REGIONAL VARIATIONS IN THE LEAD ISOTOPIC CHARACTERISTICS OF LATE CENOZOIC BASALTS FROM THE SOUTHWESTERN UNITED STATES

Thesis by

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ABSTRACT

Over a hundred new analyses on late Cenozoic basalts characterize and delimit regional patterns of lead isotopic behavior in the southwestern United States. The lead isotopic systematics of these volcanic rocks can be divided into three broad regional groups: one characteristic of Colorado Plateau (CP) volcanic fields, a second found in many areas of the Basin and Range (BR) province, and in neighboring areas along the Pacific coast, and a third peculiar to an area in southern Nevada (SN) Colorado Plateau volcanic rocks have generally unradiogenic leads ($^{206}Pb/^{204}Pb \leq 18.7$), locally exhibit large variations in isotopic ratio, and define linear arrays (secondary isochrons) on a $^{206}Pb/^{204}Pb$-$^{207}Pb/^{204}Pb$ diagram. Basin and Range type samples are characterized by relatively radiogenic leads ($18.7 \leq {}^{206}Pb/^{204}Pb \leq 19.6$) and, comparatively, a uniformity of isotopic composition in local areas. Southern Nevada leads are somewhat unradiogenic ($18.2 \leq {}^{206}Pb/^{204}Pb \leq 18.5$), appear to display a local uniformity in isotopic composition, and lie off the Colorado Plateau secondary isochrons. Literature sources indicate that southern Nevada basalts are also characterized by relatively high $^{87}Sr/^{86}Sr$ ratios (.7060-.7080).

The isotopic properties of volcanic rocks from each of these regions do not appear to record crustal contamination. The general uniformity of isotopic characteristics over large areas (hundreds to thousands of kilometers in size) of the Southwest suggests a fundamental consistency in volcanic source region character over comparable dimensions.

Isotopic variations within each province seem to record smaller scale source region heterogeneities.

Isotopic variability observed within individual Colorado Plateau volcanic fields may be interpreted in terms of kilometer-sized mantle heterogeneities developed approximately 1.4-1.8 by ago. These heterogeneities may record the effects of magma extraction from mantle sources during the primary generation of Precambrian crystalline basement and the formation of the continental lithosphere. A rough but apparently significant correlation between the chemical and lead isotopic compositions of CP basalts suggests that the mantle of the continental lithosphere may be crudely "stratified" in its lead isotopic composition, with the uppermost mantle generally less radiogenic in lead (and by inference more depleted in uranium relative to lead) than the deeper lithosphere. Isotopic differences distinguishable between different portions of the Colorado Plateau may relate to heterogeneities hundreds of kilometers in size which developed in different mantle domains prior to and in the course of continental lithosphere formation.

Basin and Range basalts have lead isotopic properties (and Sr and Nd isotopic compositions) similar to volcanic rocks from oceanic island and volcanic arc settings, suggesting a correspondence between BR volcanic source regions and "oceanic" mantle. Within the Basin and Range province $^{206}Pb/^{204}Pb$ ratios tend to be rather uniform laterally for distances measured in hundreds of kilometers; this implies that the underlying mantle may be isotopically rather homogeneous for similar distances. One 200 km long section of the Rio Grande rift is characterized by CP type leads. This may possibly indicate that a large body of "oceanic" mantle has penetrated the continental lithosphere beneath this segment of the Rio Grande rift.

Older (Pliocene and Miocene) calc-alkaline volcanic rocks from the Basin and Range province tend to display somewhat higher $^{207}Pb/^{204}Pb$ ratios than the Quaternary alkaline basalts within each area of the Basin and Range province. This could suggest that adjustments in BR type source region characteristics continued very late into the Cenozoic era, perhaps in conjunction with changes in the tectonic environment.

SN type isotopic systematics resist a unique interpretation, but may reflect long term (of the order of a billion years or so) evolutionary characteristics of a source region in the mantle or the lower crust.

Although the different isotopic province boundaries appear to record discontinuities deep within the earth (most probably fundamental discontinuities in mantle character), they follow the trends of major geological and structural boundaries in the crust. The SN isotopic province, for example, appears to be associated geographically with a "fundamental, west-trending, transverse crustal boundary" (Eaton, 1975) which demarcates the northern and southern portions of the Basin and Range province. The Basin and Range - Colorado Plateau isotopic province boundary approximately follows the Mesozoic-early Tertiary Cordilleran foreland thrust belt and the limit of late Cenozoic normal faulting. Thus the BR-CP isotopic boundary appears to be geographically related to the boundary between tectonically unstable, "orogenic" areas of the

Basin and Range province and Pacific border regions, and the more stable "platform" areas of the Colorado Plateau, Southern Rocky Mountains, and Great Plains.

BR type leads occur in some areas (notably southern Arizona and southeastern California) characterized by known Precambrian basement. These areas were presumably underlain originally by "old" mantle belonging to the continental lithosphere. The inferred presence of BR type, "oceanic" mantle beneath these regions during late Cenozoic times seems to imply a disruption of continental lithosphere and the emplacement of "new" oceanic mantle. The geographic association of Mesozoic and Cenozoic structural boundaries in the crust and the BR-CP isotopic boundary suggests that this mantle disruption may be related either to the compressional tectonism of Mesozoic-early Tertiary times or to the extensional tectonism of the late Cenozoic.

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CHAPTER 5: INTERPRETATION OF COLORADO PLATEAU TYPE LEAD ISOTOPIC DATA

CHAPTER 1: INTRODUCTION

1.1 Overview

This thesis utilizes data on the lead isotopic systematics of late Cenozoic basalts to investigate the nature and history of volcanic source regions (presumably in the mantle) beneath the southwestern United States. The relationship between the provincial variations in lead isotopic characteristics, which can be interpreted to reflect regional differences in source region properties, and the geologic development of the overlying crust is of particular interest to this study.

1.2 A Geologic Context for this Geochemical Study

The geologic development of the western United States has been the subject of a number of reviews, including King (1977) and Burchfiel and Davis (1975). The geologic events most pertinent to this study are the initial formation of continental crust during the Precambrian and its structural alteration during latest Mesozoic and Cenozoic times.

The oldest continental rocks in the southwestern United States are Precambrian plutonic, extrusive, and variously metamorphosed supracrustal rocks which occur in northeast-trending geosynclines and orogenic belts (Silver and others, 1977). The igneous rocks in these Precambrian orogenic belts range from 1610 to 1740 my in age. A slightly younger episode (1410-1465 my) involving widespread intrusion of anorogenic granite plutons has also been recorded.

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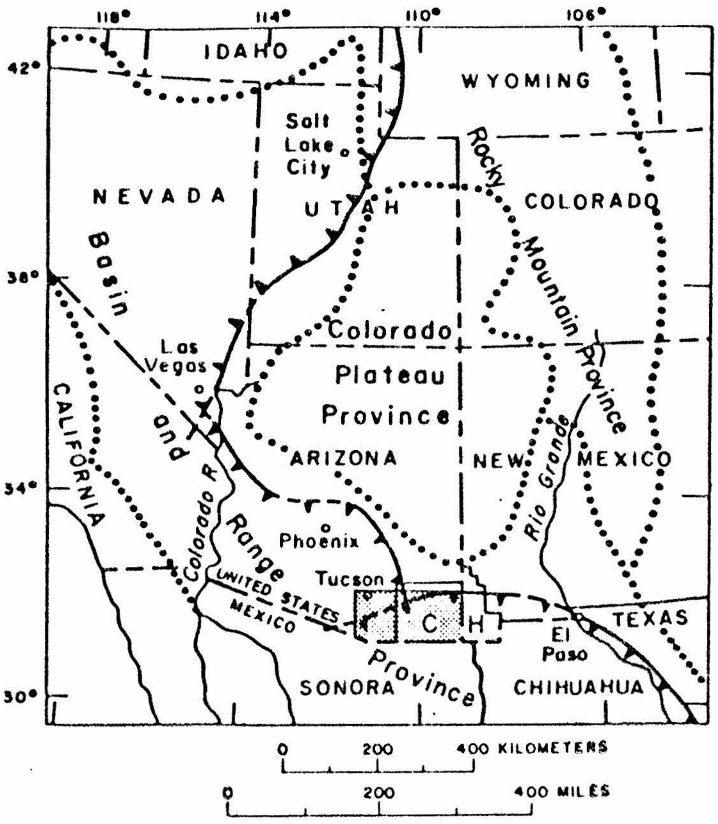
*Appendix A contains a short discussion of Pb-U-Th systematics pertinent to this study.

Precambrian rocks are not uniformly distributed in the Southwest; they appear to be completely absent in central and northern Nevada, and in the coastal regions of California. The boundary of Precambrian in southern California appears to follow the late Cenozoic San Andreas fault. The limit of Precambrian outcrops in Nevada and Utah may relate to a late Precambrian rifting of the proto-American continent (Burchfiel and Davis, 1975; Stewart, 1972).

The late Mesozoic to early Tertiary history of the Southwest is characterized by extensive plutonism and thrust faulting (the Nevadan-Sevier-Laramide orogenies). Burchfiel and Davis (1975) have suggested a genetic relationship between magmatism and tectonism in this orogenic episode. They have argued that heat supplied by the mantle generated plutonic activity in the crust, that the occurrence of plutonism in a given area increased the ductility of the crust in that area, and that crustal ductility in turn controlled the expression of tectonic activity. The approximate limits of late Mesozoic-early Tertiary thrusting are shown in Figure 1.1, which was taken from Drewes (1978).

The present day physiography of the western United States (Figure 1.2) was largely established in the late Cenozoic, although older structural features have undoubtedly influenced Cenozoic structural development. The Colorado Plateau boundary in Utah, for example, follows the hinge line between Paleozoic platform and miogeosynclinal sedimentation in the Cordillera. The boundary of the Colorado Plateau also appears to approximately coincide with the eastern limit of late Mesozoic-early Tertiary thrust faulting (Figure 1.1). Some workers have used the



Index map of the southwestern United States, showing geologic provinces, dotted lines; foreland zone of Cordilleran orogenic belt; area of tectonic synthesis in southeastern Arizona, stippled; C, Cochise County; and, H, Hidalgo County.

Figure 1.1 (After Drewes, 1978)

Figure 1.2: A map showing the physiographic provinces of the western United States (after Fenneman, 1931) and the localities of various Cenozoic volcanic fields mentioned in the text. LC, Lunar Crater; BR, Black Rock Desert; HP, High Plateaus; WCP, Western Colorado Plateau; SF, San Francisco; S, Sentinel; PIN, Pinacate; SC, San Carlos; SB, San Bernardino; WM, White Mountains; MD, Mogollon-Datil; POT, Potrillo; MT, Mount Taylor; JM, Jornada del Muerto; J, Jemez Mountains, SJ, San Juan. Numbers indicate the locations of various cities mentioned in the text. 1, Cortez; 2, Tonopah; 3, Baker; 4, St. George; 5, Flagstaff; 6, Prescott; 7, Tucson; 8, Las Cruces; 9, Socorro; 10, Albuquerque.

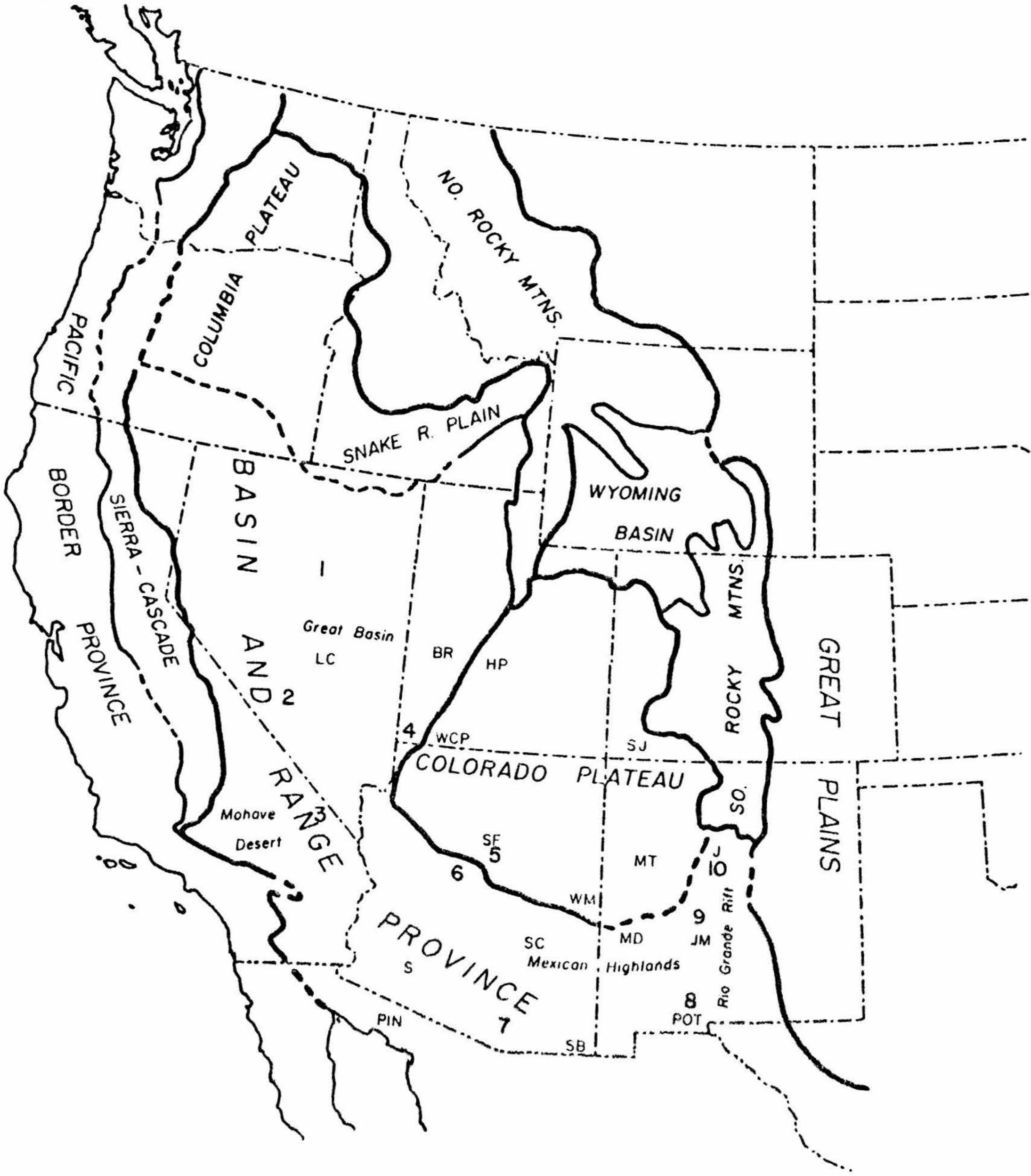

NO. ROCKY MTNS.
COLUMBIA PLATEAU
PACIFIC
SNAKE R. PLAIN
WYOMING
BASIN
BORDER
SIERRA - CASCADE
BASIN AND RANGE
1
Great Basin
LC
2
PROVINCE
BR
HP
ROCKY MTNS.
GREAT
4
WCP
SJ
COLORADO PLATEAU
SO.
PLAINS
Mohave
Desert
3
RANGE
SF
5
6
MT
J
10
WM
9
PROVINCE
SC
MD
JM
Mexican Highlands
Rio Grande Rift
S
8
POT
PIN
7
SB

Figure 1.2

eastern extent of Laramide plutons as a criterion to define the boundary of the Colorado Plateau in Arizona. In New Mexico the coincidence of Laramide block faulting and the late Cenozoic faulting associated with the development of the Rio Grande rift also suggests a control of Late Cenozoic tectonism by older structures.

