1957; Damon, 1968; Livingston and others, 1967; Dalrymple, 1969). Excess ^{40}Ar in volcanic and plutonic rocks, although rare, does occur. Livingston and others (1967) found excess ^{40}Ar in potassium feldspar (orthoclase) from a quartz monzonite and Damon and others

(1967) reported excess ^{40}Ar in large volcanic phenocrysts, which they believed was incorporated during mineral growth and was not completely outgassed during eruption. This is a phenomenon which diffusion data (Damon and others, 1967; Foland, 1974) indicate is apparently restricted to larger phenocrysts, due to an inadequate amount of time for them to outgas completely during eruption and quick cooling. Silberman and Noble (1977) suggest pre-eruption argon as a possible explanation for the anomalously old age obtained on a large sanidine crystal from a post-mineralization dike. In an earlier study, Evernden and Curtis (1965a) stress the improbability of pre-eruption ^{40}Ar in potassium feldspar, citing a 4-6 month retention period of argon in an 800°C magma, and fervently defend their position that "available evidence indicates very low to vanishing levels of pre-eruption argon in volcanic rocks." Dalrymple (1969) also concludes that excess ^{40}Ar probably is not a problem with volcanic rocks. With the few exceptions noted, some of which are equivocal (Damon and others, 1967; Silberman and Noble, 1977), anomalously old ages in volcanic rocks are probably not a function of incorporation of excess ^{40}Ar in the mineral phases. Incorporation of excess ^{40}Ar in volcanic glass, however, is a problem. Evidence of excess ^{40}Ar in nonhydrated glass has been reported from both experimental and field work. Fyfe and others (1969) have shown experimentally that argon is soluble in granitic melts and the

glass which results from quenching of these melts retains some of the argon. Marvin and others (1970b) concluded that an anomalously old K-Ar age from nonhydrated volcanic glass was due to incorporation of excess ^{40}Ar , and Silberman and others (1979) suggest excess ^{40}Ar may have been present in a nonhydrated obsidian sample as a result of incorporation of argon in the rhyolitic magma and then failure to outgas this argon, due to rapid cooling. K-Ar ages on volcanic glass should therefore be viewed with some skepticism.

The other type of extraneous argon, that which is due to incorporation of older mineral grains in a sample, does cause a considerable problem in K-Ar dating. The contaminating grains may be due either to careless sample preparation or to natural processes in the geologic environment. Contamination in the laboratory can usually be avoided; the sample preparation for this study included thorough cleaning of equipment and work surfaces after each sample, the discarding of used sieve cloth after each sample, and storing of samples in clean, sealed vials.

Contamination in the geologic environment is much more difficult, indeed sometimes impossible, to avoid, especially in volcanic rocks and most particularly in pyroclastic rocks. Such contamination may be due to material torn from the conduit during eruption or to material which is added by later erosional processes. Early attempts to date the Bishop Tuff (Evernden and others, 1957; Evernden, 1969;

Evernden and Curtis, 1965a; 1965b;) gave erroneous ages of 0.87-1.2 m.y. due to the incorporation of older xenolithic material from the surrounding country rock, a problem which was later recognized and solved by dating only phenocrysts from primary pumice fragments (Dalrymple and others, 1965). This does not, however, solve the problem that older conduit material may be present in distal air-fall layers from such vents, as these layers are generally fine grained and pumice fragments, for the concentration of primary phenocrysts, are not available. An even greater problem of contamination arises from the presence of older detrital grains picked up during depositional processes. Unconsolidated air-fall ash is easily removed by erosion and redeposited, usually in an aqueous environment, often on top of a layer of the primary air-fall ash (Curtis, 1966). The upper, reworked part of the ash is therefore more likely to be contaminated by erosional debris. In this study, reworked ash could not be avoided in the layers which showed indications of being redeposited, due to the impracticality of obtaining bulk samples from the basal few centimeters of a laterally restricted ash layer. The presence of detrital contamination is a problem in most of the samples, as it often is with pyroclastic volcanic rocks. All samples were carefully examined both in the field and the laboratory for degree and type of contamination. In the field careful attention was paid to distinguishing any bedding within the layers and

also to the presence and type of lithic fragments, both factors which indicate reworking. During sample preparation the mineral concentrates were carefully monitored with a petrographic microscope for the presence of rounded, altered, detrital-looking grains.

Assumption 5, which assumes no gain or loss of potassium or argon, is not always valid either and must be evaluated on the basis of geologic conditions. For there to have been neither a gain or loss of potassium or argon from a mineral requires that the mineral has been a closed system since crystallization. Migration of potassium is usually not a problem, except in cases of metamorphism or hydrothermal alteration, in which accompanying argon loss would be expected also (Dalrymple and Lanphere, 1969). Hydrated volcanic glasses have also been shown to exhibit both increases and decreases in potassium content, relative to their nonhydrated counterparts (Noble, 1967; Jezek and Noble, 1978). Argon gain is usually not a problem with volcanic rocks, except in the case of incorporation of older, contaminating material, as discussed previously. Argon loss is a problem in K-Ar dating and can occur due to various geologic factors which are discussed by Dalrymple and Lanphere (1969). The only ones of importance in unmetamorphosed volcanic ash layers are the inability of a mineral or glass to retain argon, reheating of the ash layer, or weathering and alteration of the ash.

The minerals chosen for the K-Ar isotopic age determination, sanidine, plagioclase, and biotite, are retentive of argon if not subjected to significant post-emplacement thermal events (Evernden and Richards, 1962; Evernden and James, 1964; Hansen and Gast, 1967; Hart, 1964; Hart and others, 1968). Volcanic glass, particularly hydrated volcanic glass, may not retain argon well, and criteria for choosing volcanic glass samples that appear to be retentive of argon are still not well established (Dalrymple and Lanphere, 1969; M.L. Silberman, written commun., 1981).

Any reheating of a rock or mineral after crystallization may cause a loss of argon due to diffusion. This has experimentally been shown to occur (Evernden and others, 1960) and is more extensive in certain mineral species. Biotite is especially sensitive to reheating and feldspar to a much lesser degree.

No evidence for reheating in the geologic environment, either by mild metamorphism or by igneous intrusion, was observed in the field at any of the sample localities. Care was taken in the laboratory to avoid excessive heat ($>100^{\circ}\text{C}$) during sample preparation, and I conclude that thermal events subsequent to the deposition of the ash layers are not a factor in this study.

Weathering or alteration of a rock or mineral may cause argon loss due to a breakdown of the mineral lattice. In addition, the presence of altered grains is also evidence

for the incorporation of older, contaminating material from other sources. The mineral concentrates were carefully examined for the presence of altered grains (See Appendix II for petrographic descriptions of mineral concentrates).

It is important that glass samples to be dated are unaltered, a factor which usually can be established by the absence of any devitrification or hydration. The two glass concentrates (from samples BL and BU) are fresh and clean in appearance, showing no signs of devitrification and containing essentially no microlites or inclusions. It was suspected, however, that the glass is completely hydrated. The H_2O content, as weight percent, was determined for both samples. The glass shards were first heated at $105^\circ C$ for 3 hours, to remove any surficial water, then weighed, heated to $400^\circ C$ for two 8-hour periods, and re-weighed after each heating. This procedure verified that the glass shards are hydrated. Hydrated glass ages are usually considered unreliable (Dalrymple and Lanphere, 1969), as hydration indicates a migration of various elements has occurred (Ross and Smith, 1955; Noble, 1967; Noble and others, 1967; Lipman and others, 1969; Jezek and Noble, 1978).

SAMPLE SELECTION

Due to the problem of high atmospheric argon content and the effects of contamination, dating of young rocks

requires care in the selection and preparation of samples so as to ensure satisfactory results.

In order for a material to be suitable for potassium argon dating of its age of crystallization, it must contain a significant amount of potassium (usually 1% or greater - as K_2O), it must be retentive of argon, and it must be free of alteration and free of contamination by older crystals or lithic fragments. The range of materials which meet these criteria include various minerals, often whole rock samples, and sometimes volcanic glass. As discussed previously, pyroclastic volcanic material rarely meets the last criterion. The minerals which have been shown to be most useful in dating young volcanic rocks are sanidine, biotite, and plagioclase, in that order (Evernden and James, 1964; Dalrymple, 1968; Dalrymple and Lanphere, 1969; Faure, 1977). Sanidine is most desirable, as it is high in K_2O content (generally 7-10%), highly retentive of radiogenic argon, and generally contains a low amount of atmospheric argon. Biotite is also high in K_2O (7-9%) and retentive of radiogenic argon, but can sometimes be a problem in dating young rocks due to a generally higher content of atmospheric argon. Although plagioclase is low in K_2O (<1%), Evernden and James (1964) have shown high temperature (volcanic) plagioclase to be retentive of radiogenic argon. Plagioclase frequently presents a problem in dating young volcanic rocks for two reasons. First, its generally low potassium

content results in a relatively low rate of production of radiogenic argon as compared to minerals such as biotite or sanidine. The relative amount of radiogenic argon-40 to atmospheric argon-40 is therefore low and precision is affected. Secondly, contamination of plagioclase with older material is more likely to produce anomalously older ages since the radiogenic argon concentration itself is so low (i.e., a small amount of radiogenic argon, from young plagioclase crystals, when added to a larger amount of radiogenic argon, from older contamination, will result in a large error and an anomalously old age).

Volcanic glass has been used in K-Ar dating with varying degrees of success (Marvin and others, 1970a; Anderson and others, 1972; Silberman and others, 1979), as glass may contain excess radiogenic argon or, conversely, may not retain radiogenic argon well. The K_2O content is relatively high (often 4-5%), but atmospheric argon can be a problem. Glass used for analysis ideally should be nonhydrated and undevitrified.

Whole-rock analyses are often desirable, as the groundmass may be higher in potassium than the phenocrysts. In dating young, poorly consolidated volcanic material, whole rock analyses should be avoided due to the low radiogenic argon contents, possibilities of detrital contamination, and the possible effects of groundwater alteration (M.L. Silberman, personal commun.).

The selection of datable material for this study was based on the suitability of the material and its abundance in each sample. Sanidine, biotite, and plagioclase were the minerals used. In addition, glass shards were also used for two samples which did not contain a sufficient quantity of minerals for dating purposes.

In preparing the mineral and glass concentrates, care should be taken in obtaining a uniform concentrate free of foreign mineral phases. The size fraction chosen for concentration will depend primarily on which fraction contains the highest percentage of minerals. In general, the size of the grains should not be too large, as this increases the chance of obtaining a nonuniform sample during the sample splitting procedure (due to fewer grains per unit volume), nor should the grains be too small due to problems with density separation which may be encountered with small particles. It is important that the separates be very pure (98-100%), as a few foreign mineral grains (i.e., other phases) may affect the potassium and argon content. The effect generally becomes more pronounced as the K_2O content decreases.

The concentrates should ideally be free of grains which have been altered or weathered, due to the possible loss of argon which may occur (Dalrymple and Lanphere, 1969) during these processes. Although careful microscopic monitoring of the concentrates will reveal the presence of any altered

material, it is difficult, if not impossible, to remove such grains from a sample.

SAMPLE PREPARATION

Approximately three to four kg of each sample was crushed manually, to avoid contamination, using an iron pestle and buckboard, and then sieved on a ro-tap, using a set of specially constructed plastic sieves (to avoid any further metal contamination) and nylon sieve cloth. The sieves were constructed out of 8-inch plastic PVC pipe by first cutting 8-inch diameter rings (4-inches high) and then slipping similar smaller diameter rings (made by cutting 1-inch gaps in other 8-inch rings) inside these, creating inner rings which fit snugly inside the outer 8-inch rings when the sieves were stacked. Eight-inch diameter, 1-inch wide rings were slipped over the bottom of each sieve to hold the sieve cloth in place. The nylon sieve cloth was changed after each sample so as to avoid cross contamination between samples. The 100-170-mesh size fraction was chosen for further processing, as this fraction contained a higher percentage of phenocrysts than the 60-100-mesh size fraction.

Each sample was rinsed in dilute HCl to remove any carbonate material, rinsed in distilled water several times and dried. It was then placed in a methylene iodide-acetone or bromoform-neothene mixture in a separatory funnel to

separate the glass shards from the crystals by density fractionation. The crystal and glass fractions were tapped off separately, using a filter-funnel-vacuum flask arrangement, and then rinsed several times in acetone and dried.

Biotite Preparation

The crystal fractions from the two samples which contained enough biotite for dating purposes (PRU and PVL) were run through an electromagnetic separator to concentrate the biotite fraction. The nonmagnetic fraction was saved for the feldspar preparation. The biotite-rich sample was further concentrated by means of a mica table, which separates the platy biotite flakes from the other minerals. The biotite was ultrasonically and/or ball mill cleaned to remove adhering dust or mineral fragments and then wet-sieved through a 150-mesh sieve. Sample PRU required further heavy liquid separation to remove contaminating minerals, followed by acetone rinses and wet-sieving again through 150-mesh screen to remove fine-grained impurities. The final size fraction of the biotite concentration was 100-150-mesh.

Feldspar Preparation

The 100-170-mesh crystal fraction from all samples except BL and BU was placed in dilute (7%) hydrofluoric acid for 8-10 minutes to remove adhering glass, cleaned in distilled water using ultrasonic vibration for 60 seconds, and

dried. This procedure produces clean, pure feldspar crystals, reduces atmospheric argon contamination (Dalrymple, 1968), and has no undesirable effects on the K-Ar age (Evernden and Curtis, 1965a). The crystal fraction was then placed in a separatory funnel and separated into a sanidine-rich portion and a plagioclase-rich portion by means of density fractionation in a methylene iodide-acetone mixture of appropriate density. The two fractions were then concentrated into a pure sanidine and a pure plagioclase concentrate by repeating the heavy liquid procedures in a series of methylene iodide-acetone mixtures of varying densities to remove all heavy minerals, quartz¹, and any remaining glass. The concentrates were rinsed in acetone, dried under a heat lamp, and run through an electromagnetic separator repeatedly at 1.5 - 1.8 amperes to remove any remaining magnetic grains.

Glass Preparation

Samples BL and BU did not contain enough phenocrysts to make an adequate mineral concentrate, but contained undevitrified, microlite-free glass which appeared to be pure and

¹ A 100% pure plagioclase concentrate was not possible, as quartz (sp. grav. = ~2.65) could not be entirely separated from the plagioclase (sp. grav. = ~2.62-2.70). However, a small percentage of quartz is not critical because quartz is a "neutral" mineral containing negligible K₂O and therefore no radiogenic argon, and acts only as a diluting factor (M.L. Silberman, personal commun.)

fresh enough to date. The glass fraction from sample BL was ultrasonically cleaned in distilled water for 30 seconds and dried under a heat lamp. Much of the glass from sample BU had a dirty, surficial coating, requiring more extensive cleaning. This glass was ultrasonically vibrated in distilled water for 1-2 minutes, wet-sieved through 170-mesh screen, dried, and put into heavy liquid a second time. The clean glass fraction was tapped off, rinsed in acetone, etched in dilute (5%) HF for 30 seconds, rinsed and dried, and then run repeatedly through an electromagnetic separator at varying currents to remove any remaining phenocrysts or glass.

ANALYTICAL PROCEDURE

Five aliquants were taken, using a Jones-type micro-splitter, from each mineral and glass concentrate; three for the argon analyses and two for the K_2O analyses. Aliquants for the argon analyses consisted of ~2.0 grams of plagioclase or glass, and ~0.75 grams of sanidine or biotite. Aliquants for the K_2O analyses were ~0.25 grams for each analysis.

The argon extractions and analyses were performed, on one aliquant from each concentrate, at the U.S. Geological Survey Isotope Geology Laboratories in Menlo Park, California, using the argon extraction isotope dilution techniques described by Dalrymple and Lanphere (1969). Mass analyses of the argon extracted from the mineral and glass

samples was done using a Nier-type, 60° sector, 15.24 cm radius mass spectrometer operated in the static mode.

Analysts were L.B. Gray and M.L. Silberman.

Potassium was analyzed in duplicate, at the Analytical Laboratories Division of the U.S.G.S., Menlo Park, California, on other aliquants of the concentrates using a lithium metaborate flux flame photometer technique, with the lithium serving as an internal standard (Ingamells, 1970). Analysts were S.T. Neil and David Vivit.

The constants used in the calculations of ages are:

$$\begin{aligned}\lambda_e + \lambda_{e'} &= 0.581 \times 10^{-10} \text{ yr}^{-1} \\ \lambda_{\beta} &= 4.963 \times 10^{-10} \text{ yr}^{-1} \\ {}^{40}\text{K}/\text{K}_{\text{total}} &= 1.167 \times 10^{-4}\end{aligned}$$

Accuracy and Precision

There are two types of errors associated with a K-Ar date: errors in accuracy and errors in precision. Accuracy refers to how closely the determinations of ${}^{40}\text{Ar}$ and ${}^{40}\text{K}$ in a mineral sample represent the true values. Precision is a measure of the reproducibility of a determination in replicate analyses.

The analytical accuracy of a K-Ar age depends on the accuracy of the argon and potassium measurements, which are in turn dependent on the calibration of the ${}^{38}\text{Ar}$ tracer and

the potassium standards (Dalrymple and Lanphere, 1969). This error is generally less than one percent. The accuracy is also affected by uncertainties in the decay constants and in the isotopic compositions of the tracer, natural potassium and atmospheric argon, which are all considered to be small (Dalrymple and Lanphere, 1969). The accuracy of an age determination is often not included in the \pm figure with an age however, because it is not possible to know how closely a calculated age actually represents the true age.

The precision of a K-Ar age depends mainly on the atmospheric argon correction, due to the error introduced when one large number is subtracted from another, as was discussed previously. The precision ideally is the dispersion parameter of a large number of measurements made on aliquants of the same sample, but in actuality multiple measurements are not often made. The stated precision of an age is usually an estimate of what the percent error would be if multiple measurements were made. The estimates are based on the quality of the data, previous replication experiments in the same laboratory, and the factors affecting the uncertainty. Cox and Dalrymple (1967) give a formula for estimating standard deviation of analytical precision, based on the standard deviations of the potassium analyses, the tracer calibration, the $^{40}\text{Ar}/^{38}\text{Ar}$ ratio, the $^{36}\text{Ar}/^{38}\text{Ar}$ ratio, and the fraction of ^{40}Ar that is radiogenic.

The \pm figures which are quoted for the isotopic ages reported in this study are estimated analytical uncertainties based on the precision of the potassium and argon analyses. In general, this represents the combined precision of previous argon and potassium analyses at the U.S. Geological Survey, Menlo Park, California, based on replicate determinations of both argon and potassium. The \pm figures are on the order of 3% to 5% within the range of atmospheric argon content determined for the samples in this study. The analytical uncertainties for the individual samples were assigned by M.L. Silberman (written commun.) based on the duplicate potassium analyses and the atmospheric argon contents of the samples following the principles discussed in Dalrymple and Lanphere (1969). Within the period of time that the analytical work on these samples was being performed, the reproducibility of all K-Ar ages at the Menlo Park laboratory was well within the estimated 3% figure (M.L. Silberman, written commun., 1981).

POTASSIUM-ARGON RESULTS AND DISCUSSION

The K-Ar ages and the K and Ar analytical data are listed in Table 6. All of the coexisting mineral pairs and triplets which were dated yield discordant ages; that is, there is no agreement within analytical precision in the ages determined on two or three different mineral phases from the same ash layer. These discordant ages from a

Table 6. Analytical data for K-Ar age determinations of southern Nevada tephra layers. Analysts: L.B. Gray and M.L. Silberman. K_2O percents are the average of two analyses.

Sample	Tephra Layer	Mineral Dated	Percent K_2O	$^{40}Ar_{rad.}$ (móles/gm)	$\frac{^{40}Ar_{rad.}}{^{40}Ar_{total}}$	Age (m.y.)
PRL-1	Point of Rocks Lower	Sanidine	8.28	7.787×10^{-10}	0.846	64.2 ± 1.9
PRL-2		Plagioclase	0.733	1.558×10^{-10}	0.940	141.8 ± 4.2
PRU-1	Point of Rocks Upper	Biotite	7.71	0.1317×10^{-10}	0.632	11.8 ± 0.3
PRU-2		Sanidine	7.06	2.235×10^{-10}	0.754	21.9 ± 0.7
PRU-3		Plagioclase	0.820	0.7906×10^{-10}	0.284	65.7 ± 3.3
BL	Badlands Lower	Glass	5.78	0.6018×10^{-10}	0.566	7.2 ± 0.2
BU	Badlands Upper	Glass	2.76	0.2436×10^{-10}	0.287	5.9 ± 0.3
PVL-1	Pahranagat Valley Lower	Biotite	8.01	0.8153×10^{-10}	0.346	7.1 ± 0.4
PVL-2		Sanidine	7.83	2.028×10^{-10}	0.722	17.9 ± 0.5
PVL-3		Plagioclase	0.686	0.5904×10^{-10}	0.612	58.8 ± 1.8
PVU-1	Pahranagat Valley Upper	Sanidine	7.93	2.000×10^{-10}	0.810	17.4 ± 0.5
PVU-2		Plagioclase	0.370	0.4059×10^{-10}	0.777	74.5 ± 2.2
PVR-1	Pahranagat Valley	Sanidine	6.61	1.551×10^{-10}	0.708	16.2 ± 0.5
PVR-2	Roadcut	Plagioclase	0.509	0.4727×10^{-10}	0.657	63.3 ± 1.9

single layer are not surprising in view of the fragmental nature of the ash layers. As discussed previously, dating of pyroclastic rocks is often a problem due to the incorporation of contaminating material. The results obtained here serve to emphasize that this problem is especially critical in reworked ash layers and also support the supposition that the different mineral phases within a single layer will not be contaminated to the same degree. This does not indicate, however, that volcanic ash layers are entirely unsuitable for radiometric age determinations or that the results obtained from the ash are meaningless. The determinations, at the very least, provide upper and lower limits on the time of the deposition of the ash layers. The discordances are evaluated in terms of stratigraphic relationships, the source and degree of contaminants, and to a lesser extent, subjective judgements. Some reasonable interpretations and age limits are proposed for each locality.

All of the mineral and glass concentrates were carefully examined in oil with a petrographic microscope to identify the type and degree of any contamination present (See Appendix II for detailed descriptions). All possible sources of contamination were determined by reviewing geologic maps of the study area. Each of the three localities will be discussed separately.

The Point of Rocks Tephra Layers

The Point of Rocks Lower (PRL) ash layer yielded a 141.8 ± 4.2 m.y. plagioclase age and a 64.2 ± 1.9 m.y. sanidine age. The Point of Rocks Upper (PRU) ash layer yielded a 65.7 ± 3.3 m.y. plagioclase age, a 21.9 ± 0.7 m.y. sanidine age, and an 11.8 ± 0.3 m.y. biotite age. Although the plagioclase and sanidine ages for the two layers are in the correct stratigraphic order, these are anomalously old ages, as the field relations suggest a much younger age for the alluvial fan in which the ash layers occur. The discordances among phases from the same layer also indicate erroneous determinations; the plagioclase ages are much greater than the sanidine ages, for both layers, and the sanidine age of the upper layer (PRU) is greater than the biotite age from that layer. Apparently the phases contain varying degrees of contamination, which is resulting in the widely discordant ages.

On the basis of the field evidence, it appears that the 11.8 m.y. biotite age from the Point of Rocks Upper (PRU) layer is a reasonable determination. This is supported by a fission-track age of 11.5 ± 1.3 m.y. which was determined on zircons from the Point of Rocks Lower (PRL) ash layer (W.J. Carr, personal commun.). Carr sampled only one of the two ash layers, as he believed them to be either remnants of a single ash layer or to be so closely spaced in time that an age from only one layer would be sufficient to date the

deposition of the fan. On the basis of mineralogic differences, it was determined that the zircons were collected from the layer which is here termed the Point of Rocks Lower (PRL) layer (presence of clinopyroxene and absence of hornblende, as opposed to the opposite relationship in the Point of Rocks Upper (PRU) layer). The 11.8 ± 0.3 m.y. biotite age from the upper layer (PRU) and the 11.5 ± 1.3 m.y. zircon age from the lower layer (PRL) are so close in time as to be indistinguishable within the limits of analytical precision for the two determinations. This is consistent with the supposition that the two ash layers were deposited nearly contemporaneously and also accounts for the apparent inversion of the two ages which is a result of the large error in the analytical precision of the zircon age. A careful microscopic examination of the biotite concentrate used for the age determination indicates that approximately 20% is oxybiotite (red-brown oxidized biotite), a factor which apparently has not affected the age, considering that the biotite and zircon ages are concordant.