Regions like the Colorado Plateau which survived Mesozoic tectonism have also tended to remain stable during the Cenozoic. Areas which experienced previous, intense orogenic activity (e.g., the Basin and Range province) have been more susceptible to Cenozoic tectonism.

The late Cenozoic tectonic history of the southwestern United States has been characterized by: (1) broad, epeirogenic uplift of the Great Plains, Rocky Mountains, and Colorado Plateau; (2) normal, extensional block faulting in the Basin and Range province (including the Rio Grande rift), and; (3) right lateral strike-slip movement on the San Andreas and related faults in California and western Nevada. Presumably, all three of these structural activities are related and began in Oligocene time, but became more pronounced in the Miocene (see King, 1977; Hunt, 1956; Christiansen and Lipman, 1972; Hamblin and Best, 1975; and Atwater, 1970). However, the ages, both relative and absolute, and the causes of each of these three events continue to be a matter of considerable debate.

Voluminous, wide-spread volcanism is also characteristic of the Neogene history of the southwest. Intriguing correlations between the location, age, and type of volcanic activity have been noted. Armstrong and others (1969) have reported that volcanism in the Great

Basin began 40 my ago in east-central Nevada, and that later volcanism has progressively migrated outward toward the Basin margins. Scholz and others (1971) have suggested that this volcanic migration (as well as the present day seismic activity at the margins of the Great Basin, and the geophysically anomalous mantle beneath the region) can be explained in terms of upwelling of a mantle diapir, which becomes trapped beneath the sialic crust, and is thus forced to spread out laterally.

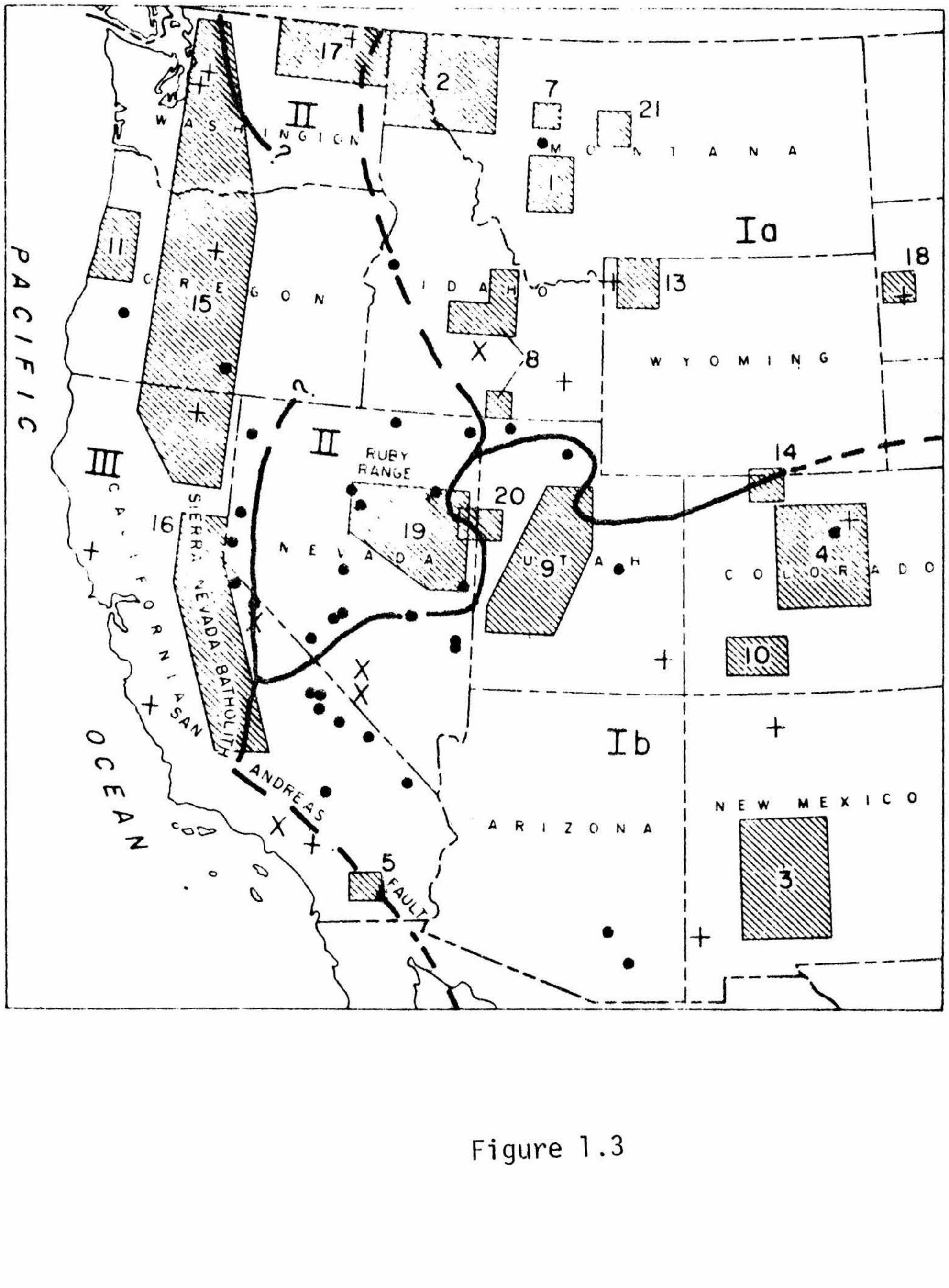
Lipman and others (1972) and Christiansen and Lipman (1972) have indicated that the earliest Cenozoic volcanism in the western United States was calc-alkalic, while later volcanics belong to a bimodal basalt-rhyolite suite. They have found the age boundary between the two different suites to vary from area to area in a way consistent with the Atwater (1970) plate tectonic predictions. Lipman and others (1972) have also shown a regular but discontinuous areal variation of the K_2O concentration of Cenozoic andesites going inland across the western United States. They interpret this pattern as evidence for the existence of a double subduction zone beneath the west in Cenozoic times. While some authors (e.g., Synder *et al.*, 1976) have concurred with the Lipman-Christiansen-Proska models, others (e.g., Elston, 1976) have pointed out inconsistencies and alternate explanations.

1.3 Previous Work

In 1968 B.R. Doe established the phenomenon on which the present study is based; namely, that Cenozoic volcanics in different parts of the western United States exhibit consistently different lead isotopic compositions. Doe (1968) analyzed the Pb and Sr isotopic compositions of a diverse collection of volcanic rocks from the western United States. Although he could not make regional distinctions on the basis of strontium isotopic data, he found that rocks from Idaho, Montana, Wyoming, Colorado, and New Mexico had a range of lead isotopic compositions distinct from that characterizing volcanics from Washington, Oregon, and California. The Rocky Mountain region yielded $^{206}Pb/^{204}Pb$ ratios in the range 16.6 to 18.8 and $^{208}Pb/^{204}Pb$ ratios in the range 37.1 to 38.8. Volcanic rocks in West Coast states consistently gave more radiogenic values with $^{206}Pb/^{204}Pb \geq 18.8$ and $^{208}Pb/^{204}Pb \gtrsim 38.6$. Doe concluded that "a fundamental difference between the two regions, in the source regions of magmas is implied by this data." Although he considered a number of possible explanations, he preferred the hypothesis that the lead isotopic differences were "due to different ages of the source regions or to different ages of dehydration" of the Precambrian lower crust or of the low velocity zone in the upper mantle.

During the analytical phase of this work a second, important paper on the provincial nature of lead isotopic compositions was published by R.E. Zartman. Using hundreds of published and unpublished isotopic analyses on Mesozoic and Cenozoic igneous rocks and ores, Zartman (1974) distinguished three lead isotopic provinces in the western United States (see Figure 1.3). Province I includes much of Doe's Rocky Mountain region. It is characterized by comparatively unradiogenic but variable rock Pb ratios in the range 16.2-18.8 for $^{206}Pb/^{204}Pb$ and

Figure 1.3 (After Zartman, 1974): Map of the western United States showing lead isotopic provinces as defined by Zartman (1974). Shaded regions, black dots, crosses, and x's show sample localities for ore and rock data used to locate province boundaries.


PACIFIC
OCEAN
WASHINGTON
OREGON
CALIFORNIA
NEVADA
IDAHO
MONTANA
WYOMING
UTAH
COLORADO
ARIZONA
NEW MEXICO
Ia
Ib
II
III
RUBY RANGE
SIERRA NEVADA BATHOLITH
SAN ANDREAS FAULT
1
2
3
4
5
7
8
9
10
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13
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16
17
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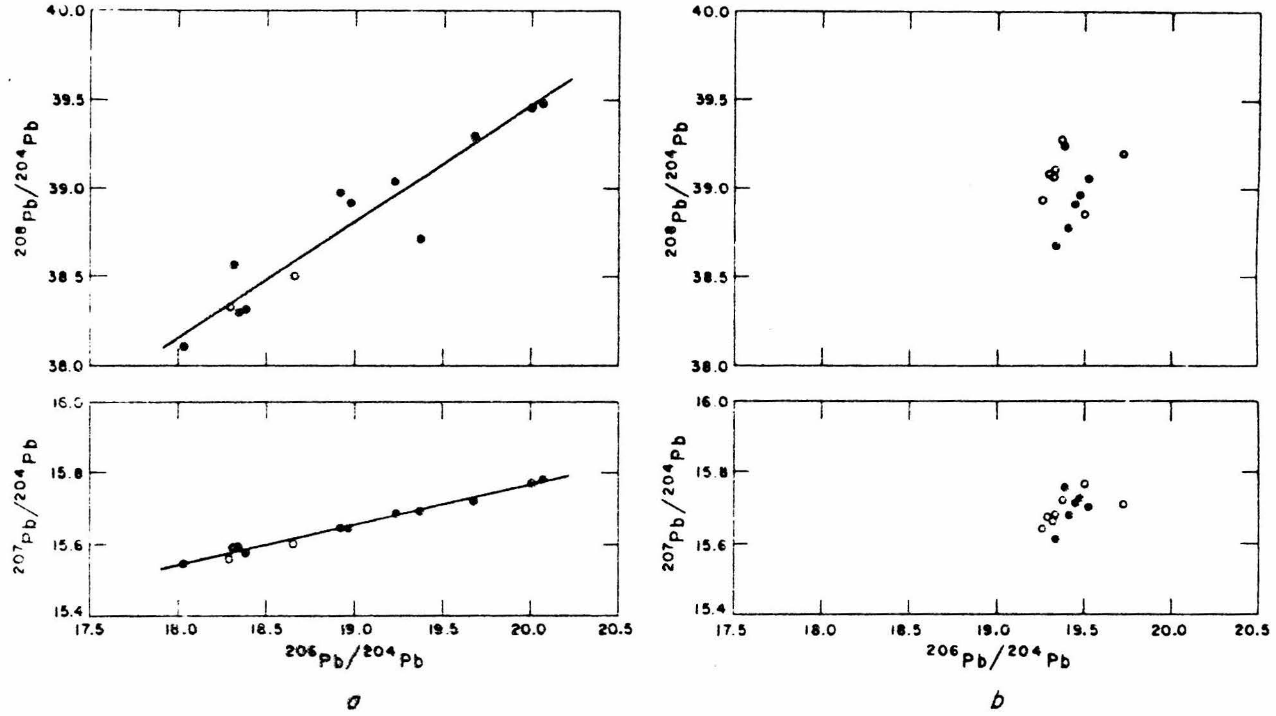
20
21

Figure 1.3



a

b

Examples of lead isotopic patterns for ore (filled circle) and igneous rock (open circle) lead from mining districts in Areas I and II. a. Area I-Milford, Utah (from Stacey et al., 1968). b. Area II-Cortez, Nevada (from Rye, R. O., et al., 1974).

Figure 1.4

(After Zartman, 1974)

36.5-39.9 for $^{208}Pb/^{204}Pb$. Ores from this province display an even wider range in isotopic ratio, and data from individual mining districts often describe long linear arrays when plotted on a $^{206}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ diagram. These "isochrons" have slopes which correspond with the age of the local Precambrian basement -- $\leq$ 1.8 by in Area Ib to the south, and $\sim$ 2.7 by in Area Ia to the north.

Area II is located in central and northern Nevada; it contains very radiogenic rock leads with $^{206}Pb/^{204}Pb$ values between 19.1 and 19.7, and $^{208}Pb/^{204}Pb$ values between 38.9 and 40.3. Contrasting with the long, linear $^{206}Pb/^{204}Pb$-$^{207}Pb/^{204}Pb$ arrays of Area I, Area II "igneous rocks and hydrothermal ore deposits have quite uniform and similar lead isotopic compositions throughout the entire area as well as within individual mining districts." This comparison is illustrated in Figure 1.4.

Area III lies along the Pacific coast and contains rocks with lead ratios generally intermediate between those of Areas I and II Area III $^{206}Pb/^{204}Pb$ ratios generally lie between 18.7 and 19.4 and $^{208}Pb/^{204}Pb$ ratios between 38.2 and 39.1.

Zartman (1974) inferred that the lead characteristics of his three areas were determined by the nature of the local basement rocks. Volcanic sources in Area I, which is underlain by Precambrian basement, are Precambrian rocks of the lower crust, or the mantle. Ore generation in Area I is thought to involve the addition of radiogenic lead from upper crustal rocks. Area II, on the other hand, does not appear to have a Precambrian crystalline basement; it lies in the heart of the Cordilleran geosyncline. Zartman has proposed that Area II volcanics were derived from "isotopically homogenized miogeosynclinal rocks eroded from the adjacent Precambrian sialic upper crust." Area III contains regions of Paleozoic eugeosynclinal basement and regions where no basement older than the Mesozoic outcrops. Zartman (1974) suggested that sources in this area were associated with the subduction of oceanic crust in the Paleozoic, Mesozoic, and/or Cenozoic eras.

We consider the data of both Doe and Zartman to be extremely significant and their analyses of the lead isotopic province problem to be perceptive. However, the detailed studies of Late Cenozoic basalt lead systematics reported in later sections lead to divergent interpretations for some key aspects of the problem pertaining to basaltic petrogenesis in the southwestern United States.

1.4 Problem Design

There are a number of parameters which could potentially be important in interpreting the lead isotopic systematics of Late Cenozoic basalts from the southwestern United States. These include the sample's location in the western United States, its age, and its chemical composition. Correlations between lead isotopic ratios and strontium isotopic composition are also important factors which require consideration.

Sample locality is considered an especially significant parameter. Spatial variation of isotopic characteristics can strongly constrain models of volcanic petrogenesis. For example, Tatsumoto and Knight (1969) have found in Japan that volcanic lead isotopic compositions become less radiogenic the greater the distance from the subduction zone trench. If volcanism in the southwestern United States were related to subduction processes like the volcanism of Japan, one might reasonably expect isotopic compositions to be proportionately richer in ^{204}Pb the greater a sample locality's distance from the coast. One might also expect lines of equal isotopic ratio to approximately parallel the continental margin. And, if the Lipman _et al_. (1972) hypothesis is correct, one might anticipate a discontinuity in isotopic composition corresponding to the locus of their second, inland subduction zone. On the other hand, if lead isotopic composition is not dependent on Cenozoic plate tectonics but dependent on the age of the underlying basement (as suggested by Zartman, 1974), one would expect samples underlain by Precambrian basement to exhibit ratios different from those samples coming from areas underlain by younger basement. For example, samples from coastal California and northern Nevada should have different lead isotopic ratios than those from Arizona or New Mexico.

Sample age is another important variable, even if it is only used to constrain the minimum age that a volcanic source region achieved its isotopic characteristics. However, a number of Cenozoic geologic features in the southwest exhibit regular time-space relationships. Atwater (1970) has proposed a model for the temporal and spatial cessation of subduction along the North American coast. Armstrong and Higgins (1973) have mapped the age that bimodal silicic-basaltic volcanism began in the western United States. Hamblin and Best (1975) have proposed a time-space progression in the age of inception of Basin-Range faulting across the Southwest. It would be extremely significant if a correlation between any of these phenomena and volcanic isotopic composition could be demonstrated.

Isotopic variation may also correlate with differences in sample major element chemical compositions. Several workers have commented on the more radiogenic nature of lead and strontium in alkalic oceanic island volcanics relative to that of abyssal tholeiites. In this case, the chemical-isotopic variation may reflect primary characteristics of the different volcanic source regions in the mantle; in other cases a correlation between chemical and isotopic properties may reflect contamination processes. For example, Lipman and others (1978) have discussed the relationship between isotopic and chemical characteristics of volcanics from the San Juan volcanic field, relations they infer to be governed by complex interactions of magmas with crustal material. Indeed, J. Eichelberger (1976, personal communication) has suggested the possibility that rhyolites come exclusively from melting of lower crustal material, and that intermediate, andesitic and dacitic magmas derive from mixing of silicic, lower crustal and mafic, mantle derived melts. If such a process is active, a clear-cut correlation between chemical and isotopic composition would be expected. Another type of contamination process may also exhibit a dependence on chemical composition. Silicic vitric tuffs tend to be more susceptible to ground water interaction than more mafic, crystalline volcanics, and thus more susceptible to the import of externally derived elements. Noble and Hedge (1969) indicate that some tuffs have acquired as much as 20 ppm of ground water transported Sr. Although this may not be especially critical for strontium, the lower concentration of Pb in these rocks makes groundwater transport of this element into vitric tuffs a matter of concern.

Covariance of lead isotopic ratios is important for two reasons. First, linear relationships between lead ratios can in some instances be used to calculate the age, U/Pb, and Th/U ratios in the volcanic source regions. Secondly, they can be taken, in other instances, to be the result of contamination or mixing processes. A covariance between a Pb isotopic ratio and $^{87}Sr/^{86}Sr$, or even a high $^{87}Sr/^{86}Sr$ ratio by itself, can be useful in detecting the presence of contamination.

CHAPTER 2: ANALYTICAL ERRORS

2.1 Summary

Whole rock lead isotopic compositions were determined by mass spectrometry on Pb extracted from powdered rock samples by volatilization, and purified by conventional dithizone procedures in a contamination controlled laboratory. Pb, U, and Th concentrations were determined by isotope dilution. Extraction of concentration samples involved $HF-HNO_3-HClO_4$ acid dissolution, $Ba(NO_3)_2$ coprecipitation, dithizone extraction for Pb, and anion exchange column extraction for U and Th.

The largest error in the Pb isotopic concentration measurements is statistical in nature. Statistical errors associated with mass spectrometry are variable but typically 0.04% or 0.05% of the isotopic ratio. Errors from the 26 ng composition lead blank usually contribute an error in a measured isotope ratio of 0.02% or less. This low contribution results from the relatively large sizes ($\sim$3 g) and high concentrations ($\geq$2 ppm) of the samples analyzed in this study. Isotopic compositions were corrected for powder preparation blanks, although the magnitude of this correction is generally $\leq$0.03% of the isotopic ratio. Total composition errors are estimated to be $\leq$0.07% (1 σ) of the stated isotope ratio.

The error in concentration determinations is about 1% of the concentration; it derives from uncertainties in the amount of spike added to rock samples, lack of equilibrium of spike and sample leads, and drift in spike solution concentrations.

2.2 Analytical Methods

A detailed discussion of the procedures - preparation, chemical, and mass spectrometric - used in this study can be found in Appendix B.

2.3 Errors in Lead Isotopic Composition Measurements

Errors in the determination of whole rock Pb isotopic composition measurements can come from three sources: from contamination of sample lead with lead from origins external to the natural sample, from instrumental inaccuracies and statistical uncertainties associated with mass spectrometry, and from incomplete extraction of lead from isotopically heterogeneous samples.

2.3.1. Contamination

In order to minimize atmospherically derived contamination, the external surfaces of all rock samples were broken off, and only the interior portions of the rock was utilized for analysis. In addition, multiple layers of clean plastic bags were used to protect samples from contamination during transport and storage.

Preparation (crushing and grinding) blank levels were investigated using fused silica glass as an essentially lead-free rock analogue. These experiments indicated that while storage, hammer crushing on an iron plate, and vacuum furnace handling procedures contributed negligible amounts of contamination, grinding with a Shatterbox consistently added 90 ng of common lead for each 3.2 g weight of silica glass crushed (28 ppb). Since the isotopic composition of the Shatterbox contaminant has been well determined, and the amount of contamination is consistent from grinding to grinding, a correction can and has been made to the measured sample isotopic compositions. This correction turns out to be small (much less than the 1 σ statistical error) for the vast majority of samples. This small effect is a result of the relatively high Pb concentrations of samples (2-12 ppm) compared to contaminant (28 ppb), and the small differences between sample and contaminant isotopic compositions.

Contamination from the volatilization and chemical procedures has been monitored periodically. The results of these experiments, tabulated in Table 2.1, indicate that the composition blank is approximately 26 ng of Pb, although it may sporadically attain a higher value. Although some 7-10 ng of this blank comes from the volatilization procedure, the majority derives from the chemical extraction, of which the reagents and glassware each donate approximately 8 ng Pb. Except in two cases where an item of glassware had been previously exposed to a radiogenic Pb, the isotopic composition of the blank Pb appears to be similar to that of modern terrestrial lead. Unfortunately, it has not been possible to determine the blank composition accurately enough to apply a correction to sample isotopic ratios. It is possible, however, to estimate the magnitude of blank derived error. This was done for each sample assuming the blank Pb derives randomly from the same statistical population as that of the samples. The errors so calculated are always substantially smaller than the statistical errors associated with the mass spectrometric measurements. This result is

Table 2.1: Composition Pb Blanks

Date	$^{206}Pb/^{204}Pb$	$^{206}Pb/^{207}Pb$	Chemistry	Chemistry + Volatilization	Chemistry + Volatilization w/o Outgassing
11/73	18 ± 2	1.19 ± .01		206 ng	
12/73	19.7 ± .3	1.234 ± .001	43 ng		
1/74	10 ± 2	1.1 ± .1		25	
6/74	20 ± 3	1.23 ± .02			53 ng
2/75		1.4 ± .2		27	
7/75		1.19 ± .02			54
9/75		1.20 ± .02		72	
12/75	18.8 ± .2	1.23 ± .02	19		
12/75	17 ± 1	1.22 ± .02		26	
12/75		1.26 ± .01	43		
12/75	14 ± 1	1.17 ± .02	16		
1/76	15 ± 2	1.20 ± .02			31
2/76	18.2 ± .4	1.20 ± .02		26	
12/76	31 ± 1	1.75 ± .05		37	
1/77	25 ± 5	1.69 ± .04		10	
7/77	17.8 ± .1	1.20 ± .02		40	
9/77	18.4 ± .2	1.26 ± .01		26	
9/77	18.8 ± .3	1.24 ± .01		≤36	
10/77	19 ± 2	1.26 ± .01		≤37	
8/78	19 ± 1	1.22 ± .02		≤43	

to be expected from the fairly low blank concentration to sample concentration ratios, which are usually ≤0.05%, and the similarity between blank and sample isotopic compositions.

2.3.2. Mass spectrometer errors and reproducibility

Statistical error, inaccuracies in the discrimination factors, as well as other instrumental errors and biases contribute to the uncertainty of mass spectrometrically determined isotopic ratios. Statistical error is the most obvious and largest of these inaccuracies. Although they vary from run to run, one sigma standard deviations are typically 0.04% of the measured $^{206}Pb/^{204}Pb$, $^{206}Pb/^{207}Pb$, and $^{206}Pb/^{208}Pb$ ratios.

Inaccuracies in the determination of silica gel discrimination factors, which convert measured ratios to "absolute" ratios, and variations in discrimination factor values from run to run are a second source of error. Discrimination factors have been established empirically by comparing this lab's analytical results on the CIT Shelf and NBS #981 isotopic lead standards to published determinations involving analytical methods which minimize or correct for isotopic fractionation. Table 2.2 shows data on the Caltech Shelf Standard. Using the Catanzaro (1967) published results for comparison, the calculated mass discrimination factor is roughly 1‰ per unit mass difference. This number is similar to, but perhaps a trifle lower than the 1.0-1.7‰ values quoted by Sun (1973) and the average value of 1.2‰ of Gancarz (1976). These differences, if real, may reflect the different characteristics of

Table 2.2: Caltech Shelf Standard Isotopic Ratios

Date	$^{206}Pb/^{204}Pb$	$^{206}Pb/^{207}Pb$	$^{206}Pb/^{208}Pb$	$e_{(6/4)}^*$	$e_{(6/7)}^*$	$e_{(6/8)}^*$	Reference
	16.625 ± .0087	1.0743 ± .202E-3	.45798 ± .105E-3	0	0	0	Catanzaro (1967)
	16.617 ± .0157	1.0744 ± .872E-3	.45834 ± .435E-3				Compston and Oversby (1969)
	16.648 ± .0088	1.0740 ± .387E-3	.45790 ± .137E-3				Sinha *et al.* (1971)
	16.637 ± .0051	1.0746 ± .100E-3	.45831 ± .374E-4				Sun (1973)
8/73**	16.674 ± .0868	1.0731 ± .168E-2	.45589 ± .116E-2				This work
6/74	16.593 ± .0030	1.0739 ± .143E-3	.45848 ± .660E-4	.95	-.40	.51	
6/74	16.600 ± .0017	1.0739 ± .132E-3	.45780 ± .791E-4	.75	-.40	-.20	
6/74	16.586 ± .0026	1.0749 ± .158E-3	.45899 ± .767E-4	1.20	.60	1.10	
10/75	16.607 ± .0021	1.0748 ± .203E-3	.45848 ± .687E-4	.54	.52	.56	
3/76	16.586 ± .0060	1.0747 ± .299E-3	.45958 ± .112E-3	1.17	.37	1.74	
4/76	16.590 ± .0048	1.0753 ± .324E-3	.45901 ± .180E-3	1.05	.89	1.12	
9/76**	16.612 ± .0025	1.0745 ± .348E-3	.45816 ± .127E-3				
1/77	16.583 ± .0014	1.0755 ± .207E-3	.45916 ± .780E-4	1.27	1.12	1.28	
4/77	16.599 ± .0012	1.0753 ± .157E-3	.45894 ± .883E-4	.78	.93	1.05	
9/77	16.583 ± .0031	1.0756 ± .218E-3	.45950 ± .129E-3	1.26	1.21	1.65	
Average	16.592 ± .285E-2	1.0749 ± .211E-3	.45888 ± .185E-3	1.00 ± .09	.54 ± .20	.98 ± .20	
Weighted Average	16.594 ± .681E-3	1.0747 ± .602E-4	.45874 ± .285E-4				

*The discrimination factor, e, is calculated from the equation: $e_{(X/Y)} = 1000[(R_{obs} - R_{abs}) - 1]/\Delta m$, where R_{obs} is the observed ratio of $^{20X}Pb/^{20Y}Pb$, R_{abs} is the absolute ratio, and $\Delta m = (20X - 20Y)$.

**These data are not included in the calculations of e or average standard ratios; pronounced fractionation occurred during the course of the mass spectrometer run.

different batches of silica gel or possibly the different filament temperatures at which data were taken by the different labs. It can also be noted from Table 2.4 that the discrimination factor calculated for the $^{207}Pb/^{206}Pb$ ratio is smaller than those calculated for the other isotopic ratios. This discrepancy is minimized if Catanzaro's data are used for comparison rather than an average of all published data.

For each isotopic ratio in Table 2.2 the standard deviation of the mean calculated from the variance of individual isotopic ratios is larger than the σ_μ calculated from the variances of individual runs. That is,

$$\frac{\Sigma(X_i - \bar{X})^2}{N(N-1)} > \frac{1}{\Sigma(1/\sigma_i)^2}$$

where σ_i is the statistical variance of X_i, the measured isotopic ratio of run i, $\bar{X}$ is the average ratio of all runs, and N is the number of runs. Thus, statistical error by itself cannot account for the observed variance in isotopic ratio. Additional sources of error contribute uncertainties up to 0.02% or 0.03% beyond statistics.

This additional error can be attributed to a number of possible sources. Variability in the discrimination factors from run to run, inaccurate or changing shunt calibrations, and non-linearity of the digital voltmeter signals are just three instrumental possibilities. Collection of data from the mass spectrometer also requires that signals be interpolated to some reference time in order to obtain an isotopic ratio. The linear interpolation done in this study introduces inaccuracies if the signal is unstable (varies in an erratic way) or even if it is curvilinear in time. Internal sample isotopic heterogeneity, especially in the case that sample Pb is incompletely extracted, can also add to the variance of the data.

With the exception of signal instability, none of the factors mentioned above seem to have much effect on the reproducibility of the data. For instance, several repeat analyses were performed on sample A5014, a rock containing quartz and alkali feldspar xenocrysts as well as large but infrequent partially melted granulitic xenoliths, and therefore considered to be a good candidate for internal isotopic heterogeneity. The results of these analyses, shown in Table 2.3, display no differences in excess of that which can be attributed to statistical error.

A second test, which compared $^{206}Pb/^{204}Pb$ and $^{206}Pb/^{207}Pb$ data from composition and concentration runs on the same sample, was used to investigate the presence of extra-statistical errors. The Welsh t-test parameter[1] was used to pick those comparisons where differences between composition and concentration ratios exceeded that explainable by statistical error. In cases where one of the runs[2] had an unstable signal, W values were almost always in excess of the

---

[1] Mack (1967) discusses the use of the W parameter statistical test.