Assuming that the 11.8 m.y. age for the Point of Rocks Upper (PRU) layer is correct, the anomalously old plagioclase and sanidine ages from both the upper and lower layers must be resolved. Careful microscopic examination of the sanidine concentrates from both layers revealed the presence of a small amount of a grid-twinned feldspar originally thought to be volcanic anorthoclase (Figure 15). It was

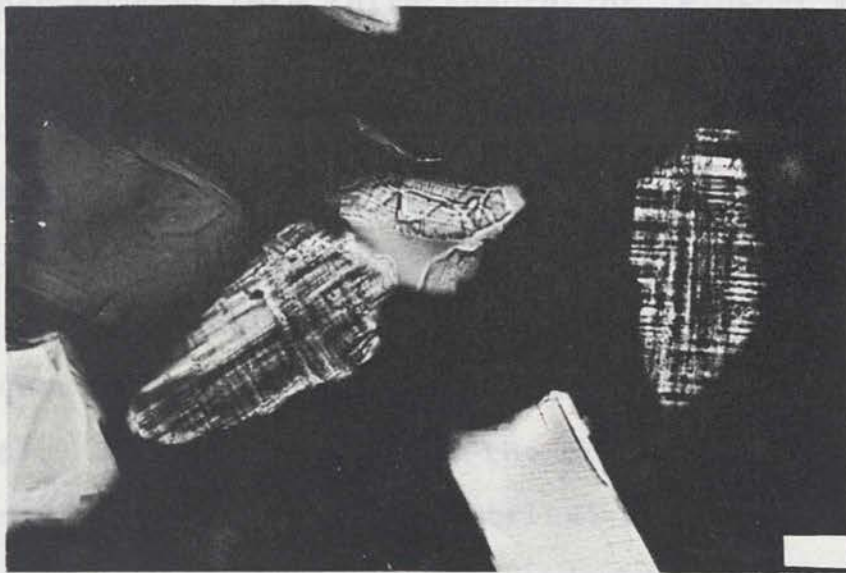


Figure 15. Grid-twinned feldspar crystals (microcline) in the Point of Rocks Lower sanidine concentrate. Scale bar = 50 μm .

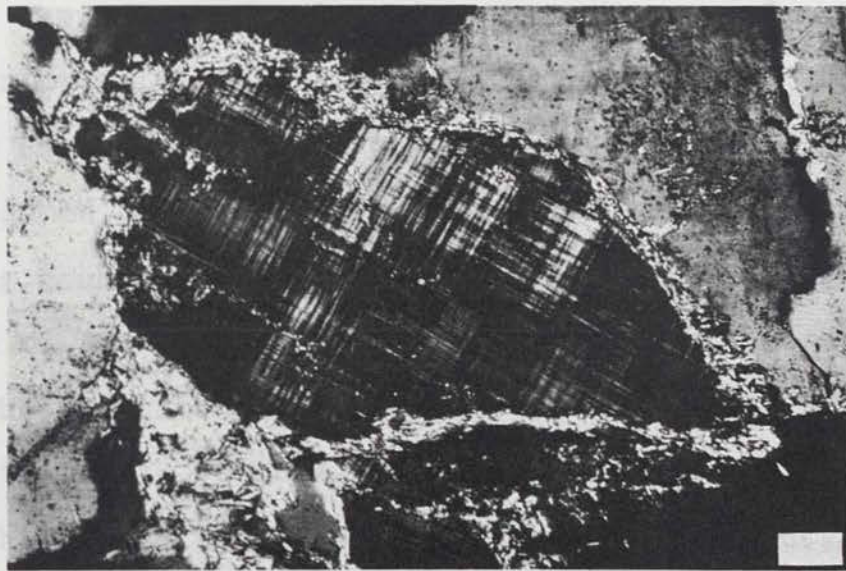


Figure 16. Microcline crystal in a clast of Precambrian Stirling Quartzite from the Point of Rocks fanglomerate. Scale bar = 50 μm .

later suspected that this third species of feldspar might be a detrital component, as the presence of three primary feldspars would not be expected under equilibrium conditions in a magma chamber. Thin-sections were prepared from quartzite clasts collected from the Point of Rocks fanglomerate. It was found on microscopic inspection of the thin-sections that the quartzite contains abundant grid-twinned microcline (Figure 16). This confirmed that the grid-twinned feldspar in the sanidine concentrates is detrital microcline and not volcanic anorthoclase as originally thought. It is not possible to remove the microcline from the sanidine concentrate by heavy liquid methods as sanidine and microcline have identical densities. It was then necessary to identify the source of the quartzite clasts so that the age of the contaminant microcline crystals could be estimated. The quartzite is fine to medium grained and grayish purple to pale purple in color. It is derived either from the northern Spring Mountains or the Specter Range (see Figure 1 for the Point of Rocks locality). The petrologic characteristics of the quartzite indicate that it is the Precambrian Stirling Quartzite (Cornwall, 1972, p. 5). It is therefore assumed that the microcline in the sanidine concentrate is of Precambrian age. Knowing the approximate age of the detrital microcline and assuming an approximate 12 m.y. true age of the Point of Rocks ash layers (from the biotite), it is possible to calculate the percent of microcline which would be necessary to cause the anomalous sanidine

ages of 21.9 m.y. for the upper layer (PRU) and 65.2 m.y. for the lower layer (PRL). This is done using the following equation:

$$X(^{40}\text{Ar}_{\text{rad}} \text{ content of primary mineral}) + (1-X)(^{40}\text{Ar}_{\text{rad}} \text{ content of contaminant}) = \text{Total } ^{40}\text{Ar}_{\text{rad}} \text{ content of mineral concentrate}$$

where:

X = proportion of the mineral concentrate which is primary phenocrysts (i.e., from the volcanic eruption)

1-X = proportion of the mineral concentrate which is contaminant phenocrysts

The radiogenic ^{40}Ar content of the primary mineral and the contaminant can be estimated using a Potassium-Argon Nomogram (Dalrymple and Lanphere, 1969). The nomogram is a graphical device for determining K-Ar ages, K_2O contents and radiogenic ^{40}Ar contents. Knowing two of these quantities, the third can be determined with the nomogram. For the upper layer (PRU), 11.8 m.y. old sanidine with a 7% K_2O content should contain 1.23×10^{-10} mole/gm of radiogenic ^{40}Ar . Precambrian microcline (assume 1 billion yrs) with 7% K_2O should contain 1.40×10^{-8} mole/gm of radiogenic ^{40}Ar . The actual measured radiogenic ^{40}Ar content from PRU sanidine is 2.24×10^{-10} mole/gm, as seen in Table 6. Presumably this total radiogenic ^{40}Ar is from both the

sanidine and the microcline. Using these values in the above equation gives:

$$X(1.23 \times 10^{-10}) + (1-X)(1.40 \times 10^{-8}) = 2.24 \times 10^{-10}$$

${}^{40}\text{Ar}_{\text{rad}}$ from Sanidine ${}^{40}\text{Ar}_{\text{rad}}$ from Microcline Total ${}^{40}\text{Ar}_{\text{rad}}$ from mineral concentrate

Solving the equation yields $X=.99$ and $1-X=.01$. In other words, an 11.8 m.y. old sanidine sample would have to contain only 1% microcline of Precambrian age (1 billion yrs) to result in an erroneous age determination of 21.9 m.y. If a 600 million year age is assumed for the Precambrian microcline, the equation indicates only 2% contamination is needed. The sanidine concentrate from the Point of Rocks Upper (PRU) layer contains approximately 1-2% microcline (Appendix II), estimated from microscopic examination.

Similar calculations were also made for the sanidine concentrate from the Point of Rocks Lower (PRL) layer. Considering the closeness in age of the PRL zircon determination and the PRU biotite determination, it would seem that the sanidine determination from the lower (PRL) layer should give an age nearly identical to the sanidine age of the upper (PRU) layer, assuming the same degree of contamination. Instead, the sanidine from PRL yields an age of 64.2 m.y., approximately three times as great as PRU! Assuming the correct age is actually near 11.8 m.y. and using 8.3%

K_2O contents for both the sanidine and the microcline, the amount of Precambrian (1 billion yrs) microcline needed to produce a 64.2 m.y. age is 4%. If a 600 million year age is assumed for the microcline, 7% contamination is required. Upon careful examination of the sanidine concentrate from PRL it was confirmed that it does indeed contain much more microcline than PRU, being on the order of 5-8% microcline.

While the observed degree of microcline contamination supports the discordant sanidine ages, such an interpretation for the plagioclase discordances is not as easily inferred. The plagioclase concentrates apparently contain a greater degree of contamination than the sanidine, as the plagioclase ages are much older. The presence of an older exotic plagioclase component is not as easily detected as the nonvolcanic microcline. Both the Upper (PRU) and Lower (PRL) plagioclase concentrates contain 15-20% subrounded, cloudy grains which appear to be of detrital origin. This evidence plus the numerous sources of Precambrian and Paleozoic plagioclase in the northern Spring Mountains supports the contention that older plagioclase grains are the cause for the anomalous ages.

Contamination calculations for the plagioclase determinations were made assuming an approximate 12 m.y. correct age and similar K_2O contents of both the primary and the contaminant plagioclase grains. The calculations indicate that the lower layer (PRL) would require approximately 10%

contamination from Precambrian (1 billion yrs) plagioclase to result in an erroneous age of 141.8 m.y. The upper layer (PRU) would require only 4% Precambrian plagioclase to result in an age of 65.7 m.y. If the calculations are made assuming an early Paleozoic age (500 million yrs) of contamination, the lower layer (PRL) requires 26% contamination and the upper layer requires 10% contamination for the resultant ages. If the plagioclase discordances are in fact the result of contamination, it appears that the source is probably Precambrian rocks and that the plagioclase exhibits approximately twice the degree of contamination as the sanidine.

The evaluation of the Point of Rocks age discordances is based on the premise that the biotite of the upper layer (PRU) is giving a correct age. That this premise is a valid one is supported by several lines of evidence. The biotite component is less likely than the feldspar phases to contain older contaminants, as biotite is physically less resistant than the feldspars. Furthermore, a petrographic examination and X-ray diffraction analysis of the biotite indicate there is no obvious exotic component. The biotite age also agrees well with the previous fission-track age determination on zircon. This zircon age provides an independent means of age control, based on a different radiometric method and a different mineral phase. Such agreement in ages obtained from different methods is considered good evidence that the

ages are correct (Dalrymple and Lanphere, 1969). On the basis of the obvious microcline contamination and the concordant fission-track determination, an approximate K-Ar age of 12 m.y. is proposed for the two Point of Rocks ash layers. The overlapping zircon and biotite ages, from the lower and upper layers, respectively, indicate that deposition of the two layers was probably nearly contemporaneous and that their ages are not resolvable within the limits of the analytical precision obtained here.

The Badlands Tephra Layers

The Badlands Lower (BL) and Badlands Upper (BU) ash layers yielded glass ages of 7.2 ± 0.2 m.y. and 5.9 ± 0.3 m.y., respectively. While the two glass ages are in agreement with the stratigraphic sequence of the ash layers, there are no other radiometric age determinations with which to compare them. The layers have sparse phenocrysts and the shards are uniform in morphology, so contamination is not considered a factor here. The ash is water-laid and shows no evidence of reworking.

The glass shards appear suitable for dating purposes; they are clean, fresh, and almost entirely free of inclusions. However, hydration of the glass has occurred and this indicates the accuracy of the age determinations is questionable. Various studies of hydrated volcanic glasses (Lipman, 1965; Noble, 1967; Lipman and others, 1969; Jezek

and Noble, 1978) have shown that such glasses have undergone secondary chemical changes as a result of leaching and ion exchange by groundwater. The most significant variations appear to be the alkali contents, especially sodium and potassium. Hydrated glasses contain appreciably less Na_2O and may contain either more or less K_2O than their nonhydrated counterparts. This gain or loss of potassium will result in erroneous K-Ar ages from the glass, but the magnitude of the error is difficult to assess. A gain of potassium would naturally be expected to result in an age that is too young, as the relative proportion of radiogenic argon to potassium will be less. This will depend, however, on how soon after deposition the potassium gain occurs. If hydration occurs shortly after deposition, then the gain in potassium should have no effect on the K-Ar age of the glass. This is because production of radiogenic argon from the added potassium begins when the alteration occurs. The ratio of this additional radiogenic argon to added potassium will correspond to the time of alteration. A short time span between deposition and alteration will therefore not produce a significant error. The longer the interval between deposition of the ash and addition of potassium, the younger will be the apparent K-Ar age. The effect of a loss of potassium similarly depends on when the loss occurs. If potassium is lost (i.e., alteration of the glass occurs) soon after deposition of the ash, then the

effect on the age is minimal, as the radiogenic argon produced from the remaining potassium will correspond to the time of alteration. At longer time intervals following deposition, the loss of potassium is probably also accompanied by loss of some or possibly even all of the radiogenic argon which has been produced up to that point. The more argon which is lost, the younger will be the apparent K-Ar age. Table 7 summarizes the effects of a gain or loss of K_2O .

It would seem reasonable to assume that hydration of the glass shards occurred soon after deposition of the ash layers. Ross and Smith (1955) indicate, in their study of volatiles in volcanic glass, that hydration may begin during the later cooling stages of the glass. Friedman and Smith (1960) have developed a hydration method of dating obsidian which shows that hydration ensues when fresh surfaces of the glass are exposed to the atmosphere. Although the rate of hydration varies with temperature and chemical composition of the glass, a significant degree of hydration occurs after only a few thousand years (Friedman, 1968; Friedman and Long, 1976). Since hydration occurs when water adsorbed on the surface of the glass diffuses inward, a smaller grain size and therefore a greater surface area to volume ratio, should facilitate hydration. Volcanic glass shards, being extremely small (predominantly less than 40-mesh or 0.42 mm) and unconsolidated, would be expected to

Table 7. Effect of a gain or loss of K_2O on the apparent potassium-argon age of hydrated volcanic glass. See text for detailed discussion.