[2] Signal instability frequently occurred in concentration runs taken during one three month period. It was very rare in isotopic composition runs and concentration runs done during other intervals of data collection.

Table 2.3: Repeat Analyses of Sample A5014

Analytical Method*	$^{206}Pb/^{204}Pb$	$^{206}Pb/^{207}Pb$	$^{206}Pb/^{208}Pb$	Yield
vol.	18.113 ± .008	1.1685 ± .0004	.48186 ± .00011	87%
vol.	18.113 ± .006	1.1675 ± .0006	.48195 ± .00027	
vol.**	18.134 ± .006	1.1671 ± .0003	.48185 ± .00009	71%
vol.**	18.115 ± .007	1.1681 ± .0005		71%
vol. avg.	18.119 ± .005	1.1678 ± .0003	.48189 ± .00003	
vol. weighted avg.	18.120 ± .003	1.1677 ± .0002	.48186 ± .00004	
HF dis.	18.103 ± .022	1.1684 ± .0008		100%

*Both volatilization (vol.) and HF dissolution (HF dis.) were used to extract sample leads.

**These two runs are different aliquots of the same sample.

critical value at the 95% confidence level. Of the remaining 22 samples, only four samples showed differences in either $^{206}Pb/^{204}Pb$ or $^{206}Pb/^{207}Pb$ between composition and concentration data that could not be attributed entirely to statistical error. This result again indicates the presence of nonstatistical errors, but also shows that errors not coming from counting statistics rarely make an observable contribution to the total imprecision.

2.3.3. Correction for *in situ* radioactive decay

It was not feasible in most cases to correct for the increment of radiogenic lead generated within each volcanic sample after its crystallization. The data required to do this calculation - Pb, U, and Th concentrations and accurate ages - were available for only a small fraction of the samples analyzed. Fortunately, most of the samples used in this study are youthful (≤5 my in age) and possess relatively low U/Pb ratios ($\mu \leq 25$). Consequently, the correction for *in situ* decay is not large. Corrections would normally be ≤0.1% for the $^{206}Pb/^{204}Pb$ ratio, insignificant for the $^{207}Pb/^{204}Pb$ ratio, and ≤0.04% for the $^{208}Pb/^{204}Pb$ ratio. The few Miocene and Oligocene samples would, however, require more significant corrections. But even for these samples, the shifts in isotope ratio due to postcrystallization decay would not affect any of the results or conclusions put forth in later chapters.

2.4 Errors in Pb, U, and Th Concentration Measurements

Concentration data presented in this study are thought to be accurate to within 1% of the stated value. Because spike and sample isotopic compositions differ sufficiently, and the uncertainties in measured isotope ratios are small ($1\ \sigma \sim 0.04\%$), the concentration errors propagating from mass spectrometric measurements are negligible, ∿0.1% of the concentration. More substantial errors may come from uncertainties relating to spike delivery, equilibrium, and concentration drift. Sample heterogeneity may also contribute to the imprecision of concentration data, but blank levels would not have a noticeable effect.

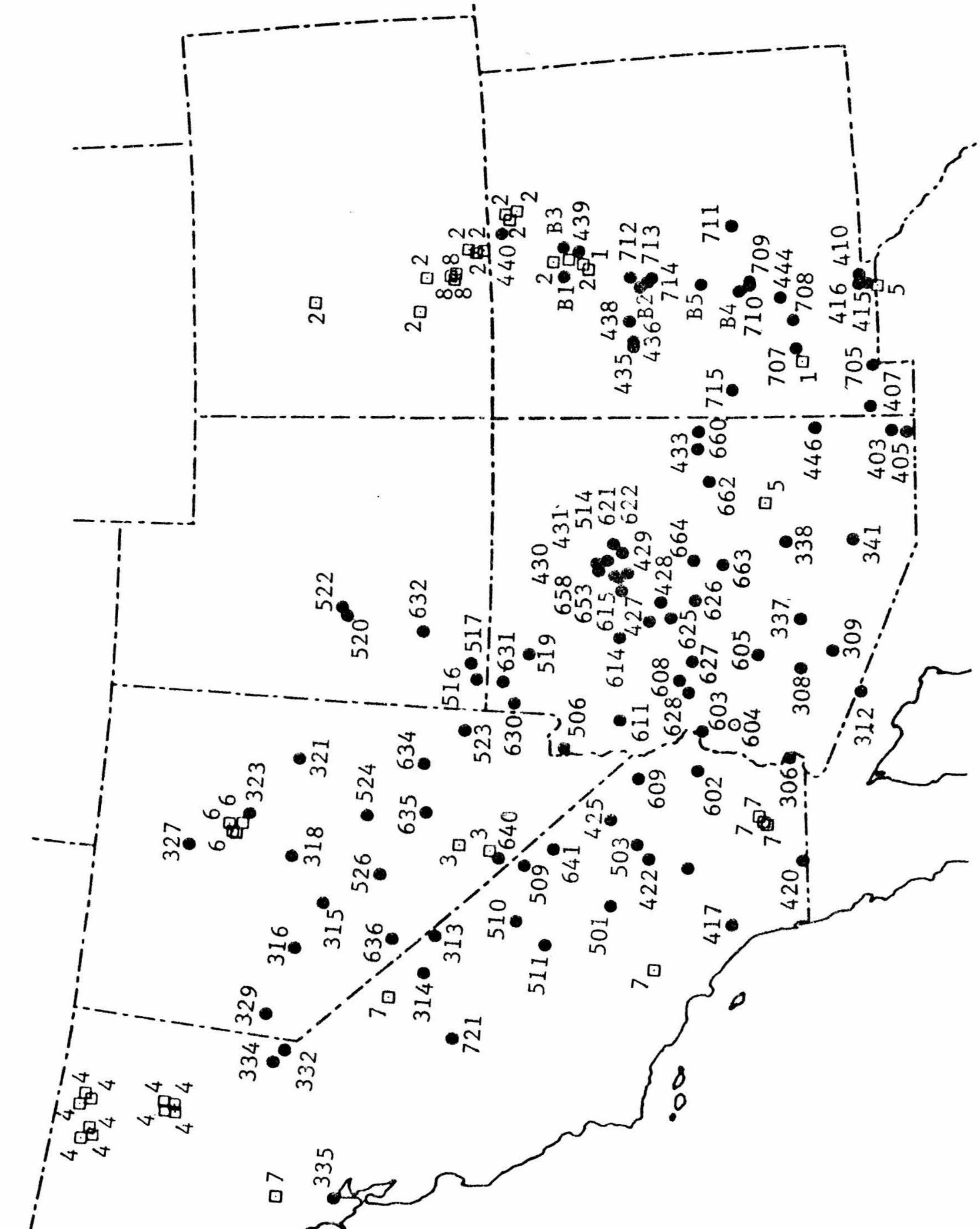
For all uses of concentration data in this work a 1% precision is quite adequate.

CHAPTER 3: SAMPLES AND DATA

3.1 Sampling Design

The major aim in sample collection has been to establish the regional variation of lead isotopic characteristics in Pliocene and Quaternary basalts from the southwestern portion of the United States. The southwestern United States was picked for investigation because of its accessibility, the importance of understanding its tectonic and volcanic history, as well as the abundance of published geologic reports and dearth of previous lead studies on the area. Basaltic samples were preferred because their chemistry makes them more likely candidates for mantle derivation, and thus more useful in investigating mantle source region characteristics. Young samples were emphasized because they are less susceptible to weathering and in situ radioactive decay corrections. However, isotopic compositions of older, Miocene and, very rarely, Oligocene volcanics have been measured in several instances in order to check for any major variation of isotopic characteristics with age, and to help fill in the regional isotopic patterns where younger rocks were not available. In addition, a number of more silicic rocks - andesites, dacites, and rhyolites - were collected from the San Francisco volcanic field to check for petrologic and chemical correlations with isotope characteristics. Only sporadic samples of intermediate and silicic rocks were taken elsewhere to fill holes in the spatial isotopic pattern, and also to check for compositionally dependent isotopic variations. Intrusive rocks, mineralized or not, were completely neglected in sampling.

Figure 3.1. Sample localities. Circles are samples analyzed in this work. Squares are localities of late Cenozoic volcanics on which published lead isotopic data are available. Three digit numbers are sample numbers abbreviated by deleting the first digit (a letter denoting state) and the third digit (always a zero). For example, C3006 is abbreviated 306. Single digit numbers prefixed by a B are samples collected by W.J. Baldridge from the Rio Grande rift. One digit numbers by squares are data references, 1 = Doe (1967); 2 = Doe et al. (1969); 3 = Doe (1970); 4 = Church and Tilton (1973); 5 = Zartman and Tera (1973); 6 = Rye et al. (1974); 7 = Doe and Delevaux (1973); 8 = Lipman et al. (1978).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335
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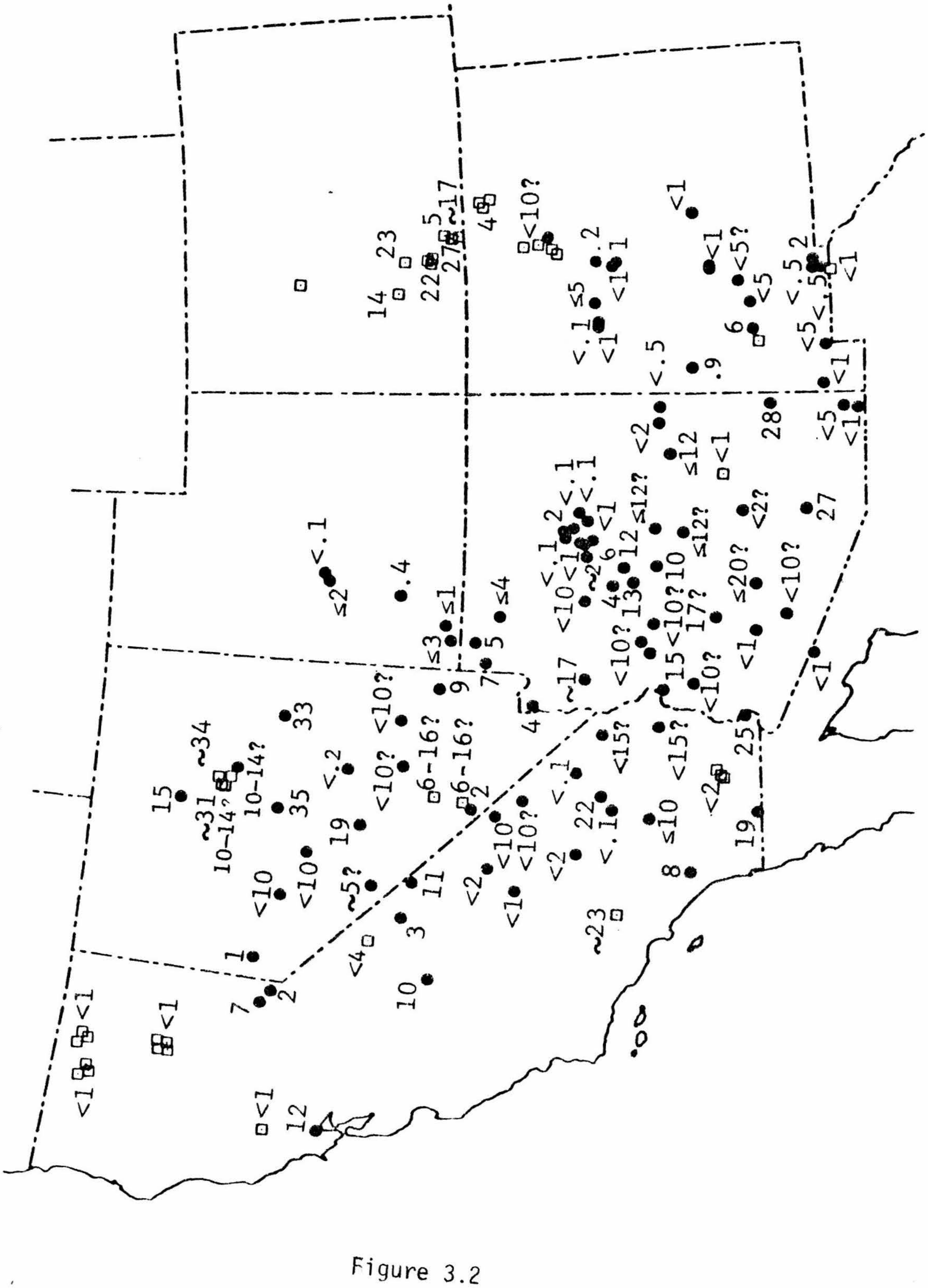
Figure 3.1

Figure 3.2. Sample ages in millions of years. Dates attended by a $\leq$ or ? were estimated according to stratigraphic and/or geomorphological criteria. Other, unattended numbers represent K/Ar dates.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≤12?
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17?
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10-14?
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<10?
<10?
6-16?
6-16?
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<.1
22
<.1
<15?
<15?
25
<2
≤10
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19
<10
<10
~5?
11
<2
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<10?
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8
<1
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1
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10
7
2
<1
<1
<1
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12

Figure 3.2

Figure 3.3. Classification of samples according to petrographic criteria. B = basalt; BA = basaltic andesite; A = andesite; and S = undifferentiated intermediate and silicic rocks (andesite, dacite, and rhyolite).

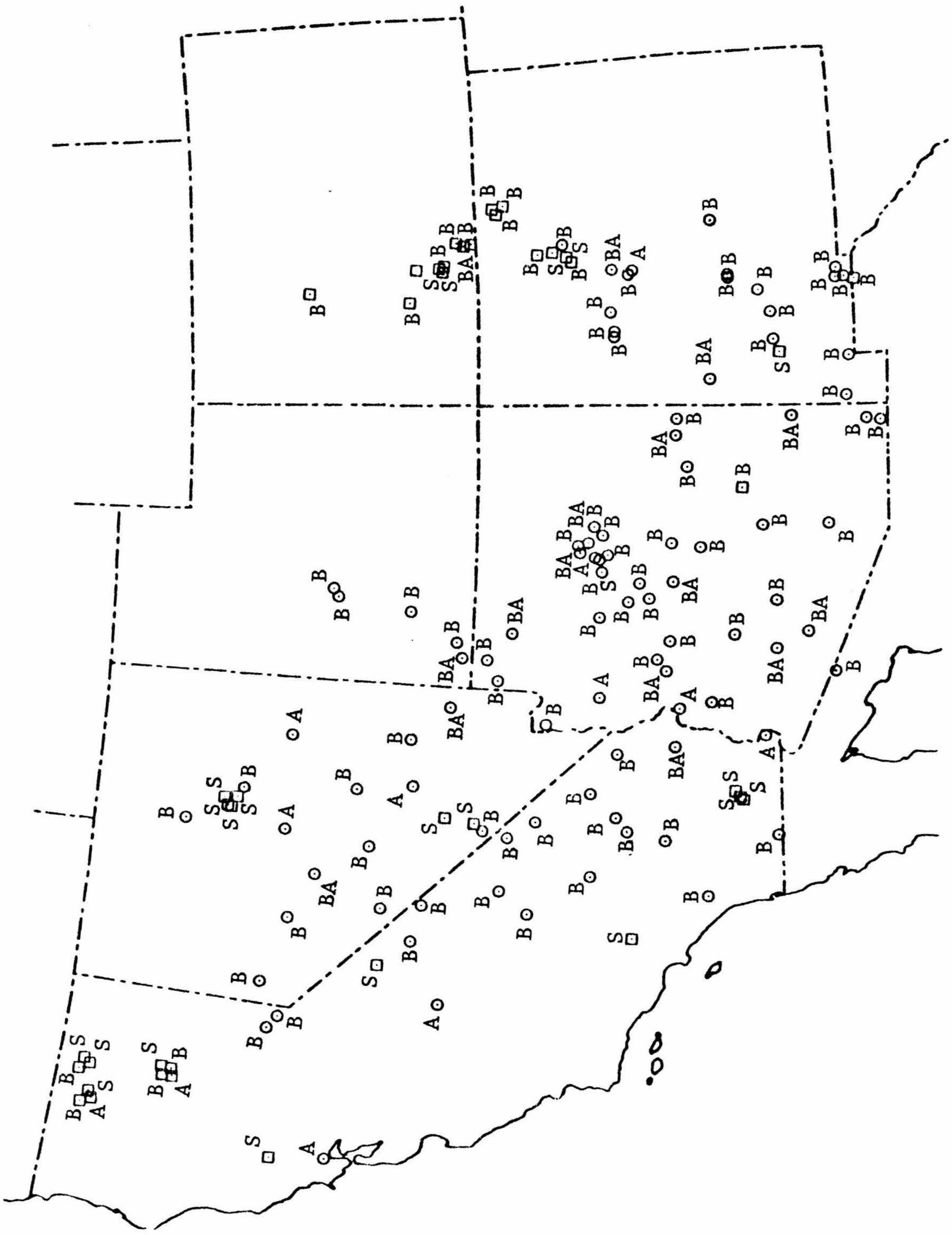


Figure 3.3

Table 3.1. Descriptive Data

Sample Number	County	Locality	Longitude (°W)	Latitude (°N)	Rock Type	Age (my)*
CALIFORNIA SAMPLES						
C3006	Imperial	Chocolate Mountains	114.553	39.949	Hornblende andesite	24.7 ± 2.1
C3013	Inyo	Deep Springs Valley	117.964	37.412	Olivine basalt	10.8 ± 1.0
C3014	Mono	Owens Gorge	118.608	37.554	Olivine basalt	3.2 ± 0.1
C3032	Placer	Tahoe City	120.145	39.168	Feldspathic basalt	1.9 ± 0.1
C3034	Nevada	Boreal Ridge	120.349	39.327	Feldspathic basalt	7.4 ± 0.2
C3035	Marin	Burdell Mountain	122.568	38.136	Andesite	11.8 ± 0.8
C4017	Riverside	Murrieta	117.247	33.535	Olivine basalt	8.5 ± 0.5
C4020	San Diego	Jacumba Peak	116.199	32.625	Feldspathic basalt	18.7 ± 1.3
C4022	San Bernadino	Pisgah	116.323	34.649	Alkali olivine basalt	<0.1
C4025	San Bernadino	Black Tank	115.726	35.288	Alkali olivine basalt	<0.1
C5001	San Bernadino	Black Mountain	117.139	35.108	Alkali olivine basalt	<2
C5003	San Bernadino	Bristol Mountains	116.094	34.849	Feldspathic basalt	22.2 ± 1.1
C5009	Inyo	Death Valley Junction	116.598	36.335	Feldspathic basalt	<10
C5010	Inyo	Darwin	117.649	36.353	Feldspathic basalt	≤2
C5011	Inyo	Little Lake	117.846	35.952	Feldspathic basalt	<1
C6002	San Bernadino	Turtle Mountains	114.845	34.117	Basaltic andesite	<15?
C6009	San Bernadino	Goffs	115.057	34.910	Feldspathic basalt	<15?
C6041	Inyo	Shoshone	116.275	35.980	Feldspathic basalt	<10

Table 3.1 (continued)

Sample Number	County	Locality	Longitude (°W)	Latitude (°N)	Rock Type	Age (my)*
C7001	San Bernadino	Yucca Valley	116.400	34.175	Olivine basalt	≤10
C7021	Fresno	Millerton Lake	119.584	37.026	Andesite	9.5 ± 0.3
ARIZONA SAMPLES						
A3008	Maricopa	Sentinel Peak	113.141	32.883	Basaltic andesite	<1
A3009	Pima	Batamonte Mountains	112.815	32.461	Basaltic andesite	15 ± 2.2
A3037	Maricopa	Freeman Road	112.318	32.852	Feldspathic basalt	≤20
A3038	Pinal	Florence	111.084	33.084	Feldspathic basalt	<2?
A3041	Pima	Tucson Mountains	110.990	31.215	Feldspathic basalt	27.0 ± 1.2
A4003	Cochise	Tex Canyon	109.309	31.658	Alkali olivine basalt	<5
A4005	Cochise	Cinder Hill	109.312	31.445	Basanitoid	<1
A4027	Yavapai	Pauldin	112.471	34.869	Olivine-augite basalt	4.5 ± 0.2
A4028	Yavapai	Mingus Mountain	112.142	34.704	Tholeiitic feldspathic basalt	~12
A4029	Coconino	Switzer Mesa	111.635	35.204	Olivine tholeiite	5.8 ± 0.3
A4030	Coconino	SP Crater	111.608	35.610	Basaltic andesite	<0.1
A4031	Coconino	Black Point	111.516	35.619	Feldspathic basalt	2.39 ± 0.32
A4033	Apache	Cerro Montoso	109.578	34.266	Basaltic andesite	<2
A4046	Greenlee	Flattop	109.195	32.682	Mafic andesite	27.5 ± 0.8
A5006	Mohave	Black Canyon Quadrangle	114.646	35.950	Feldspathic basalt	4.7 ± 0.3
A5014	Coconino	Strawberry Crater	111.465	35.439	Basaltic andesite	<0.1
A5019	Mohave	Mt. Trumbell	113.064	36.467	Basaltic andesite	≤4
A6003	Yuma	Parker	114.216	34.122	Andesite	16.4 ± 0.7

Table 3.1 (continued)

Sample Number	County	Locality	Longitude (°W)	Latitude (°N)	Rock Type	Age (my)*
A6004	Yuma	Golden Nugget Road	114.072	33.676	Basaltic andesite	≤10?
A6005	Maricopa	Palo Verde Hills	112.935	33.452	Tholeiitic feldspathic basalt	<16.7
A6008	Mohave	Arrastra Mountains	113.368	34.485	Diabase	<10
A6011	Mohave	Kingman	114.102	35.208	Andesite	~17
A6014	Yavapai	Seligman	112.835	35.279	Feldspathic basalt	<10
A6015	Coconino	Wright Hill	111.957	35.300	Rhyolite	~2
A6018	Coconino	Strawberry Crater	111.467	35.443	Dacite vitrophyre	<0.1
A6021	Coconino	Grand Falls	111.203	35.427	Basanitoid	<0.1
A6022	Coconino	Jumpoff Crater	111.329	35.299	High alumina basalt	<1
A6023	Coconino	Sunset Crater	111.528	35.381	Alkali olivine basalt	0.1
A6025	Yavapai	Glassford Hill	112.347	34.579	Feldspathic basalt	13.4 ± 0.5
A6026	Yavapai	Horseshoe Ranch	112.041	34.275	Basaltic andesite	10.4 ± 0.4
A6027	Yavapai	Malpais Mesa	113.093	34.324	Diabase	<10?
A6028	Mohave	Plancha Mountain	113.622	34.325	Basaltic andesite	<10?
A6030	Mohave	Jacobs Well	113.900	36.659	Hawaiite	6.7 ± 0.2
A6031	Mohave	Wolf Hole Mountain	113.586	36.823	Ankaramite	5.2 ± 1.3
A6053	Coconino	Humphreys Peak	111.677	35.346	Andesite	<1
A6054	Coconino	Humphreys Peak	111.675	35.346	Andesite	<1
A6058	Coconino	Core Ridge	111.680	35.334	High alumina basalt	<1
A6060	Apache	Lyman Lake	109.356	34.254	Olivine basalt	<0.5
A6062	Navajo	Corduroy Creek	110.153	34.106	Olivine-augite diabase	≤12

Table 3.1 (continued)

Sample Number	County	Locality	Longitude (°W)	Latitude (°N)	Rock Type	Age (my)*
A6063	Maricopa	Mazatzal Mountains	111.464	33.928	Olivine basalt	≤12?
A6064	Gila	Buckhead Mesa	111.416	34.321	Olivine-augite diabase	≤12?
MEXICO SAMPLES						
M3012	Sonora	Pinacate Mountain	113.494	32.039	Basalt	<1
NEVADA SAMPLES						
N3015	Nye	Ione	117.615	38.978	Basaltic andesite	5-20?
N3016	Churchill	Stillwater Range	118.415	38.278	Feldspathic basalt	10
N3018	Lander	Cape Horn	116.841	39.392	Andesite	35 ± 3.5
N3021	White Pine	Robinson Summit	115.150	39.431	Dacite	32.9 ± 0.7
N3023	Eureka	Cadet Trough Spring	116.393	40.074	Tholeiite	14.7 ± 1.0
N3027	Lander	Battle Mountain	116.863	40.748	Diabase	14.8 ± 1.5
N3029	Storey	Long Valley	119.618	39.488	Olivine basalt	1.14 ± 0.4
N5023	Lincoln	Leith Station	114.460	37.265	Basaltic andesite	8.5 ± 0.3
N5024	Nye	Lunar Crater	116.012	38.480	Basanitoid	<0.2
N5026	Nye	Thunder Mountain	117.027	38.190	Feldspathic basalt	18.9 ± 1.5
N6034	Lincoln	White River	115.093	37.789	Tholeiite	<10?
N6035	Lincoln	White Blotch Springs	115.885	37.729	Andesite	<10?
N6036	Esmeralda	Volcanic Hills	118.052	37.999	Feldspathic basalt	~5?
N6040	Nye	Big Dune Quadrangle	116.509	36.680	Feldspathic basalt	2.0 ± 0.6

Table 3.1 (continued)

Sample Number	County	Locality	Longitude (°W)	Latitude (°N)	Rock Type	Age (my)*
UTAH SAMPLES						
U5016	Washington	St. George	113.555	37.124	Basaltic andesite	≤3
U5017	Washington	La Verkin	113.282	37.225	Hawaiite	≤1
U5020	Millard	Hole-in-the-Rock	112.629	38.872	Feldspathic diabase	≤2
U5022	Millard	Ice Springs	112.462	38.980	Feldspathic basalt	<0.1
U6032	Iron	Pargonah	112.779	37.877	Feldspathic basalt	0.44 ± 0.04
NEW MEXICO SAMPLES						
NM4007	Hidalgo	Animas	108.852	31.944	Alkali olivine basalt	<5
NM4014	Dona Ana	Santo Thomas	106.770	32.019	Alkali olivine basalt	2.35 ± 2
NM4015	Dona Ana	Kilbourne Hole	106.967	31.958	Alkali olivine basalt	<0.5
NM4016	Dona Ana	Aden	106.92	32.05	Alkali olivine basalt	<0.5
NM4035	Valencia	La Ventana Road	107.788	35.078	Tholeiite	<0.1
NM4036	Valencia	La Ventana Road	107.789	35.078	Tholeiite	<1
NM4038	Valencia	Wheat Mountain	107.425	35.118	Alkali olivine basalt	<5
NM4039	Los Alamos	Ancho Canyon	106.244	35.775	Tholeiite	<10
NM4040	Taos	Arroyo Hondo	105.709	36.535	Basaltic andesite	4 ± 1
NM4044	Sierra	Elephant Butte	107.148	33.129	Alkali olivine basalt	<5
NM7005	Grant	Hachita	108.289	31.922	Alkali olivine basalt	<5
NM7007	Grant	Rio Mimbres	107.991	32.920	Alkali olivine basalt	6.29 ± 0.41
NM7008	Sierra	Hillsboro	107.502	32.980	Alkali olivine basalt	<5
NM7009	Socorro	Bat Caves	106.874	33.519	Basanitoid	<1

Table 3.1 (continued)

Sample Number	County	Locality	Longitude (°W)	Latitude (°N)	Rock Type	Age (my)*
NM7010	Socorro	Hackberry Well	106.906	33.507	Basanitoid	<1
NM7011	Lincoln	Carrizozo	105.914	33.684	Tholeiite	<1
NM7012	Bernalillo	Albuquerque	106.711	35.140	Feldspathic basalt	0.19 ± 0.4
NM7013	Valencia	Los Lunas	106.785	34.785	Andesite	1.12 ± 0.04
NM7014	Valencia	Sandia site	106.845	34.824	Alkali olivine basalt	<1
NM7015	Catron	Apache Creek	108.617	33.824	Basaltic andesite	0.9 ± 0.2
74-005(B1)	Rio Arriba	Abiquiu	106.367	35.089	Alkali olivine basalt	≤5
75-114(B2)	Bernalillo	Isleta	106.727	34.919	Alkali olivine basalt	≤5
75-230(B3)	Santa Fe	White Rock	106.178	35.834	Basaltic andesite	≤5
75-256(B4)	Socorro	San Marcial	106.967	33.660	Alkali olivine basalt	≤5
75-259(B5)	Socorro	San Acacia	106.886	34.259	Mafic andesite	≤5

*Dates given with a ± error are K/Ar dates, the sources of which are tabulated in Appendix C. Other dates were estimated from geologic constraints.

3.2 Samples

Table 3.1 is a brief tabulation of descriptive data on each sample analyzed in this work. Appendix C is a more complete compilation of locality data, petrographic characteristics, and geologic information on individual samples. Figure 3.1 shows localities and field numbers of samples analyzed in this work on a map of the southwestern United States. This figure also shows the localities of a number of late Cenozoic rocks on which published lead data are available. Figure 3.2 shows sample ages and Figure 3.3 shows sample rock types.

3.3 Data

Analytical results are listed in Table 3.2. As shown in Figure 3.4, $^{206}Pb/^{204}Pb$ ratios range from 16.98 to 19.61; $^{208}Pb/^{204}Pb$ values range from 36.65 to 40.30. $^{207}Pb/^{204}Pb$ values fall between 15.40 and 15.73. This variation in lead isotopic composition nearly spans the range displayed by all modern terrestrial leads (see Doe, 1970).