K_2O Gain	Effect on Age	K_2O Loss	Effect on Age
EARLY	Minimal - apparent age may be slightly too young.	EARLY	Minimal - apparent age will correspond to time of K_2O loss.
LATE	Apparent age will be much too young; the later the time of K_2O gain, the younger will be the apparent age.	LATE - without argon loss - with argon loss	Apparent age will be older, as the $^{40}K/^{40}Ar_{rad}$ will be decreased Depends on relative amounts of K_2O and ^{40}Ar which are lost. If ^{40}Ar loss exceeds K_2O loss, age will be too young.

hydrate rapidly. If a simple gain or loss of potassium occurred only during hydration, then the error in the K-Ar age determinations would be small. Noble (1967) and Jezek and Noble (1978) indicate, though, that hydration of glass is a continuing process which occurs in stages. The early stage involves only a slight amount of ion exchange, followed by additional hydration and more intense ion exchange. Potassium content may initially increase and then later be leached during continued alteration. The hydration and alteration history of the glass, therefore, may be a complex process involving a time span which is virtually impossible to evaluate. Moreover, if the hydrated glass does not represent a closed system with respect to potassium, then it may not be closed with respect to argon either. As stated previously, early argon loss will not have a significant affect on the K-Ar age. Continued diffusion of argon, though, will render the age determination meaningless.

To evaluate the likelihood of a quantitative retention of argon, it is useful to review some previous K-Ar age determinations on hydrated glass. Armstrong (1970) suspected that volcanic glass might yield unreliable K-Ar age determinations due to a loss of argon. In order to assess the expected argon loss, he dated unweathered, hydrated glass from two ash-flow tuffs in Nevada and Utah. The tuffs had previously been precisely dated, by the K-Ar method,

using the mineral phases. The ages obtained on the hydrated glass were 7-10% too low, a much smaller discrepancy than was expected. Marvin and others (1970b) compared the isotopic ages of welded, hydrated glasses with their associated mineral phases to determine if the glasses had been closed systems with respect to argon. Three of the hydrated glasses gave ages close to the apparent K-Ar age of the mineral phases, but the analytical error on two of the glass determinations is high (30-50%). Two of the hydrated glass ages are younger than the apparent mineral ages, one being 16% low and the other 28% low. Marvin and his co-workers concluded that the welded, hydrated glasses were quantitatively to nearly quantitatively retentive of radiogenic argon. Evernden and others (1964) dated hydrated glass shards from two ash layers in stratigraphic sequence in the Glens Ferry Formation, Idaho, obtaining ages of 3.2 m.y. for the upper and 3.3 m.y. for the lower layer. They considered these ages to be only slightly too young, as an age of 3.5 m.y. was obtained on fresh plagioclase and pyroxene phenocrysts from an intervening, altered basalt flow. Armstrong and others (1975) later indicated that these Glens Ferry dates were much too young, as they obtained ages ranging from 4.4 to 6.2 m.y. on fresh lava flows in the Glens Ferry Formation. They consider the Evernden and others (1964) dates to be anomalous due to the use of altered material, and suggest exposure to geothermally

heated groundwater as the cause of the alteration. They concede, however, that the 6.2 m.y. figure may be too high due to errors in atmospheric argon correction. If the correct age for the Glenns Ferry ash is approximately 4.4 m.y. then the hydrated glass yielded ages which are 27% too low. In a more recent study involving these same Glenns Ferry volcanic units, Neville and others (1979) report that the results of their paleomagnetic investigations favor the 3.5 m.y. age of Evernden and others (1964), and they accept this younger age as being correct. This indicates an error in the hydrated glass ages of only 8.5% (3.2 m.y. compared to 3.5 m.y.) which is identical to the analytical error (± 0.3 m.y.) associated with the 3.5 m.y. plagioclase and pyroxene age. Silberman and others (1978) report an age on hydrated glass, from a vitrophyre in an ash-flow tuff in Nevada which apparently agrees within analytical uncertainty with the associated mineral ages.

These previous K-Ar determinations on hydrated glass yield ages which range from 7% to 28% too young, presumably due to either a gain or loss of potassium, loss of argon, or both. Analysis of the two Badlands ash layers indicate they are appreciably hydrated, the lower (BL) containing about 4.5% H_2O and the upper containing 5.5% H_2O . According to Jezek and Noble (1978), hydration in excess of about 3% H_2O is accompanied by significant amounts of ion exchange. The potassium analysis of the Badlands Lower glass shows a K_2O

content of 5.78% (see Table 6). This is slightly higher than the microprobe results (see Table 4) due to the fact that probe analyses are generally done on the central and therefore less altered portions of the shards. The 5.78% K_2O is higher than the 4.5-5% generally expected from a rhyolitic glass, and almost certainly signifies a gain of potassium in the hydrated glass. The Badlands Upper glass, on the other hand, contains a much lower K_2O content of only 2.76% (Table 6). Although this might be interpreted as a considerable loss in potassium, the dacitic composition of this glass (Table 4: low SiO_2 , high FeO , CaO , and Na_2O) indicates a lower initial K_2O content would be expected. The 2.76% probably represents a gain in potassium content. Both of these glasses are, in all likelihood, yielding low K-Ar ages due to the fact that they are not closed systems to potassium or argon. The previous errors obtained on hydrated glasses suggest 10% to 30% to be a possible range in error. The Badlands Lower ash, with an apparent age of 7.2 m.y., may actually be from 8.0 to 10.3 m.y., which represents 10% and 30% errors, respectively. Similarly, the Badlands Upper ash, with a 5.9 m.y. apparent age, may actually be from 6.5 to 8.4 m.y.

As stated previously, the apparent glass ages are stratigraphically correct. In addition, the apparent time span between their deposition (1.3 m.y.) appears reasonable from their field relation. If these glasses have been dif-

fusing argon continuously since the time of their hydration, or even at various times since, then the stratigraphically correct time gap between them requires that they have both lost the same relative proportion of their radiogenic argon. In view of the widely differing potassium percentages of the two glasses, which is assumed to reflect original difference, proportionate argon losses is not considered likely, as they have produced very different amounts of argon. It would seem reasonable to assume, then, that a continuous diffusion of argon has not taken place and that if there have been periods of argon loss they were probably early in the hydration history of the glasses. This reasoning favors a relatively small error in the glass ages, indicating an estimated error of 30% is probably excessive. If 10% to 20% errors are calculated for the glass ages, this results in an 8.0 to 9.0 m.y. range for the Badlands Lower ash and a 6.5 and 7.4 m.y. range for the Badlands Upper ash. This precludes the possibility of the Badlands Lower (BL) being correlative with the 2.0 m.y. old Pearlette B tephra, as the chemical and petrographic results seemed to suggest.

Although the 8.0-9.0 m.y. and 6.5-7.4 m.y. glass ages for the Badlands Lower and Upper, respectively, are considered to be reasonable, there is no independent means of evaluating the validity of the glass determinations. Ideally, glass ages should be determined for the Point of Rocks tephra layers, and then compared to the K-Ar and

fission-track mineral ages, to provide an approximation of the magnitude of error which might be expected from hydrated glass shards of this age. In addition, determination of the K-Ar mineral ages from the Badlands layers would be desirable, as these two water-laid ash layers almost certainly are the least contaminated of the seven tephra layers and would be expected to yield reliable mineral age determinations for this study. Concentration of a sufficient quantity of mineral grains from these phenocryst-poor layers would be difficult and time consuming.

The Pahrnagat Valley Tephra Layers

The Pahrnagat Valley Lower (PVL) ash layer yielded a 58.8 ± 1.8 m.y. plagioclase age, a 17.9 ± 0.5 m.y. sanidine age, and a 7.1 ± 0.4 m.y. biotite age. The Pahrnagat Valley Upper (PVU) ash layer yielded a 74.5 ± 2.2 m.y. plagioclase age and a 17.4 ± 0.5 m.y. sanidine age. The Pahrnagat Valley Roadcut (PVR) ash layer yielded a 63.3 ± 1.9 m.y. plagioclase age and a 16.2 ± 0.5 m.y. sanidine age. The discordances of the three mineral phases exhibit a relationship similar to that of the Point of Rocks phases. The plagioclase ages are consistently much greater than the sanidine age from the same layer, and in the lowermost layer (PVL) the sanidine age is greater than the biotite age. In view of the seemingly accurate biotite determination from the Point of Rocks, it is tempting to accept the 7.1 m.y.

biotite age from Pahranaagat Valley Lower as a correct determination. The biotite is remarkably fresh and uniform, and contains only a small percentage (5%) of oxybiotite (see Appendix II). Such an acceptance would indicate the sanidine concentrates (and the plagioclase) from the three layers are contaminated with older grains. The chronological order of the sanidine ages, however, is in excellent agreement with their stratigraphic sequence (17.9 m.y., 17.4 m.y., and 16.2 m.y., from lowermost to uppermost). This would not be expected from a series of contaminated ash layers, as it indicates they are all contaminated to the same degree. The plagioclase ages are obviously anomalous. They are much older than the geologic environment would suggest, as the deposition of the alluvial fan which contains the ash layers clearly postdates basin and range faulting. The plagioclase ages also show no order or relationship to their stratigraphic sequence, as the lowermost (oldest) ash layer (PVL) yields the youngest plagioclase age.

Examination of aerial photographs (1:60,000 scale) of the Pahranaagat Valley and Alamo Range areas reveal that the alluvial material in which the ash layers were deposited lies above the Kane Wash Tuff (Noble, 1968). The Kane Wash Tuff, with a K-Ar age of about 13 m.y., conformably overlies the Hiko Tuff, which has been dated by the K-Ar method at 18-19 m.y. (Noble and McKee, 1972). Both of these tuffs,

which comprise the Alamo Range east of Pahrana-gat Valley, are tilted approximately 20° to the west. The alluvial gravels and sediments overlying these tuffs are also tilted to the west, gently along the valleyward parts of the fans, gradually increasing and approaching the 20° regional tilt at the apex of the fans. The Pahrana-gat ash layers occur in the lowermost distal portion of the fan. They must, on the basis of stratigraphic evidence, have been deposited after the Kane Wash Tuff and are therefore younger than 13 m.y. The increased tilting in the upper portions of the fans suggest that deposition of the fan-glomerate began soon after emplacement of the Kane Wash ash-flows, before and/or during faulting and tilting of the Kane Wash and Hiko tuffs.

On the basis of the aerial photo interpretation, the sanidine and plagioclase determinations represent anomalous ages, as deposition of the ash took place sometime after 13 m.y. A review of the geologic units exposed in the Alamo Range shows no source of contamination, other than the Hiko and Kane Wash tuffs, which might account for the excessive plagioclase discordances. Paleozoic units do occur to the north in the Hiko Range and on the west side of Pahrana-gat Valley in the Pahrana-gat Range. It does not seem likely that these could be the source of any detrital material on the east side of Pahrana-gat Valley, considering the present topographic configuration. If the contamination was derived at a time when a more subdued topography existed in this

area, such as before uplift and tilting of the Kane Wash Tuff, then incorporation of Paleozoic material is possible. Later reworking of the ash layers would account for their present position in the fan. Alternatively, contamination may also be the result of older material torn from the surrounding country rock during the eruption of the Pahrana-gat Valley tephra layers.

It seems more than coincidental that the sanidine ages from Pahrana-gat Valley Lower (PVL) and Upper (PVU) are very close to the age of the Hiko Tuff (18-19 m.y.). The overlap in the analytical errors between the two layers makes them indistinguishable in age from one another. The glass shard morphology and chemistry indicates PVL and PVU are distinctly different, but their mineralogy and sanidine ages argue in favor of association with the Hiko Tuff. Geologic relationships, conversely, attest to an age younger than 13 m.y. This does not preclude the possibility that the phenocryst assemblages of the two layers are largely the result of detrital contamination, presumably from the Hiko Tuff. The presence of many subrounded, altered grains in the sanidine concentrates confirms detrital contribution. Mixing of phenocrysts, though, from both the ash fall and the older Hiko Tuff should result in an age younger than Hiko. In addition, it seems likely that sediment would also have been derived from the Kane Wash tuff, as this is more extensively exposed in the vicinity of the fan than is the

Hiko Tuff. The sanidine ages are probably the result of contamination from both Hiko and Kane Wash Tuffs plus older material also, as suggested by the plagioclase ages. The Pahrnagat Valley Roadcut sanidine age (16.2 m.y.) reflects sources of contamination similar to those for the lower two layers. The major weakness in this explanation is that it does not account for the correct stratigraphic relationship between the sanidine ages, as this apparently demands all three layers are contaminated to nearly the same degree. As demonstrated by the Point of Rocks locality, reworked tephra from the same depositional environment are likely to contain differing percentages of contamination.