Table 3.3 shows the averages of the isotope ratios quoted in Table 3.2. The average values quoted in this table ($^{206}Pb/^{204}Pb$ = 18.57, $^{207}Pb/^{204}Pb$ = 15.55, and $^{208}Pb/^{204}Pb$ = 38.33) are rather similar to estimates of the average modern terrestrial lead. For example, this laboratory has found common lead contamination to be well represented by 18.6, 15.6, and 38.0 for $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ ratios, respectively. Vollmer (1977) has estimated the average isotopic composition of the crust-mantle system to be $^{206}Pb/^{204}Pb$ = 18.6, $^{207}Pb/^{204}Pb$ = 15.54; while Stacey and Kramers

Table 3.2: Analytical Data

Sample Number	$^{206}Pb/^{204}Pb$	$^{206}Pb/^{207}Pb$	$^{206}Pb/^{208}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Pb (ppm)	U (ppm)	Th (ppm)	Th/U
CALIFORNIA SAMPLES									
C3006	19.017	1.2182	.48981	15.611	38.825				
C3013	18.215	1.1705	.47094	15.561	38.678				
C3014	18.862	1.2088	.48760	15.603	38.683				
C3032	19.298	1.2312	.49215	15.675	39.212				
C3034	18.920	1.2160	.49166	15.560	38.482				
C3035	19.144	1.2256	.49385	15.596	38.704				
C4017	19.107	1.2268	.49332	15.575	38.731	1.32	.29	1.53	5.28
C4020	19.018	1.2170	.49165	15.628	38.683	11.65	.65	2.29	3.52
C4022	19.100	1.2319	.49300	15.504	38.743	2.54	1.21	4.39	3.63
C4025	19.048	1.2269		15.526		2.19	1.40	4.73	3.38
C5001	19.189	1.2308	.49555	15.591	38.723				
C5003	19.320	1.2335	.49553	15.663	38.990				
C5009	18.272	1.1734	.47210	15.573	38.705	6.39	.76	5.51	7.25
C5010	19.086	1.2180	.49176	15.670	38.812				
C5011	19.043	1.2205	.49386	15.603	38.559				
C6002	18.998	1.2156	.48905	15.628	38.847				
C6009	18.627	1.1974	.48205	15.556	38.641				
C6041	19.043	1.2146	.48596	15.678	39.187				
C7001	18.794	1.2115	.48523	15.514	38.733				

Table 3.2 (continued)

Sample Number	$^{206}Pb/^{204}Pb$	$^{206}Pb/^{207}Pb$	$^{206}Pb/^{208}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Pb (ppm)	U (ppm)	Th (ppm)	Th/U
C7021	19.070	1.2205	.49218	15.626	38.747				
ARIZONA SAMPLES									
A3008	18.952	1.2213	.49451	15.518	38.325	2.17	.76	3.99	5.25
A3009	19.045	1.2184	.49007	15.632	38.862				
A3037	18.750	1.2022	.48629	15.596	38.556	11.41	1.53	6.34	4.14
A3038	18.727	1.2071	.49216	15.514	38.051	2.01	.75	3.09	4.12
A3041	18.674	1.1946		15.631		8.09	1.56	8.35	5.35
A4003	18.842	1.2149	.49399	15.509	38.142	3.16	1.74	6.51	3.74
A4005	18.862	1.2187	.49595	15.477	38.032	2.19	1.25	3.56	2.85
A4027	18.558	1.1947	.48817	15.534	38.015	4.14	.70	3.68	5.26
A4028	18.970	1.2183	.49820	15.570	38.077	3.11	.34	1.04	3.06
A4029	18.608	1.1986	.49358	15.525	37.699	2.98	.47	2.17	4.62
A4030	18.207	1.1757	.48397	15.487	37.621	10.61	3.32	11.90	3.58
A4031	18.196	1.1744	.48144	15.493	37.795	3.37	.78	2.74	3.51
A4033	18.116	1.1699	.47752	15.495	37.937	4.26	.97	4.66	4.80
A4046	17.901	1.1569	.47093	15.473	38.013				
A5006	18.481	1.1881	.47924	15.555	38.564	6.18	1.41	7.28	5.16
A5014	18.904	1.1691	.48223	15.477	37.514	11.36	3.04	9.27	3.05
A5019	18.417	1.1846	.47837	15.547	38.499				
A6003	18.056	1.1643	.47323	15.507	38.155				
A6004	19.883	1.2094	.48732	15.614	38.749				

Table 3.2 (continued)

Sample Number	$^{206}Pb/^{204}Pb$	$^{206}Pb/^{207}Pb$	$^{206}Pb/^{208}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Pb (ppm)	U (ppm)	Th (ppm)	Th/U
A6005	19.006	1.2193	.50028	15.588	37.991				
A6008	18.525	1.1861	.48055	15.619	38.550				
A6011	18.394	1.1836	.47201	15.540	38.969				
A6014	18.574	1.1947	.48176	15.547	38.554				
A6015	17.439	1.1293	.47133	15.442	36.999				
A6018	18.025	1.1643	.48257	15.481	37.351				
A6021	18.721	1.2036	.48816	15.555	38.351	3.33	1.29	4.25	3.29
A6022	17.625	1.1425	.47465	15.426	37.132	7.03	1.24	4.71	3.80
A6023	18.248	1.1770	.48104	15.504	37.934				
A6025	18.429	1.1856	.48454	15.544	38.034				
A6026	18.110	1.1699	.48087	15.480	37.661	9.98	2.03	6.45	3.18
A6027	17.491	1.1294	.45689	15.486	38.282				
A6028	17.469	1.1311	.46061	15.445	37.927				
A6030	17.896	1.1542	.47083	15.505	38.009				
A6031	18.337	1.1820	.48074	15.514	38.143				
A6053	17.582	1.1375	.47590	15.458	35.945	9.06	1.67	4.58	2.74
A6054	17.613	1.1407	.47604	15.440	36.999				
A6058	17.715	1.1469	.47862	15.446	37.012	9.69	1.51	3.69	1.51
A6060	18.479	1.1915	.48219	15.510	38.323				
A6062	18.083	1.1654	.47624	15.517	37.971				
A6063	18.418	1.1850	.48256	15.542	38.167				
A6064	19.344	1.2391	.50718	15.612	38.141				

Table 3.2 (continued)

Sample Number	$^{206}\mathrm{Pb}/^{204}\mathrm{Pb}$	$^{206}\mathrm{Pb}/^{207}\mathrm{Pb}$	$^{206}\mathrm{Pb}/^{208}\mathrm{Pb}$	$^{207}\mathrm{Pb}/^{204}\mathrm{Pb}$	$^{208}\mathrm{Pb}/^{204}\mathrm{Pb}$	Pb (ppm)	U (ppm)	Th (ppm)	Th/U
MEXICO SAMPLES									
M3012	19.456	1.2457	.49725	15.619	39.127	2.22	1.17	4.23	3.62
NEVADA SAMPLES									
N3015	18.976	1.2174	.49235	15.587	38.542				
N3016	18.919	1.2131	.48938	15.595	38.658				
N3018	19.568	1.2470	.49881	15.692	39.230				
N3021	18.997	1.2074	.47459	15.734	40.027				
N3023	19.268	1.2327	.49472	15.631	38.974				
N3027	19.049	1.2209	.49326	15.603	38.618				
N3029	18.976	1.2160	.49181	15.605	38.584				
N5023	18.746	1.1995	.48580	15.628	38.587				
N5024	19.162	1.2324	.49916	15.548	38.388	2.69	2.23	7.47	3.35
N5026	19.065	1.2210	.49299	15.614	38.673				
N6034	18.426	1.1838	.47685	15.565	38.641				
N6035	19.064	1.2182	.48863	15.650	39.016				
N6036	18.833	1.2080	.48758	15.589	38.625				
N6040	18.486	1.1884	.48097	15.555	38.436	11.74	1.64	4.42	3.37
UTAH SAMPLES									
U5016	17.322	1.1222	.46585	15.435	37.183				
U5017	17.823	1.1517	.47206	15.475	37.756				
U5020	17.501	1.1330	.47016	15.446	37.223				

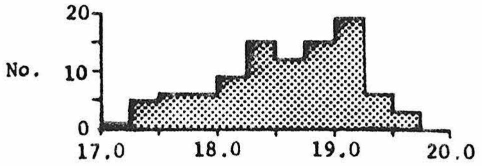
Table 3.2 (continued)

Sample Number	$^{206}Pb/^{204}Pb$	$^{206}Pb/^{207}Pb$	$^{206}Pb/^{208}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Pb (ppm)	U (ppm)	Th (ppm)	Th/U
U5022	17.693	1.1428	.47037	15.482	37.614				
U6032	16.982	1.1028	.46341	15.399	36.646				
NEW MEXICO SAMPLES									
NM4007	18.523	1.1911	.48483	15.551	38.205	2.34	.65	2.76	4.25
NM4010	18.462	1.1880	.48160	15.540	38.335	2.86	.70	4.94	7.06
NM4015	18.434	1.1882	.48202	15.515	38.243	2.46	1.05	4.18	3.98
NM4016	18.423	1.1893	.48243	15.491	38.188	2.57	1.09	4.44	4.07
NM4035	18.498	1.1898	.48309	15.548	38.292	3.65	.60	2.95	4.92
NM4036	18.428	1.1855	.47656	15.544	38.669				
NM4038	18.916	1.2187	.49193	15.522	38.453	2.78			
NM4039	17.844	1.1519	.47433	15.490	37.610				
NM4040	17.310	1.1202	.46987	15.453	36.840				
NM4044	19.607	1.2586	.49880	15.578	39.309				
NM7005	17.891	1.1570	.47321	15.464	37.808				
NM7007	19.238	1.2376	.49522	15.544	38.846				
NM7008	19.522	1.2539	.49875	15.569	39.142	3.38	.90	3.24	3.60
NM7009	19.214	1.2326	.49488	15.588	38.825				
NM7010	19.500	1.2476	.49940	15.630	39.047	3.18	.59	3.02	5.12
NM7011	17.878	1.1539	.46462	15.493	38.478				
NM7012	18.521	1.1943	.48618	15.508	39.096				
NM7013	17.698	1.1445	.46937	15.464	37.706				

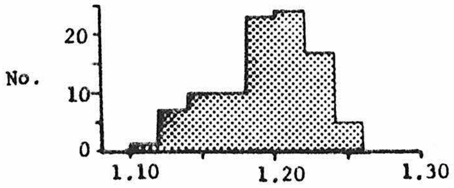
Table 3.2 (continued)

Sample Number	$^{206}Pb/^{204}Pb$	$^{206}Pb/^{207}Pb$	$^{206}Pb/^{208}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Pb (ppm)	U (ppm)	Th (ppm)	Th/U
NM7014	18.186	1.1748	.48206	15.480	37.726				
NM7015	17.448	1.1324	.46675	15.408	37.383				
75-005(B1)	18.849	1.2078	.49063	15.596	38.394				
75-114(B2)	19.013	1.2161	.49050	15.634	38.763				
75-230(B3)	18.987	1.2154	.49446	15.622	38.400				
75-256(B4)	19.157	1.2256	.49237	15.632	38.909				
75-259(B5)	18.111	1.1675	.47597	15.513	38.051				

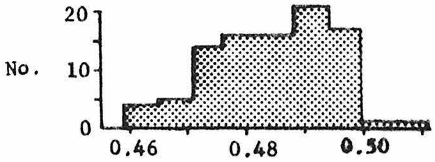
FIGURE 3.4: ISOTOPE RATIO HISTOGRAMS



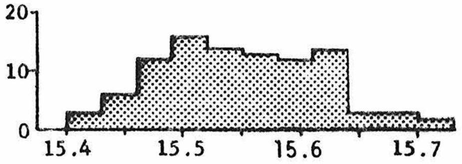
(a. Distribution of $^{206}Pb/^{204}Pb$ ratios



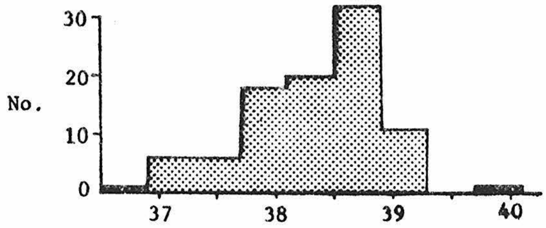
(b. Distribution of $^{206}Pb/^{207}Pb$ ratios



(c. Distribution of $^{206}Pb/^{208}Pb$ ratios



(d. Distribution of $^{207}Pb/^{204}Pb$ ratios



(e. Distribution of $^{208}Pb/^{204}Pb$ ratios

Table 3.3: Isotope Ratio Averages

Ratio	Mean	Standard Deviation	Standard Deviation as Percent
$^{206}Pb/^{204}Pb$	18.57	0.58	3.15%
$^{206}Pb/^{207}Pb$	1.194	0.034	4.00%
$^{206}Pb/^{208}Pb$	0.4843	0.010	2.12%
$^{207}Pb/^{204}Pb$	15.55	0.07	0.44%
$^{208}Pb/^{204}Pb$	38.33	0.59	1.55%

(1975) have chosen 18.700, 15.628, and 38.63 to represent the ratios of average terrestrial lead.

Table 3.3 also shows the isotopic ratio standard deviations for the population of samples analyzed in this work. The spread of ratios indicated by these standard deviations (>1% for every ratio but $^{207}Pb/^{204}Pb$) is much larger than the analytical errors estimated in Chapter 2 (<0.1% errors). Thus, variations in the measured isotopic ratios are real; they cannot be attributed to analytical error.

Lead concentrations vary from approximately 2 ppm for basanites and alkali olivine basalts to around 10 ppm for basaltic andesites and andesite samples. This reflects a five-fold increase in Pb content for a 5-7% increase in silica content. Uranium concentrations also show a correlation with major element chemistry and vary from 0.3 ppm to 3.0 ppm. Thorium concentrations range from 1.5 to 12 ppm. Th/U ratios vary from 1.51 to 7.25, have a mean of 4.1, and a standard deviation of 1.2.

CHAPTER 4: GENERAL RESULTS

4.1 Intent of This Chapter

The purpose of this chapter is two-fold. It intends, first, to identify those factors (such as covariances between different isotopic ratios, sample age, chemical composition, and locality) which will be most useful in characterizing the major variations in isotopic properties observed in lead data from the southwestern United States. Its second aim is to determine the areal extent of the several types of lead isotopic systematics that will be identified.

4.2 Relationships between Sample Age, Chemistry, and Isotopic Properties

Geographically related samples of different ages and compositions tend to exhibit similar isotopic characteristics. For example, data from southern California samples (Table 4.1) are rather uniform in their isotopic properties - their isotopic compositions span only a small portion of the range exhibited by the total southwestern data set - even though these samples range in chemistry from basanite to rhyolite and in age from Recent to Oligocene. Neither the youngest nor the oldest samples are consistently the most radiogenic. Nor are the more mafic or more silicic rocks consistently the ones with the extreme isotopic ratios. No simple, obvious correlation between sample ages or chemical composition and lead isotopic compositions is apparent - a conclusion which can be extended to the sample population from the southwestern United States as a whole.