The biotite age of 7.1 m.y. from Pahrnagat Valley Lower probably represents the most reasonable determination from this locality. The biotite concentrate is very fresh and uniform. This would not be expected if older contaminating biotite were present. In the absence of any other age control, the biotite can only be taken as a minimum age for the lower layer (PVL). It is therefore concluded that the Pahrnagat Valley ash layers were erupted sometime between 13 m.y. and 7 m.y. and have been extensively reworked and redeposited since that time. In view of the uniform appearance of the biotite, the lower half of the age range is probably more reasonable.

SUMMARY

Seven silicic tephra layers from southern Nevada have been determined, on the basis of their chemical and petrographic characterization, to represent seven distinct volcanic eruptions. Their K-Ar determinations of 6-12 m.y. indicate they are the result of Miocene volcanism. The tephra layers are summarized here.

THE POINT OF ROCKS TEPHRA LAYERS

The Lower (PRL) and Upper (PRU) tephra layers yield zircon fission-track (11.5 ± 1.3 m.y.) and biotite K-Ar (11.8 ± 0.3 m.y.) ages which are not resolvable within the limits of their analytical error. That the tephra represent two separate eruptions is substantiated by both chemical and petrographic analyses. Although their major element compositions are similar, the lower layer (PRL) contains significantly more Fe and Cl than the upper layer (PRU). The XRF analyses result in a similarity coefficient of only .74, well below the level expected for correlation. Petrographic distinctions include the presence of pyroxene in the lower layer (PRL) and not in the upper (PRU), and conversely, the presence of hornblende in the upper layer (PRU) and not in the lower. In addition, the upper layer (PRU) contains biotite as a major component of its phenocryst assemblage

and has a much lower percentage of plagioclase than the lower layer (PRL).

Both the layers contain predominantly pumiceous glass shards, with common nonvesicular shards also. Their average refractive indices are identical (1.497).

K-Ar age determinations, when evaluated in terms of the probable age and percentage of contamination, indicate an approximate 12 m.y. age is likely. The two layers were deposited in a fanglomerate sequence, probably nearly contemporaneously. The fanglomerate is considered correlative with equivalents of the Muddy Creek Formation (W.J. Carr, personal commun.).

THE BADLANDS TEPHRA LAYERS

Both of the Badlands tephra layers exhibit a very distinctive platy shard morphology, although the upper layer (BU) contains abundant pipe-like vesicle shards also. Phenocrysts are sparse in both layers. The lower layer (BL) is silvery gray and resembles the Pearlette ashes from the Yellowstone area. As discussed previously, the mineralogy, the glass shard morphology and refractive index, and the glass chemistry are all suggestive of a correlation with the 2.0 m.y. old Pearlette B tephra. The K-Ar age determination of 7.2 m.y., which is considered to be a minimum due to hydration of the glass shards, precludes the possibility of this correlation. The lower layer has relatively high Fe

and Cl contents and is similar in major element chemistry, though not minor and trace elements, to the Point of Rocks Lower tephra (PRL). It has an indistinctive refractive index of 1.499, but contains considerably more quartz (45%) than any of the other six tephra layers. An approximate K-Ar age of 8.0-9.0 m.y. (rather than the 7.2 m.y. determination) is considered probable in terms of the hydration effects on the glass shards.

The Badlands Upper layer is distinguished from all of the tephra layers of this study because it is dacitic rather than rhyolitic in composition. The glass contains significantly less Si than the rhyolitic tephra and more Fe, Mg, Mn, Ca, Ti and Na. Its refractive index of 1.521 is much higher than the general 1.497-1.503 range of the other tephra. It is petrographically distinctive in its lack of sanidine and high percentage of pyroxene. These features provide a unique characterization for the Badlands Upper (BU) tephra, thereby constituting an ideal stratigraphic marker horizon. The K-Ar age determination of 5.9 ± 0.3 m.y. is considered slightly low due to the hydration of the glass shards; 6.5-7.5 m.y. is considered a more reasonable age.

Field evidence indicates the two Badlands tephra were deposited in a lacustrine environment and have experienced very little reworking. The sequence of lake deposits in which they occur is part of the Muddy Creek Formation.

THE PAHRANAGAT VALLEY TEPHRA LAYERS

The Pahrnagat Valley tephra occur in stratigraphic succession in an alluvial fan. The two lowermost layers (PVL and PVU) contain abundant detrital lithic clasts of volcanic origin. The lowest layer (PVL) consists of two populations of glass shards; a microlite-rich population with a high refractive index (1.510) comprises 75% of the sample and a nonmicrolitic population with a lower refractive index (1.498) comprises 25% of the sample. Although the microprobe analysis of the microlitic glass (LM-7) is not considered meaningful due to the concentrations being in part a result of the microlites, the nonmicrolitic population (T25-4) is similar in major element chemistry to the Point of Rocks Lower (PRL) tephra. The XRF analyses of T25-4 and PRL are not similar. The nonmicrolitic shards (T25-4) are slightly high in Ca and Cl compared to the other rhyolitic tephra, and contain essentially no Ba. The Pahrnagat Valley lowest tephra contains large percentages of hornblende and biotite, which, along with its lack of pyroxene, is distinctive. A biotite K-Ar determination of 7.1 ± 0.4 m.y. is considered a minimum age, whereas the underlying 13 m.y. Kane Wash Tuff (ash-flow) provides an upper age limit. An age in the 7-10 m.y. range is considered likely.

The Pahrnagat Valley Upper layer is predominantly pumiceous, nonmicrolitic glass shards. It is distinguished

from the lower layer both in shard morphology and in its much lower percentages of biotite and hornblende. The upper layer (PVU) is remarkably similar to the Point of Rocks Lower in its mineralogy, shard morphology and refractive index (1.498), and chemistry. The only significant difference in mineralogy is the lack of hornblende in PRL (6% in PVU) and the presence of only one pyroxene in PVU (lacks orthopyroxene). The major element similarity coefficients range from .90-.95 and the minor and trace element coefficient is .91. Although the .91 is not high enough to be considered a correlation, it seems highly likely that these two tephra layers (PVU and PRL) are closely related, possibly even different eruptions from the same vent. Although the 17.4 m.y. sanidine age is undoubtedly the result of contamination, the upper layer (PVU) is probably very close in age to the lower layer (PVL). As with the lower layer, the Kane Wash Tuff provides an uppermost age constraint of 13 m.y., but an age closer to the 7 m.y. biotite determination of PVL is considered more likely (7-10 m.y.).

The Pahrnagat Valley Roadcut layer occurs above the other two Pahrnagat tephra, exposed in a roadcut to the south of the gully exposure. This tephra layer resembles the Badlands tephra in its platy shard morphology and sparse phenocrysts, but is distinctive in its refractive index (1.503) and chemistry. The major element suite is distinguished from the other rhyolitic tephra by the higher Fe,

Mg, Ca, and Ti, slightly higher Na, and lower K. Its Na and K values more closely resemble those to be expected from a nonhydrated rhyolitic glass (D.C. Noble, personal commun.). The minor and trace element concentrations are similar to PVU (.89 similarity coefficient). It is petrographically distinctive in its lack of biotite and higher percentage of sanidine than the other tephra layers. The discordant K-Ar ages are again considered excessive due to incorporation of detrital contamination. Although a 16.2 m.y. age is obtained on sanidine, PVR has a 13 m.y. upper age limit, as discussed previously for the lower two Pahrnagat Valley tephra (PVL and PVU), and is probably closer to 7 m.y. in age.

The seven tephra layers are each the result of a different volcanic eruption. In addition, none of the layers represents a previously known tephra, as no correlations with other late Cenozoic tephras in the western United States are obtained. Evaluation of the K-Ar age determinations indicate all of the tephra layers are in the 6-12 m.y. age range and are therefore late Miocene in age.

Each of the tephra layers is chemically and petrographically distinctive enough that it could be recognized if it were found to occur elsewhere in southern Nevada. However, the similarities in chemistry between some of these tephra layers and other known late Cenozoic tephras indicate the need for caution in future tephrostratigraphic studies in

CONCLUSIONS

Various conclusions are drawn from this investigation, some of which are more obvious and direct than others. The more direct conclusions, concerning the tephra layers themselves and their means of characterization, are discussed first. Some possible sources are suggested, based on the K-Ar age determinations. Additional conclusions regarding the Muddy Creek and equivalent formations are then discussed. These conclusions are indirect in nature and concern the age of the late Cenozoic basin-fill and its implication for the timing of basin-range faulting and subsequent basin-filling in the southern Great Basin region.

The seven tephra layers are each the result of a different volcanic eruption. In addition, none of the layers represents a previously known tephra, as no correlations with other late Cenozoic tephra in the western United States are obtained. Evaluation of the K-Ar age determinations indicate all of the tephra layers are in the 6-12 m.y. age range and are therefore late Miocene in age.

Each of the tephra layers is chemically and petrographically distinctive enough that it could be recognized if it were found to occur elsewhere in southern Nevada. However, the similarities in chemistry between some of these tephra layers and other known late Cenozoic tephra indicate the need for caution in future tephrostratigraphic studies in

this area. The similar major element suites of the Point of Rocks Upper tephra and the 0.7. m.y. Bishop Ash, and also of the Badlands Lower Tephra and the 2.0 m.y. Pearlette B tephra (Yellowstone) well illustrate the potential for erroneous correlations and once again emphasize the importance of multiple methods of analysis. As Sarna-Wojcicki (written and personal commun.) indicates, numerous older tephra layers in the western United States have characteristics similar to the Bishop Ash and the Pearlette tephra layers. The minor and trace element compositions have proved to be the most definitive means of distinguishing such tephra; comparisons based on petrography and major elements alone are not sufficient for correlation.

The results obtained here suggest that some methods which have proven useful in previous correlations of Quaternary tephra are not particularly diagnostic with late Tertiary tephra. The refractive indices in most instances do not vary enough to provide distinctions. The mineral assemblages, similarly, often resemble one another, although in several cases they do provide important distinctions. Of the chemical components, the minor and trace elements are much more distinctive than most of the major elements. The microprobe analyses, in fact, attest to the hazards of basing correlations of late Tertiary tephra of this region on major element chemistry. The minor and trace elements, on the other hand, have provided the strongest criteria for

the conclusion that none of the seven tephra layers are correlative. The K-Ar determinations have also provided much valuable information. Although detrital contamination resulted in erroneous apparent ages, the determinations have proven very useful in placing approximate limits on the time of eruption and indicate the tephra are undoubtedly older than Quaternary.

The similar chemical and petrographic characteristics of the majority of the tephra suggest that derivation from the same volcanic source area may be likely. The 6-12 m.y. age range is highly suggestive that at least some of the tephra are derived from the southwestern Nevada volcanic field (on and adjacent to the NTS). As described previously, numerous silicic tuffs were erupted from this field between 16 and 6 m.y. ago (Figure 17). Correlations of the air-fall tephra of this study with ash-flows on the NTS are difficult to assess on the basis of chemistry. Air-fall tephra, which is erupted during an initial explosive outburst, often does not have the same chemical composition as the subsequently erupted ash-flow tuff. This is due to the chemical differentiation that occurs in the upper portion of a magma chamber, resulting in compositional gradients within the magma (Smith and Bailey, 1966; Lipman and others, 1966; Hildreth, 1979; Smith, 1979). This compositional variation within an eruptive episode greatly hampers attempts to correlate air-fall tephra with their associated ash-flows. For

FIGURE 17. General stratigraphy of tuffs erupted from the southwestern Nevada volcanic field.

CALDERA	AGE m. y.	TUFF	MEMBER
Black Mountain Caldera	7.5-6	Thirsty Canyon Tuff	Labyrinth Canyon Member Gold Flat Member Dry Lakes Member Trail Ridge Member Spearhead Member
Timber Mountain Caldera	11.5-9.5	Timber Mountain Tuff	Ammonia Tanks Member Rainier Mesa Member
Claim Canyon-Oasis Valley Caldera	13-12.5	Paintbrush Tuff	Tuff of Pinyon Pass Tiva Canyon Member Yucca Mountain Member Pah Canyon Member Topopah Spring Member
Silent Canyon Caldera	15-13	Belted Range Tuff	Grouse Canyon Member Tub Spring Member
Sleeping Butte Caldera	16-14	Tuff of Tolicha Pk. Crater Flat Tuff Redrock Valley Tuff	

this reason, chemical correlations with the tuffs of the southwestern Nevada volcanic field are not attempted here. Such an investigation would require sampling and chemical analyses of air-fall tephra from basal exposures of the southwestern Nevada ash-flows, if such exposures could be found. However, some possible sources in the southwestern Nevada volcanic field can be speculated upon.

On the basis of the fission-track age of 11.5 ± 1.3 m.y., Carr (personal commun.) considers the Point of Rocks Lower tephra to be correlative with the Paintbrush Tuff from the Claim Canyon-Oasis Valley caldera complex. This tuff consists of five members erupted between 13.2 and 12.5 m.y. ago (Byers and others, 1976). Correlation with the Paintbrush Tuff requires that the uppermost age limit ($11.5 + 1.3 = 12.8$ m.y.) be accepted as the probable age of the lower layer (PRL). The upper layer (PRU), with an analytical error of 0.3 m.y. on its biotite determination, has an apparent biotite age of 11.5 to 12.1 m.y. Although it is chemically and petrographically distinctive from the lower layer (PRL), it may correspond to a later member of the Paintbrush Tuff (indicating the 11.8 ± 0.3 m.y. biotite age is slightly too young). Alternatively, the upper layer (PRU) may be air-fall tephra which preceded the eruption of the Timber Mountain Tuff. This tuff consists of two members erupted between 11.5 and 9.5 m.y. ago from the Timber Mountain Caldera. The lowermost Rainier Mesa Member seems a

more likely possibility than does the upper Ammonia Tanks Member, due to the similarity in age of PRU and the Rainier Mesa Member.

The two Badlands tephra, considered to be approximately 8-9 m.y. and 6.5-7.5 m.y. in age, may also be correlative with the southwestern Nevada volcanics. The 8-9 m.y. age of the lower layer (BL) is within a time range during which no volcanic activity was occurring in the southwestern Nevada volcanic field. Perhaps this indicates the lower layer is slightly older than 8-9 m.y. and possibly is correlative with the Ammonia Tanks Member of the Timber Mountain Tuff (11.5-9.5 m.y.). Conversely, the lower layer may be younger than 8 m.y. and possibly correlative with the 6 to 7.5 m.y. old Thirsty Canyon Tuff of the Black Mountain Caldera. The Badlands Upper (BU) tephra, which is interpreted to be 6.5-7.5 m.y. old, corresponds well with the age of the Thirsty Canyon Tuff. However, the Thirsty Canyon Tuff is peralkaline (alkalis > alumina) in composition and neither the Badlands Upper or Lower is peralkaline. Due to the compositional variations which may exist between a genetically related ash fall and ash-flow it would still seem possible that the Black Mountain Caldera may be the source of the Badlands Upper tephra and perhaps even the Lower (BL) tephra as well (i.e., they may be related to two different members of the Thirsty Canyon Tuff). Alternatively, the Badlands tephra may be correlative with the Greenwater volcanics or

the "older volcanics" which are derived from sources east of Death Valley, California, near the Nevada-California border (Drewes, 1963). These rhyolitic to rhyodacitic volcanic rocks yielded K-Ar ages of 5.3-8 m.y. (Fleck, 1970).

The Pahrnagat Valley tephra are not as easily compared to the southwestern Nevada volcanics as are the other tephra due to the wide range in possible ages (7-12 m.y.). The lower layer (PVL) appears to be a mixture of two different types of shards, indicating it probably contains reworked ash from two eruptions. The upper layer (PVU) is chemically and petrographically very similar to the Point of Rocks Lower tephra. If the Point of Rocks Lower is indeed correlative with a member of the Paintbrush Tuff, then it seems likely that the Pahrnagat Valley Upper is correlative with a different member of the Paintbrush Tuff, in which case PVU is approximately 12 m.y. rather than the 7-10 m.y. suggested. The Pahrnagat Valley Roadcut (PVR) layer is morphologically similar to the Badlands tephra, but chemically it is very different. Again, the 7-12 m.y. age range indicates the southwestern Nevada volcanic field is a probable source, but a correlation is only speculative.

IMPLICATIONS REGARDING THE MUDDY CREEK AND EQUIVALENT FORMATIONS

The Muddy Creek Formation and its equivalents have been the subject of some debate. The Muddy Creek Formation

represents the interior basin-fill deposits, in the southern Great Basin, which accumulated in subsiding structural troughs created by basin-range faulting (Armstrong 1970; Lucchitta, 1972; 1979). The formation, which is believed to be the result of alluvial fan and lacustrine deposition, occurs in adjacent topographic depressions with interior drainage and independent geomorphic and tectonic histories (Longwell, 1928; Hunt, 1956; Lucchitta, 1972). Recently, some geologists (Blair, 1978; Blair and others, 1979; Bradbury and Blair, 1979) have proposed that the Hualapai Limestone Member (uppermost Muddy Creek Formation), in the Lake Mead area, was deposited under marine conditions, probably in an estuarine environment in the ancestral Gulf of California. Hunt (1969) and Lucchitta (1972, 1979) both consider the Hualapai to be lacustrine (saline) in origin, similar to the Muddy Creek deposits in other adjoining basins to the north. This limestone is not present in the Muddy Creek or its equivalent formations at localities north of Lake Mead.

The age of the Muddy Creek Formation is somewhat controversial. As the formation consists of basin-fill deposits, deposition is considered to have begun soon after the onset of basin-range faulting (Lucchitta, 1972; 1979). The formation's similarity to the Panaca Formation of Lincoln County prompted Longwell's (1928) tentative Pliocene designation (then considered to be 13-1 m.y. - see Figure 18

Subdivisions in use by the U.S. Geological Survey		Age estimates of boundaries in million years (m.y.)	
Cenozoic Era	Quaternary Period	Holocene	0.010
		Pleistocene	2
	Tertiary Period	Pliocene	5
		Miocene	24
		Oligocene	38
		Eocene	55
		Paleocene	63

FIGURE 18. Geologic time scale of the Cenozoic Era. Modified from Isochron/West.

for the current U.S.G.S. time scale). In a later study Longwell (1963) mapped remnants of the Fortification Basalt Member of the upper Muddy Creek Formation (intercalated with and overlying Muddy Creek deposits in the Lake Mead area), assuming it was a formerly continuous sheet of lava. Ages of 10.6 to 11.3 m.y. were obtained on this basalt (Damon, 1965; Anderson and others, 1972), but Anderson (1971; Anderson and others, 1972) indicates the Fortification Basalt cannot be mapped as a single, time-stratigraphic flow sheet. He reports an age of 5.8 m.y. on the basalt at a locality south of Longwell's (1963) locality and also 4-5 m.y. ages on mafic dikes and lavas which are assigned to the Fortification Basalt Member. Recently, Damon and others (1978) redetermined the K-Ar age of Fortification Basalt overlying the Muddy Creek Formation at Longwell's (1963) locality (10.6 ± 1.1 m.y.) and obtained an age of 5.9 m.y. Anderson (1978) also determined new ages of 4.9 and 5.8 m.y. for the basalt from nearby localities. The uppermost Muddy Creek Formation in the Lake Mead area is therefore considered to be approximately 5-6 m.y., which is early Pliocene. This is contrary to the 8.4 ± 2.2 m.y. age which Blair (1978) obtained on air-fall tuff from the Hualapai Limestone. The Hualapai Limestone and Fortification Basalt are stratigraphically in the same position, both on top of and intercalated with the Muddy Creek Formation (Lucchitta, 1978). Lucchitta (1978) considers the tuff probably to be

from a lower part of the Hualapai Limestone and the 8.4 m.y. age does not represent the uppermost Muddy Creek Formation.

Due to the nearly identical stratigraphy and lithology of the Muddy Creek and Panaca formations, the two are considered to be equivalent (Phoenix, 1948; Longwell and others, 1965; Tschanz and Pampeyan, 1970). Tschanz and Pampeyan (1970) consider the formations to be in part equivalent to the lower member of the Indian Trail Formation on the Nevada Test Site, which consists of ash-flow and ash fall tuffs dated 16-13.5 m.y. (Orkild, 1965). This supports a middle Miocene age for at least part of the Muddy Creek and Panaca Formations.

It might be concluded from the foregoing discussion of the Muddy Creek and Panaca Formations that deposits have been assigned to the Muddy Creek or its time-correlative formations in a contradictory manner, due to the discrepancies in age and environment of deposition. However, the units are entirely consistent with the concept of a formation. As recently defined (Bates and Jackson, 1980, p. 242) a formation is a product of uniform or uniformly alternating conditions, and may contain one lithologic type, repetitions of two or more types, or heterogeneous types that in themselves define a unit. The formation may represent a short or long time interval, consist of material from one or several sources, and include breaks in stratigraphic

sequence so that the age or time interval may not be the same at all localities. It is apparent from numerous studies that the Muddy Creek Formation (and probably the Panaca) spans a range of geologic time, probably beginning shortly after the onset of basin-range faulting and continuing to the early Pliocene. That the Muddy Creek interval was of long duration is suggested by the great thickness of deposits in some localities (Longwell, 1963). The Muddy Creek and Panaca Formations also reflect a variety of depositional environments which included lacustrine, terrestrial, and possibly even marine conditions. Deposition does not seem to have been continuous or of the same type throughout the extent of the formation, but the deposits are everywhere believed to be late Cenozoic basin-fill sediments laid down during a relatively stable tectonic period. Perhaps the limestone deposition ceased in the south, while lacustrine and alluvial deposition continued in the interior basins to the north, in which case the Muddy Creek equivalents may be even younger than 5-6 m.y.

The results of this investigation suggest that the Muddy Creek and Panaca formations are indeed equivalent, as tephra from Pahrnagat Valley, intercalated with undifferentiated Muddy Creek and Panaca formation deposits, yield K-Ar ages in the same time range as the Badlands and Point of Rocks tephra. The Badlands tephra occur in Muddy Creek deposits and the Point of Rocks tephra occur in deposits

considered correlative with the Muddy Creek Formation (W.J. Carr, personal commun.). In addition, the K-Ar results suggest substantial parts of the Muddy Creek and its equivalent formations are 6-12 m.y. in age, supporting the previous middle to late Miocene determinations by other investigators. That the deposition of the Muddy Creek Formation extended into the Pliocene is considered probable, as there is no evidence that the deposits containing the tephra represent the uppermost Muddy Creek Formation. The Muddy Creek and its equivalent formations are often similar in appearance to Quaternary deposits and in fact have been mapped as Quaternary alluvium in places. The distinction between the Tertiary basin-fill deposits and Quaternary deposits is not clear in the literature nor in the field environment. The tephra layers described here serve to differentiate Miocene-Pliocene alluvium from younger deposits.

The 6-12 m.y. ages suggested for much of the Muddy Creek and equivalent formations have important implications for the time of basin formation in southern Nevada. As Stewart (1978; 1980) indicates, there are two types of evidence for dating the development of basin-range faulting. Indirect evidence is based on the change from andesitic to predominantly basaltic volcanism, which is presumably the result of the transition from compressional tectonics to extensional tectonics. This onset of extensional tectonics

and therefore basin-range faulting is considered to have begun approximately 17 m.y. ago (Christiansen and Lipman, 1972; Noble, 1972; McKee and Noble, 1974). Direct evidence is based on the development of fault-controlled sedimentary basins and topographic forms similar to present day forms. Stewart (1978) and Christiansen and McKee (1978) indicate that many sedimentary basins were well-defined by 11 to 13 m.y. ago. Ekren and others (1968), however, state that while some faults on the NTS started to form between 17 and 14 m.y., the present day topography developed from 11 to 7 m.y. ago. They indicate that the basin and range topography about 11 m.y. ago was very subdued in this area. The tephra ages obtained in this study suggest that much basin filling occurred between 6 and 12 m.y. ago. This indicates that basin-range faulting began prior to at least 12 m.y. in southern Nevada and that the present day topographic basins existed at this time. That the majority of faulting and deformation occurred before 6 m.y. is suggested by the relatively undeformed nature of the deposits which contain the tephra layers. This is consistent with Lucchitta's (1979) observation that the uppermost Muddy Creek Formation in the Lake Mead area also is undeformed. This does not necessarily indicate tectonic stability in the past 6-12 m.y.; it may simply be indicative of essentially vertical movement of the basin-range fault blocks during and after sediment accumulation. The resemblance of the Tertiary

basin-fill to Quaternary deposits indicates that little physiographic change, other than headward erosion by tributaries of the Colorado River, has occurred during the last 6-12 m.y. Although these conclusions are somewhat contrary to Ekren and others (1968) contention that the majority of deformation on the NTS occurred between 11 and 7 m.y. ago, it would seem likely that much of the NTS faulting is related to cauldron subsidence, as well as to basin-range tectonics. This additional volcanic-related subsidence on the NTS may have resulted in a thicker accumulation of basin-fill on the NTS than in surrounding areas.

Basin-range faulting is considered by some to have begun at approximately the same time throughout the Basin and Range Province (Noble, 1972; Christiansen and McKee, 1978), and by others to have migrated northward through time (Profett, 1972; Best and Hamblin, 1978). Further tephrochronologic studies in the Muddy Creek and equivalent formations would be very useful in determining the ages of basin-fill in the Great Basin region and might therefore provide further evidence for the age of basin development and the onset of basin-range faulting.