Table 4.1: Lead Isotopic Data on Southern California Samples

No.	Locality	Age	Rock Type	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
	Vasquez Fm.[1]	23 my?[2]	rhyodacite	19.16	15.65	39.07
C5001	Black Mtn.	Pleist.?	basalt	19.19	15.59	38.72
C4022	Pisgah Crater	Recent	basanitoid	19.10	15.50	38.76
C5003	Bristol Mtns.	22.2 my[3]	basalt	19.32	15.66	38.99
C4025	Halloran Summit	Recent	basalt	19.10	15.50	38.74
C7001	Yucca Valley	Pliocene	basalt	18.79	15.51	38.73
C4017	Murrieta	8.5 my[4]	basalt	19.11	15.58	38.73
C4020	Jacumba	18.7 my[4]	basalt	19.02	15.63	38.68
	Salton Sea[1]	Recent	obsidian	18.87	15.57	38.40
	Salton Sea[1]	Recent	obsidian	18.85	15.56	38.40
	Salton Sea[1]	Recent	obsidian	18.88	15.59	38.53
C3006	Chocolate Mtns.	24.7 my[5]	andesite	19.02	15.61	38.83

[1] Data as quoted in Doe and Delevaux (1973).

[2] L.T. Silver, personal communication.

[3] Armstrong and Higgins (1973).

[4] Hawkins (1970)

[5] Damon *et al.* (1968).

Figure 4.1 shows $^{206}Pb/^{204}Pb$ analyses on a number of basaltic, intermediate, and silicic volcanics from the southwest. Basalts exhibit roughly the same range in $^{206}Pb/^{204}Pb$ as the more silicic rocks. If basalts from a local area have high (or low) $^{206}Pb/^{204}Pb$ ratios, so do the silicic volcanics from the same area. For example basalts from southern Nevada have unradiogenic ratios like their tuffaceous counterparts. The basalts from north-central Nevada are quite radiogenic, like their felsic analogs.

A comparison can also be made between the isotopic compositions of young and old volcanic samples in the same area. For instance, data from young basalts in south-central Arizona are found to bracket the lead isotope ratio of an older (27 my) basaltic andesite from the same area. The 35 my old, Oligocene volcanics from northern Nevada have very radiogenic leads, but so do the nearby 15 my old rocks. As Figure 4.2 shows, there is no simple correlation between sample age and lead isotopic composition.

Indeed, substantial variations in isotopic composition are present even when rocks of the same age and petrographic characteristics are compared. Figure 4.3, which shows isotopic data from a number of Quaternary alkaline basalts and basanitoids, illustrates this fact. Although samples from each volcanic field show a limited variability, the data as a whole exhibit a variation in $^{206}Pb/^{204}Pb$ several hundred times that of analytical error. Factors independent of sample age and chemical composition must be responsible for this variation.*

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*Later sections (i.e. Section 5.8, Section 6.3, and Appendix D) consider

Figure 4.1. A plot of sample SiO_2 concentrations and whole rock $^{206}Pb/^{204}Pb$ ratios for Cenozoic volcanic rocks from the southwestern United States. Open symbols indicate lead analyses done in this work. Filled symbols are published analyses from Rye *et al*. (1974), Doe and Delevaux (1973), and Doe (1970). Horizontal lines show the probable error associated with SiO_2 concentrations estimated from petrographic descriptions. Circles are Colorado Plateau samples from Arizona, Utah, and New Mexico. Diamonds indicate data from Basin and Range areas of New Mexico. Upward pointing triangles are data from the Great Basin of northern and central Nevada, and downward pointing triangles are samples from southern Nevada. Squares denote samples from the Basin and Range province (and coastal regions) of California and Arizona.

Figure 4.1

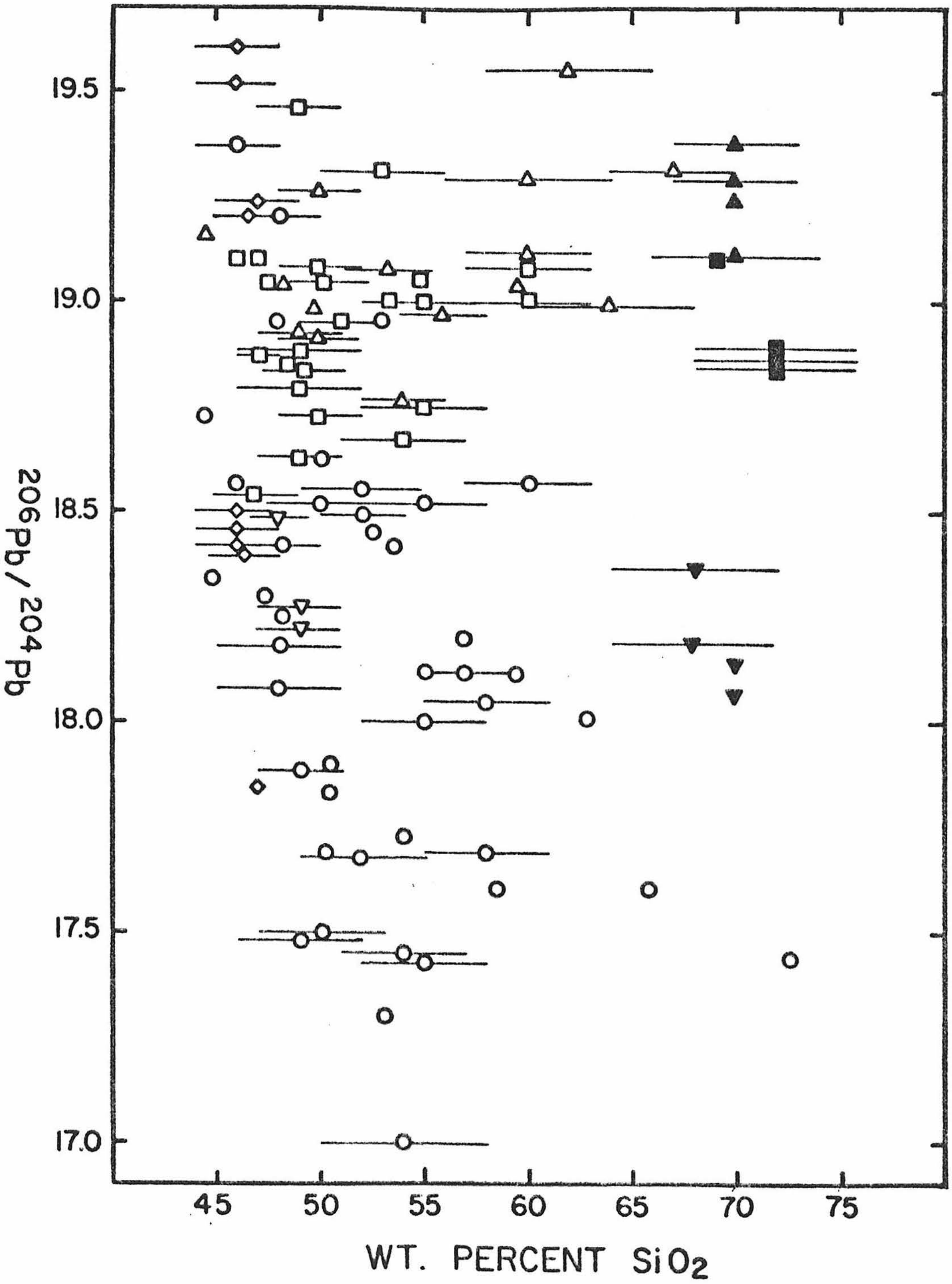

19.5
19.0
18.5
18.0
17.5
17.0
$^{206}Pb/^{204}Pb$
45
50
55
60
65
70
75
WT. PERCENT SiO_2

Figure 4.2. Ages and whole rock $^{206}Pb/^{204}Pb$ ratios on Cenozoic volcanic rocks from the southwestern United States. Symbols are the same as those used in Figure 4.1. Open symbols represent data from this work and closed symbols represent data from published sources on generally older volcanics. Many of the latter data points are taken from the Lipman *et al*. (1978) paper on the San Juan volcanic field, although data from the sources quoted in Figure 4.1 are also included. Horizontal lines show the estimated errors in age data in cases where dates were estimated from geologic, generally stratigraphic, constraints.

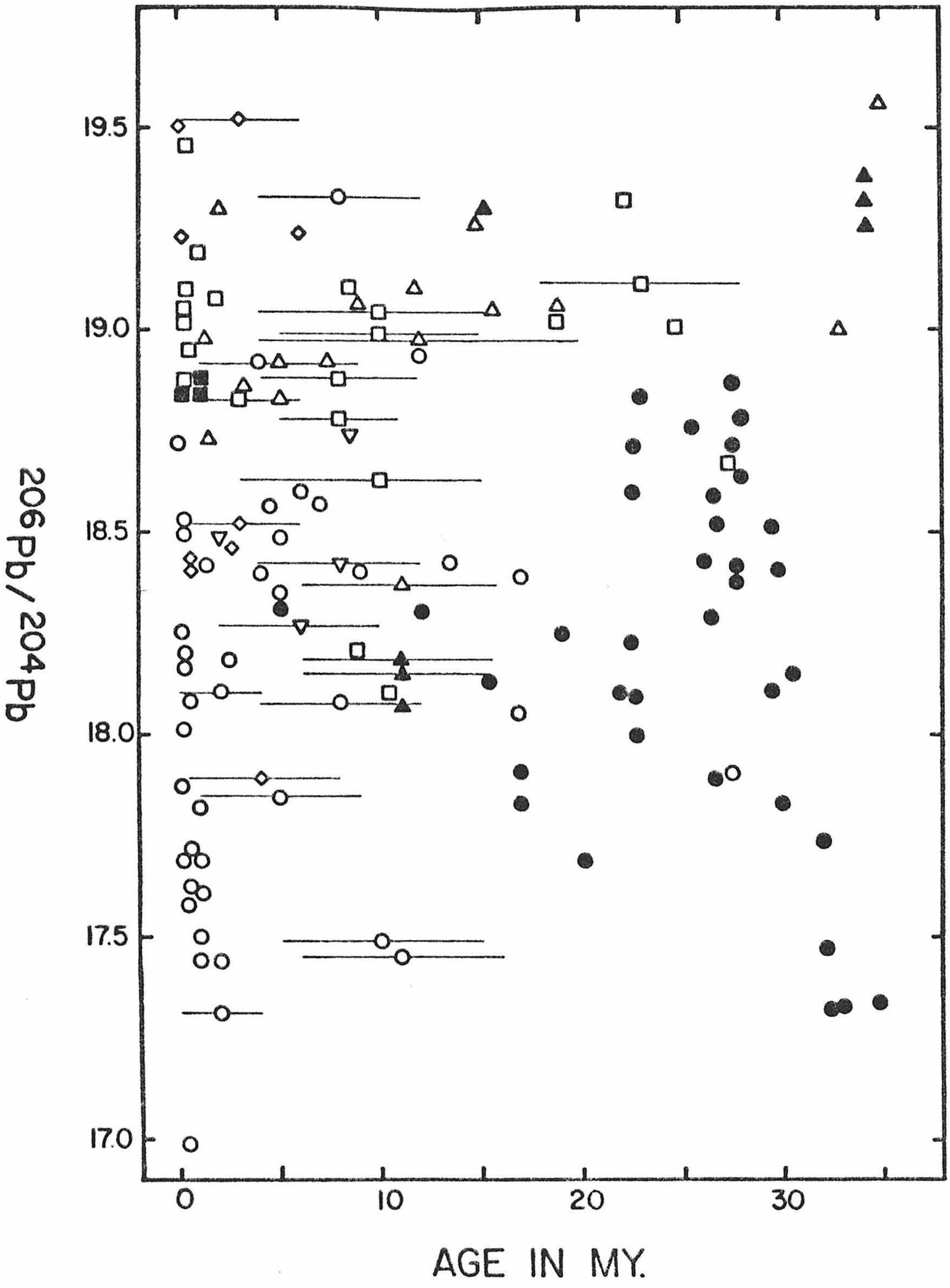
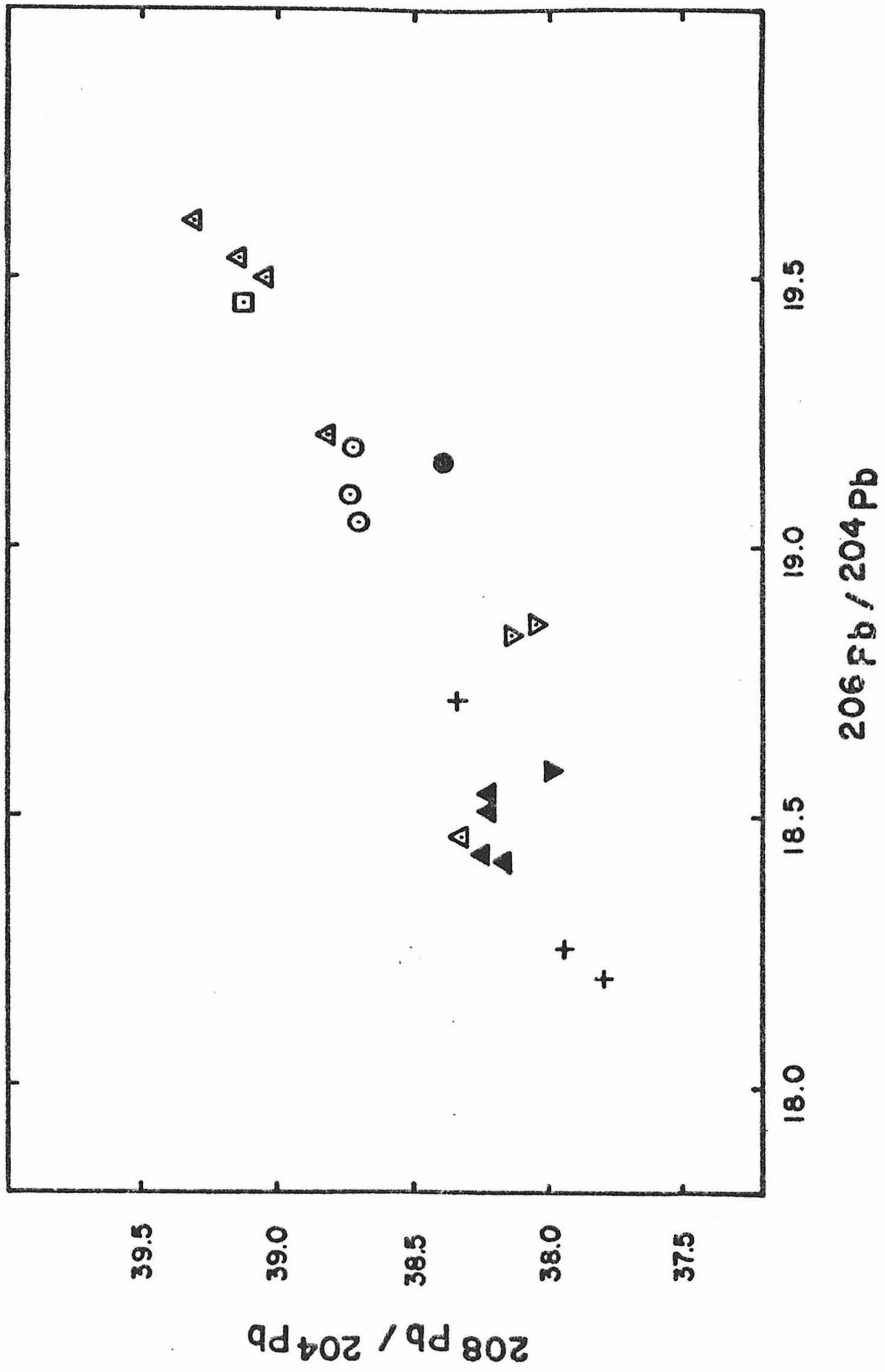


Figure 4.2

Figure 4.3. Lead isotopic data on Quaternary basalts and basanitoids from the southwestern United States. The different symbols indicate different volcanic fields. Upward pointing triangles are data from the Jornada del Muerto and nearby volcanic fields in the Rio Grande rift. The open square is a sample from the Pinacate volcanic field of Sonora. Open circles denote basalts from the Mohave desert fields of California. The filled circle is from the Lunar Crater field of central Nevada. Open, downward pointing triangles represent samples from the San Bernardino field of southeast Arizona, and the filled, downward pointing triangle is a sample from the San Carlos field of Arizona. The filled upward pointing triangles denote samples from the Potrillo volcanic field and adjacent areas in southern New Mexico. The data include two points taken from Zartman and Tera (1973).