The seven (and possibly more) tephra layers which occur in the Muddy Creek and equivalent formations are also of great potential value in stratigraphic investigations. The tephra are sufficiently distinctive to constitute stratigraphic marker horizons in the 6 to 12 m.y. old Muddy Creek

equivalents. As the Muddy Creek Formation is considered to represent the late Tertiary basin-fill in the intermontane basins of the southeastern Great Basin, it is very likely that its equivalents comprise the basin-fill sequences throughout the Great Basin region. The area in southern Nevada, northwestern Arizona and southwestern Utah is one of the few areas where this basin-fill has been exposed by subsequent erosion. Most basins of the Great Basin region are presently characterized by interior drainage and a constantly rising base level due to continuing deposition. The basins in southern Nevada, however, are now drained by tributaries of the Colorado River and are therefore constantly down-cutting to keep pace with the lowering base level of the Colorado River. As a result much of the Muddy Creek and Panaca formations are now exposed due to dissection by the drainage system, whereas much of the equivalent basin-fill elsewhere in Nevada, including deposits on the NTS, are concealed by younger alluvium. The tephra layers, if found at additional localities in this area, perhaps in the subsurface, could prove very useful in correlating between diverse and widespread deposits of the Muddy Creek equivalents.

Further investigations of the late Cenozoic basin-fill in this area would be greatly facilitated by establishing a stratigraphic sequence in an area of extensive exposure of the Muddy Creek equivalents. Such exposures occur at local-

ities in both Clark and Lincoln counties, Nevada. A stratigraphic study in these areas would be most beneficial to an understanding of the NTS basin-fill. Although the individual basins have experienced independent tectonic and geomorphic histories and are characterized by locally derived sediments, the timing of deformation and the processes and rates of deposition are probably very similar. It is highly likely that the seven tephra layers discussed here occur at additional localities in the Muddy Creek alluvium and would be ideal for stratigraphic correlation. If some of the tephra are indeed correlative with the NTS volcanics, then the unsaturated zone of the NTS may be comprised of Muddy Creek or equivalent alluvium intercalated with the tephra of the southwestern Nevada volcanic field.

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Each of the tephra layers and its sample locality are described in detail below. There are a total of seven different tephra layers, collected from three localities. Two of the localities contain two layers, in stratigraphic succession, and the third locality contains three layers in apparent stratigraphic succession.

POINT OF ROCKS LOCALITY

Point of Rocks Lower (PRL) and Point of Rocks Upper (PRU)

Latitude 36°33'15", Longitude 116°04'10", Nye County Nevada, Altitude 2940 feet (574 m).

APPENDIX I

SAMPLE LOCALITIES AND GEOLOGIC DESCRIPTIONS

Located approximately 16.2 miles southeast of Lathrop Wells, Nevada, along U.S. Highway 95, exposure is approximately 0.75 miles southeast of the junction of U.S. Highway 95 and State Highway 160 (old Highway 16). Access is by a dirt road which turns east from State Highway 160, 0.5 miles south of the 95 and 160 junction.

Two tephra layers are exposed in the wall of a broad, east-west channel which cuts into the toe of an alluvial fan. The fan dips gently west and is composed of poorly sorted sand to boulder size clasts of Precambrian and Paleozoic quartzite and carbonate from the nearby mountain range. The matrix is indurated due to partial cementation with carbonate and contains some silt material in poorly

Each of the tephra layers and its sample locality are described in detail below. There are a total of seven different tephra layers, collected from three localities. Two of the localities contain two layers, in stratigraphic succession, and the third locality contains three layers in apparent stratigraphic succession.

POINT OF ROCKS LOCALITY

Point of Rocks Lower (PRL) and Point of Rocks Upper (PRU)

Latitude 36°33'15", Longitude 116°06'50", Nye County, Nevada, Altitude 2840 feet (874 m).

Located approximately 16.2 miles southeast of Lathrop Wells, Nevada, along U.S. Highway 95; exposure is approximately 0.75 miles southeast of the junction of U.S. Highway 95 and State Highway 160 (old Highway 16). Access is by a dirt road which turns east from State Highway 160, 0.5 miles south of the 95 and 160 junction.

Two tephra layers are exposed in the wall of a broad, east-west channel which cuts into the toe of an alluvial fan. The fan dips gently west and is composed of poorly sorted sand to boulder size clasts of Precambrian and Paleozoic quartzite and carbonate from the nearby mountain ranges. The matrix is indurated due to partial cementation with carbonate and contains some ashy material in poorly

defined lenses. The upper surface of the fan is a carbonate-cemented gravel capping.

The lower of the two tephra layers dips gently west, with the same attitude as the fan, lensing in and out for several hundred meters, eventually disappearing in both directions. At the sampling location it occurs approximately 13 meters above the wash and eight meters below the top of the exposure. The sampled outcrop appears to be a channel deposit, varying in thickness from about 20-45 cm and having a maximum of five horizontal bedding planes, defined by fine to coarse textural breaks. The tephra is fine-grained, pale gray to white, and poorly indurated. The fairly well defined basal and upper contacts have pebble to boulder size clasts of the alluvial fan material mixed in with the tephra.

The upper tephra layer also dips gently west and was sampled approximately 0.5 miles west of the lower sampling location, where it occurs approximately eight meters above the wash and three meters below the top of the exposure. It is exposed discontinuously for several hundred meters, and the lower tephra layer is observed approximately five meters beneath it in places. The tephra is fine-grained, pale gray to white, poorly indurated and contains finely laminated cross-bedding. The layer varies in thickness from about

10-20 cm, has sharp upper and lower contacts and some lithic contamination.

BADLANDS LOCALITY

Badlands Lower (BL) and Badlands Upper (BU)

Latitude $36^{\circ}46'10''$, Longitude $114^{\circ}48'55''$, Clark County, Nevada, Altitude 2160 feet (665 m).

Located approximately 13 miles northwest of Moapa, Nevada, along State Highway 168 (old Highway 7), 0.5 miles south of the highway. Access is by a jeep trail which turns south from State Highway 168 at Benchmark 2231.

Two tephra layers are exposed in the stream-cut cliffs of an area of dissected badlands topography. The layers occur in a sequence of buff to greenish beige, fine-grained, non-indurated lake sediments, approximately 15 meters thick, capped by a five meter thick layer of resistant carbonate. The sediments are mapped as part of the Tertiary Muddy Creek Formation on the geologic map of Clark County, Nevada (Longwell and others, 1965).

The lower tephra layer is approximately five meters above the base of the exposure and is continuous for many hundreds of meters throughout the area, varying in thickness from 30-40 cm. It is a fine-grained, water-laid ash, silvery gray and nonindurated. The lower third of the layer is massive, while the upper two thirds is finely laminated. The upper and lower contacts are well-defined.

The upper tephra layer occurs five meters above the lower layer and is also continuous in this badlands area. It is approximately 30 cm thick, finely laminated, and contains abundant horizontal partings 0.25-0.50 cm apart. The tephra is a dark gray, fine-grained, nonindurated water-laid deposit. The upper and lower contacts are sharp. Four meters above the upper tephra layer is a five meter thick cap of carbonate.

PAHRANAGAT VALLEY LOCALITY

Pahranagat Valley Lower (PVL), Pahranagat Valley Upper (PVU), and Pahranagat Valley Roadcut (PVR)

Latitude 37°18'33", Longitude 115°07'20", Lincoln County, Nevada, Altitude 3440 feet (1058 m)

Located adjacent to State Highway 93 (east side of highway), 3.75 miles south of Alamo, Nevada; near the northeast edge of Upper Pahranagat Lake.

Three tephra layers are exposed at this locality. Two are in the north wall of a gully which cuts an alluvial fan; they are not exposed in the south wall. The third layer occurs approximately 100 meters south of the first two, in the east bank of the State Highway 93 roadcut; it is not exposed in the west bank. The roadcut tephra layer appears to be stratigraphically above the two gully ash layers, as no faulting is apparent. The three layers occur in a

fanglomerate sequence composed of poorly sorted pebbles, cobbles and boulders of volcanic origin in a silty matrix of tuffaceous sediments. The fan material is stratified in 0.25-1 m layers and the tephra layers form slightly more resistant ledges in the exposure. The fan is tilted approximately 5° west and has a dissected upper surface. It is mapped as part of the undifferentiated Panaca and Muddy Creek Formations on the geologic map of Lincoln County, Nevada (Tschanz and Pampeyan, 1970).

The lower tephra layer in the gully occurs approximately 0.25-0.50 m above the base of the exposure and dips 5° west with the tilt of the alluvial fan. It is continuous for 10 m to the west, where it dips beneath the level of the gully bottom. The layer is 10-12 cm thick, fine-grained, light gray and poorly cemented. The upper and lower contacts are sharp. The lower 2 cm of the layer is a grayish brown, sandy ash and the upper 3 cm of the layer contains pebble-size and smaller clasts of volcanic origin. The upper portion of the layer also contains some sand, and erosional contamination from older material is certain.

The upper tephra layer in the gully occurs three meters above the lower and is continuous for some 20 m; it dips 5° west. The tephra is fine-grained, buff colored, poorly indurated, and varies in thickness from 5-15 cm. Pebbles and smaller size lithic clasts of volcanic origin are

dispersed through the layer. Upper and lower contacts are sharp.

The tephra layer in the roadcut occurs above the level of the gully exposure, approximately 13 m above the highway, in the same dissected alluvial fan sequence. The layer is 10-12 cm thick, dips to the west, and is exposed for only three meters. The tephra is fine-grained, pale gray, nonindurated and is moist from groundwater. A pale yellow precipitate, presumably from groundwater contamination, is present in the upper part of the layer. The upper contact is sharp and the lower contact grades into a sandy ash, which in turn overlies pebbles and cobbles of volcanic origin in a finer matrix.

POINT OF ROCKS LOWER

Sample 781

The sample is composed of approximately 10% phenocrysts and 90% glass shards. The glass consists of nearly equal amounts of vesicular and nonvesicular shards. Some of the shards have a surficial devitrification (clay?), but most are unaltered, clean angular glass with smooth to occasionally rough edges. Inclusions are not common, but some shards are slightly clouded with dust. Most vesicles are free of liquid; some are filled. Nonvesicular glass is predominantly chunky.

APPENDIX II

Phenocrysts:

PETROGRAPHY OF THE TEPHRA LAYERS

Plagioclase	64%	pipes	10%
Sandstone	11%	spindles	10%
Quartz	7%	vesicles	8%
Biotite	1%	silica	2%
Clinopyroxene	4%	shards	38%
Orthopyroxene	4%	shatter	15%
Zircon	2%		
Opaques	5%	colored glass	-
		phenocryst-containing	4%

Refractive Index of Glass:

average - 1.497 ± .001
range - 1.496 - 1.498

Mineralogy

The majority of phenocrysts are fresh, angular grains with little evidence of alteration; some altered, subrounded grains are present. Most grains are subhedral to anhedral.

POINT OF ROCKS LOWER

Sample PRL

The sample is composed of approximately 10% phenocrysts and 90% glass shards. The glass consists of nearly equal amounts of vesicular and nonvesicular shards. Some of the shards have a surficial devitrification (clay?), but most are unaltered, clean angular glass with smooth to occasionally rough edges. Inclusions are not common, but some shards are slightly clouded with dust. Most vesicles are free of liquid; some are partially filled. Nonvesicular glass is predominantly chunky.

Phenocrysts:

Plagioclase	64%
Sanidine	11%
Quartz	9%
Biotite	1%
Clinopyroxene	4%
Orthopyroxene	4%
Zircon	2%
Opagues	5%

Glass Morphology:

pipes	20%
spindles	10%
vesicles	8%
mix	9%
chunks	38%
shatter	15%
colored glass	-
phenocryst-containing	4%

Refractive Index of Glass:

average - 1.497 ± .001
range - 1.496 - 1.498

Mineralogy

The majority of phenocrysts are fresh, angular grains with little evidence of alteration; some altered, subrounded grains are present. Most grains are subhedral to anhedral.

The scanning electron microscope (SEM) data indicate that the clinopyroxenes present are a high iron pigeonite and augite. The opaque minerals are ilmenite, magnetite, and possible pyrrhotite.

K-Ar Mineral Concentrates

The plagioclase concentrate contains approximately 20% altered, subrounded grains. The sanidine concentrate also contains some subrounded, altered grains and approximately five to eight percent microcline (presumably from the Precambrian Stirling Quartzite from the Spring Mountains). The presence of microcline in the quartzite clasts from the alluvial fan was confirmed in thin-section examination.

Sanidine
Quartz
Mica
K-feldspar
Iron
Apatite
Opaque

Refractive Index of Glass

average = 1.487 ± 0.001
range = 1.484 - 1.490

Mineralogy

The majority of the phenocrysts are fresh, anhedral, subhedral and euhedral grains. A small percentage of the phenocrysts are rounded and have smooth surfaces or surficial coatings (apatite). The groundmass is fresh, green to greenish brown, and generally has a fibrous texture.

POINT OF ROCKS UPPER

Sample PRU agiclast concentrate contains approximately 30%

The sample is composed of approximately 10% phenocrysts and 90% glass shards. The glass consists of predominantly pumiceous shards (vesicular), although nonvesicular shards are common. Some of the stretched, elongate vesicles are deformed into a wavy pattern. Most of the shards are clean, subangular to subrounded, moderately microlitic grains, often slightly clouded with dust and occasionally containing inclusions. Surfaces of many grains appear slightly altered or coated. Some filling of vesicles with liquid is present.

Phenocrysts:

Plagioclase	36%
Sanidine	9%
Quartz	14%
Biotite	25%
Hornblende	5%
Zircon	4%
Apatite	1%
Opauques	6%

Glass Morphology:

pipes	30%
spindles	30%
vesicles	8%
mix	7%
chunks	22%
shatter	3%
colored glass	-
phenocryst-containing	6%

Refractive Index of Glass:

average - 1.497 ± .001
range - 1.494 - 1.498

Mineralogy

The majority of the phenocrysts are fresh, angular, subhedral and anhedral grains. A small percentage of the phenocrysts are rounded and have corroded surfaces or surficial coatings (clay?). The hornblende is fresh, green to greenish brown, and commonly has adhering glass.

K-Ar Mineral Concentrates

The plagioclase concentrate contains approximately 20% altered, subrounded grains and about 10% quartz grains. The sanidine concentrate also contains altered, subrounded grains and approximately one to two percent microcline (presumably from the Precambrian Stirling Quartzite from the Spring Mountains). The biotite concentrate contains 80% greenish brown biotite and 20% reddish brown biotite.

nearly filled with liquid, indicating that the glass is hydrated. The glass appears fresh and unaltered.

Phenocrysts:

Plagioclase	25%
Sanidine	10%
Quartz	45%
Biotite	8%
Hornblende	1%
Clinopyroxene	4%
Ilmenite	4%
Opaques	3%

Glass Morphology:

pipes	6%
spindles	4%
vesicles	-
air	-
chunks	-
insects	92%
colored glass	2%
phenocryst-containing	3%

Refractive Index of Glass:

average - 1.499 ± .001
range - 1.498 - 1.501

Mineralogy

The phenocrysts are sparse, often rounded, and have reddish brown to black coatings (iron?). These grains are not included in the mineral counts. The phenocrysts are usually anhedral. Clay minerals are present.

BADLANDS LOWER concentrates

Sample BL - the small percentage of phenocrysts in this

The sample is composed of approximately 2% phenocrysts and 98% glass shards which are almost entirely platy shards of the bubble-wall type. The platy shards are clear, clean, and angular with smooth, usually slightly curved edges. They contain few microlites. A small number of shards contain spindle or pipe-shaped vesicles which are often nearly filled with liquid, indicating that the glass is hydrated. The glass appears fresh and unaltered.

Phenocrysts:

Plagioclase	25%
Sanidine	10%
Quartz	45%
Biotite	8%
Hornblende	1%
Clinopyroxene	4%
Zircon	4%
Opauques	3%

Glass Morphology:

pipes	4%
spindles	4%
vesicles	-
mix	-
chunks	-
shatter	92%
colored glass	2%
phenocryst-containing	3%

Refractive Index of Glass:

average - 1.499 ± .001
range - 1.498 - 1.501

Mineralogy

The phenocrysts are sparse, often rounded, and have reddish brown to black coatings (iron?). These grains are not included in the mineral counts. The phenocrysts are usually anhedral. Clay minerals are present.

K-Ar Mineral Concentrates

Due to the small percentage of phenocrysts in this sample, it was not feasible to prepare a mineral concentrate for K-Ar dating. A clean, undevitrified glass concentrate was prepared for age determination. Hydration of the glass was confirmed by a weight loss after heating to 400°C.

$H_2O = 4.54\%$

The glass is pale brown in color, with a few shards exhibiting a deeper brown color. The shards are clean, clear, angular grains with smooth edges. The pumiceous shards are usually elongate, tabular grains with pipe-like vesicles that are often curved and partially filled with liquid. The majority of the glass is microlite-free, although there are occasional inclusions of biotite.

Phenocrysts:

Plagioclase	463
Quartz	261
Biotite	31
Hornblende	23
Clinopyroxene	73
Orthopyroxene	38
Zircon	37
Opakes	74

Glass Morphology:

plates	353
spindles	33
vesicles	53
pix	10
chunks	7
shatter	573
colored glass	43
phenocryst-containing	43

Refractive Index of Glass:

average = 1.521 ± 0.001
range = 1.519 - 1.523

Mineralogy

The phenocrysts are sparse and most are angular fragments, although a few quartz grains are rounded and

BADLANDS UPPER

Sample BU

The sample is composed of approximately 2% phenocrysts and 98% glass shards which are dominantly platy, bubble-wall fragments with a lesser number of pumiceous shards. Most of the shards have a dirty, surficial coating which was removed by a slight hydrofluoric acid etch before the sample was examined. The glass is pale brown in color, with a few shards exhibiting a deeper brown color. The shards are clean, clear, angular grains with smooth edges. The pumiceous shards are usually elongate, tabular grains with pipe-like vesicles that are often curved and partially filled with liquid. The majority of the glass is microlite-free, although there are occasional inclusions of biotite.

Phenocrysts:

Plagioclase	46%
Quartz	26%
Biotite	3%
Hornblende	2%
Clinopyroxene	7%
Orthopyroxene	5%
Zircon	4%
Opagues	7%

Glass Morphology:

pipes	32%
spindles	3%
vesicles	5%
mix	3%
chunks	-
shatter	57%
colored glass	4%
phenocryst-containing	4%

Refractive Index of Glass:

average - 1.521 ± .001
range - 1.519 - 1.523

Mineralogy

The phenocrysts are sparse and most are angular fragments, although a few quartz grains are rounded and

possibly of detrital origin. The crystals are usually subhedral to anhedral. Zircon phenocrysts occur as inclusions in glass shards and biotite phenocrysts are common inclusions in both the glass and the feldspars. Plagioclase occasionally exhibits a slight zonation. The biotite occurs in both reddish brown and green varieties and the hornblende is bluish green in color. One grain of blue amphibole (riebeckite?) was observed (no adhering glass).

K-Ar Mineral Concentrates

A pure glass separate was prepared for the K-Ar age determination, as phenocrysts were too sparse for concentration. The glass is very clean and undevitrified, but was determined to be hydrated (weight loss after heating to 400°C). $H_2O = 5.50\%$

Phenocrysts:

Plagioclase	25%
Sandstone	5%
Quartz	10%
Biotite	20%
Hornblende	27%
Zircon	1%
Opaque	5%

Glass Morphology:

pipes	8%
spindles	-
vesicles	72%
mix	6%
chunks	12%
shatter	2%
colored glass	1%
phenocryst-containing	20%

PAHRANAGAT VALLEY LOWER:

Sample PVL

The sample is composed of approximately 25% phenocrysts and 75% glass shards, the majority of which are pumiceous. There are two populations of glass shards present, distinguished on the basis of morphology and refractive index. The larger population is composed of rounded or subrounded, partially devitrified shards with profuse spherical to subspherical vesicles and abundant microlites. Many of these shards have a brownish to orange coating of oxide on the surfaces and are hydrated, indicated by the vesicle filling. The smaller population is composed of chunky, nonvesicular shards and tabular, vesicular shards with pipe-like vesicles. These shards are subangular to subrounded, clear to occasionally cloudy, have a lower refractive index than the first population, and contain very few microlites.

Reworking of both populations is apparent from the worn grains.

Phenocrysts:

Plagioclase	25%
Sanidine	6%
Quartz	10%
Biotite	28%
Hornblende	27%
Zircon	1%
Opaques	3%

Glass Morphology:

pipes	8%
spindles	-
vesicles	72%
mix	6%
chunks	12%
shatter	2%
colored glass	1%
phenocryst-containing	20%

Refractive Index of Glass:

1st population - 75% of sample (vesicular, microlitic)
 average - $1.510 \pm .001$
 range - 1.507 - 1.514

2nd population - 25% of sample (chunky and pipe vesicles)
 average - $1.498 \pm .001$
 range - 1.496 - 1.503

Mineralogy

There are two populations of phenocrysts. The first is composed of clean, angular, fresh-looking grains which are subhedral and anhedral. The second population consists of subrounded to rounded, dirty, coated grains which were not included in the phenocryst counts. The SEM analysis indicates the sanidine of the second population has sericitic alteration. The SEM analysis of the opaque minerals indicates some magnetite. The biotite consists of both greenish brown and reddish brown varieties and the hornblende is mostly blue-green, with minor brown hornblende. Some of the plagioclase is faintly zoned. The phenocryst inclusions in the glass shards are dominantly plagioclase with biotite, hornblende and pyroxene.

K-Ar Mineral Concentrates

The plagioclase concentrates contain abundant (20-30%) detrital phenocrysts (subrounded, altered) and approximately 10% quartz, much of which appears detrital. The sanidine concentrate contains 20-30% subrounded, detrital grains.

PAHRANAGAT VALLEY UPPER

Sample PVU

The sample consists of approximately 15% phenocrysts and 85% glass shards, the majority of which are pumiceous and a smaller percentage which are nonvesicular. The pumiceous shards are predominantly of the pipe-like vesicle type, frequently curved or ropey, although spindle and spherical vesicles are common. The vesicles are filled up to 85% with liquid. Nonvesicular shards are usually blocky; a few are platy. The majority of the glass is clean, clear angular to subangular shards, but there are also subrounded, detrital, dirty shards. Microlites and inclusions are not common.

Phenocrysts:

Glass Morphology:

Plagioclase	38%	pipes	40%
Sanidine	19%	spindles	7%
Quartz	22%	vesicles	19%
Biotite	5%	mix	7%
Hornblende	6%	chunks	22%
Clinopyroxene	4%	shatter	5%
Zircon	1%		
Opauques	5%	colored glass	1%
		phenocryst-containing	1%

Refractive Index of Glass:

average - 1.498 ± .001
range - 1.495 - 1.500

Mineralogy

There are two approximately equal populations of phenocrysts. The first group is fresh, clean, clear,

angular to subangular and usually subhedral to anhedral. The second group consists of rounded and altered grains that were not included in the phenocryst counts. The biotite is yellowish brown to green, and the hornblende is blue-green and occasionally greenish brown. A third feldspar, anorthoclase (?), is also present (~2%), but was not counted due to the absence of adhering glass and a subrounded, detrital appearance.

K-Ar Mineral Concentrates

The sanidine concentrate contains approximately 15-20% altered, detrital-looking grains. In addition, the fresher looking population of sanidine also contains subrounded grains. Less than 1% anorthoclase (?) is present. The plagioclase concentrate contains approximately 30% rounded quartz grains and 15-20% subrounded, detrital-looking grains.

Refractive Index of Glass:

average - 1.503 ± .001
range - 1.501 - 1.504

Mineralogy

Most crystals are clean, fresh, subangular grains with subhedral to anhedral shapes. There is a detrital component, especially in the quartz fraction and to a lesser degree in the feldspar fractions. Quartz is more abundant in the sample than is indicated in the recorded percentages.

PAHRANAGAT VALLEY ROADCUT

Sample PVR

The sample is composed of approximately 3% phenocrysts and 97% glass shards consisting of nearly equal amounts of platy, bubble-wall fragments and pumiceous grains. The bubble-wall shards are clean, clear, angular grains with no vesicles and often ribbed due to bubble junctions. The pumiceous shards are clean and clear and are predominantly elongate grains with straight or wavy, pipe-like vesicles. The vesicles are commonly partially filled with fluid. Microlites and inclusions are rare.

Phenocrysts:

Plagioclase	53%
Sanidine	33%
Quartz	8%
Hornblende	1%
Clinopyroxene	2%
Opaques	3%

Glass Morphology:

pipes	38%
spindles	-
vesicles	7%
mix	2%
chunks	6%
shatter	47%
colored glass	-
phenocryst-containing	-

Refractive Index of Glass:

average	- 1.503 ± .001
range	- 1.501 - 1.504

Mineralogy

Most crystals are clean, fresh, subangular grains with subhedral to anhedral shapes. There is a detrital component, especially in the quartz fraction and to a lesser degree in the feldspar fractions. Quartz is more abundant in the sample than is indicated in the recorded percentage,

but much of it is rounded and has no adhering glass.

K-Ar Mineral Concentrates

Both the sanidine and plagioclase mineral concentrates contain subrounded, altered grains (20%). In addition, the plagioclase concentrate contains abundant quartz grains which could not be removed due to the small sample size (too much plagioclase would be lost in the density separation process). Much of the quartz is rounded and obviously detrital, as are many of the feldspar grains.

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