Figure 4.3



4.3 Regional Isotopic Variations

The lead isotopic characteristics of late Cenozoic volcanics change in a rather regular and systematic way across the southwestern United States. The approximate isotopic properties of a sample can, in fact, be predicted from the geographic coordinates of sample locality alone.

The systematic change of $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios from area to area is diagrammatically displayed in Figures 4.4 and 4.5. Figure 4.4a shows $^{206}Pb/^{204}Pb$ ratio isopleths derived from a second order trend surface analysis of $^{206}Pb/^{204}Pb$ data; these contours might be considered to represent an areal running average or smoothing of the ratio data. Figure 4.5b shows equivalent information for the $^{208}Pb/^{204}Pb$ ratio. Both diagrams display similar patterns of isotope ratio variation. Higher ratios are generally in the western part of the map, while less radiogenic ratios are found to the east or northeast. The contours show that $^{206}Pb/^{204}Pb$ ratios greater than 19.0 and $^{208}Pb/^{204}Pb$ ratios greater than 38.8 are common in California, northern Nevada, and southwestern Arizona. Average values of $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ drop below 18.4 and 38.0 (respectively) farther inland, in eastern Utah and northeastern Arizona.

Unfortunately, the trend surface analyses shown in Figures 4.4a and 4.5b smear out sharp lateral changes in isotope ratio and

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in more detail the relationship between sample age, chemical composition, and isotopic ratios. They suggest that there is evidence for correlations between these variables, even if these correlations do not appear to be most significant in explaining the lead isotopic variations observed in the southwestern United States as a whole.

Figure 4.4a. Isopleths derived from a second order trend surface analysis of $^{206}Pb/^{204}Pb$ data on late Cenozoic volcanics from the southwestern United States. Individual data points are shown for comparison.

Figure 4.4b. $^{206}Pb/^{204}Pb$ ratio isopleths drawn according to the author's subjective judgment. Ratios on individual samples are shown for comparison.

Figure 4.4a

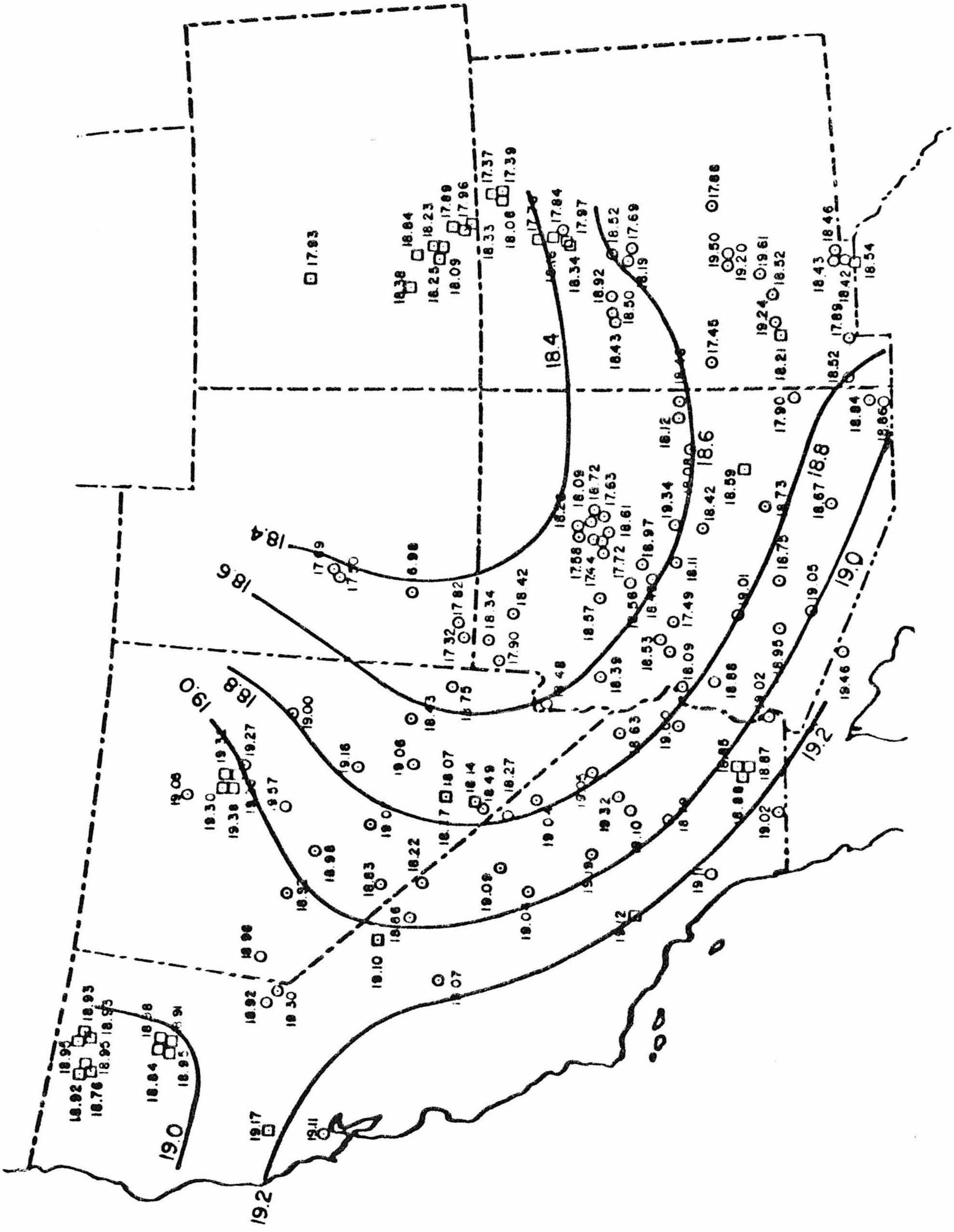


Figure 4.4b

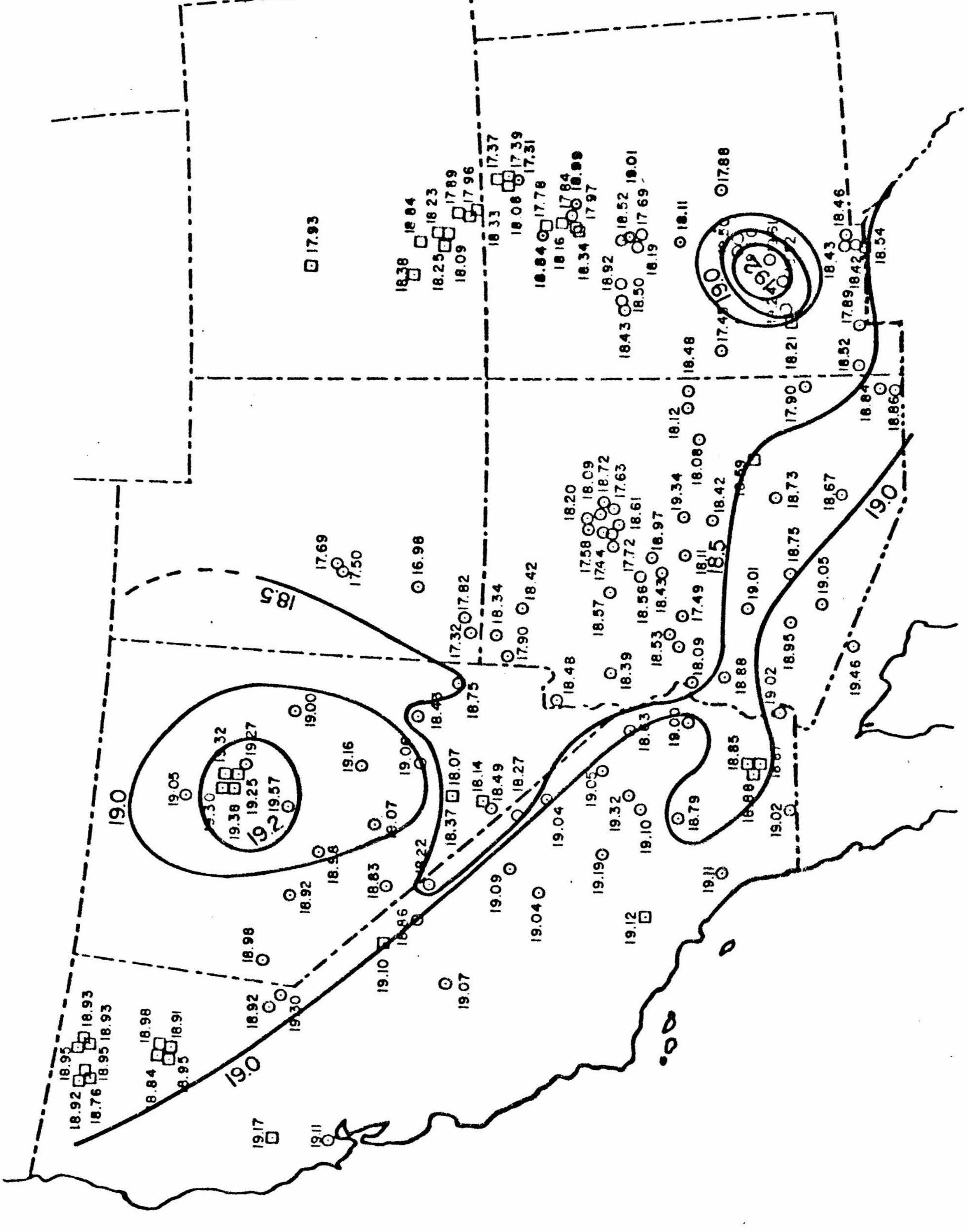


Figure 4.5a. $^{208}Pb/^{204}Pb$ data on individual samples from the southwestern United States.

Figure 4.5b. Isopleths from a second order trend surface analysis of $^{208}Pb/^{204}Pb$ data.

Figure 4.5c. $^{208}Pb/^{204}Pb$ ratio isopleths drawn according to the author's subjective judgment.

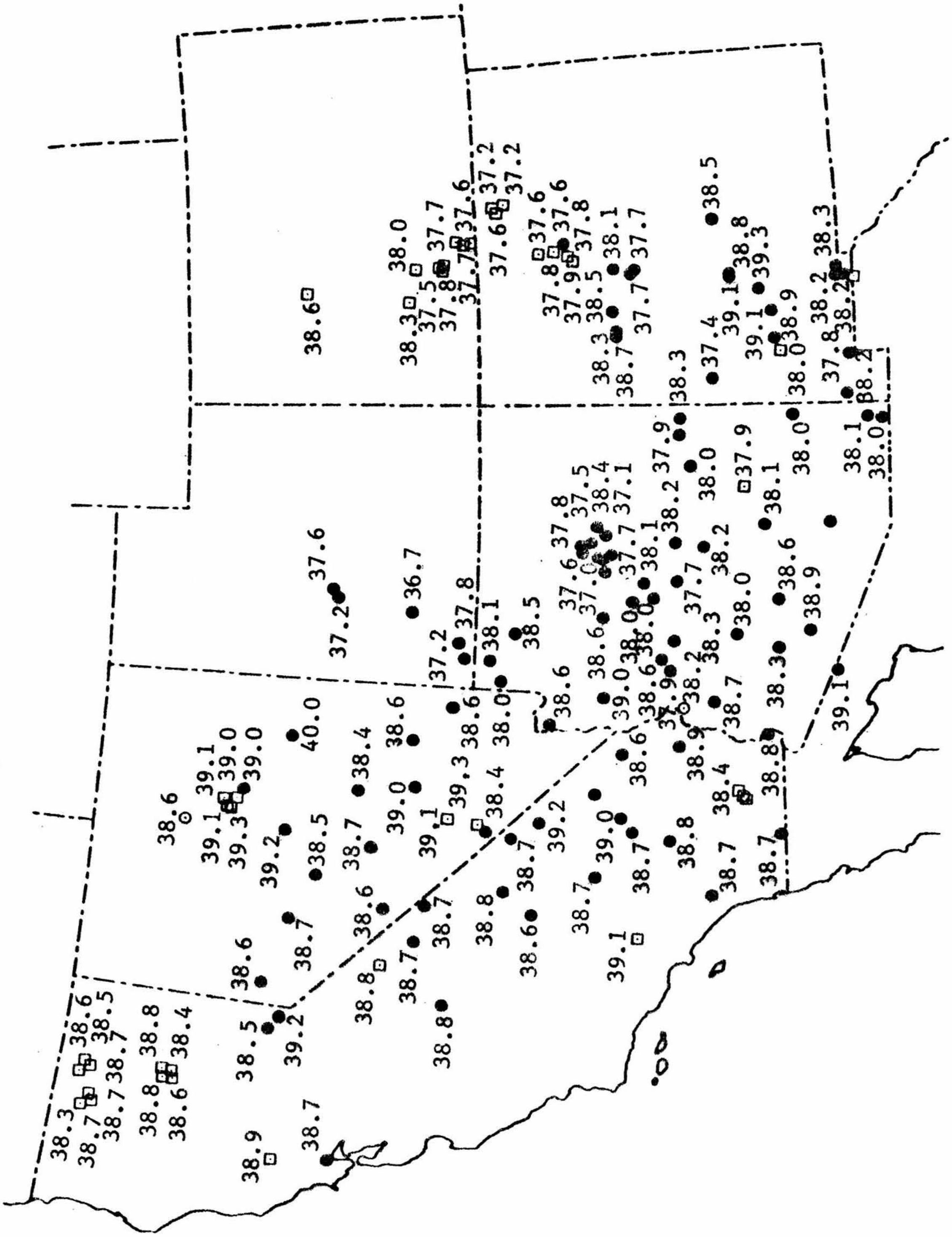


Figure 4.5a

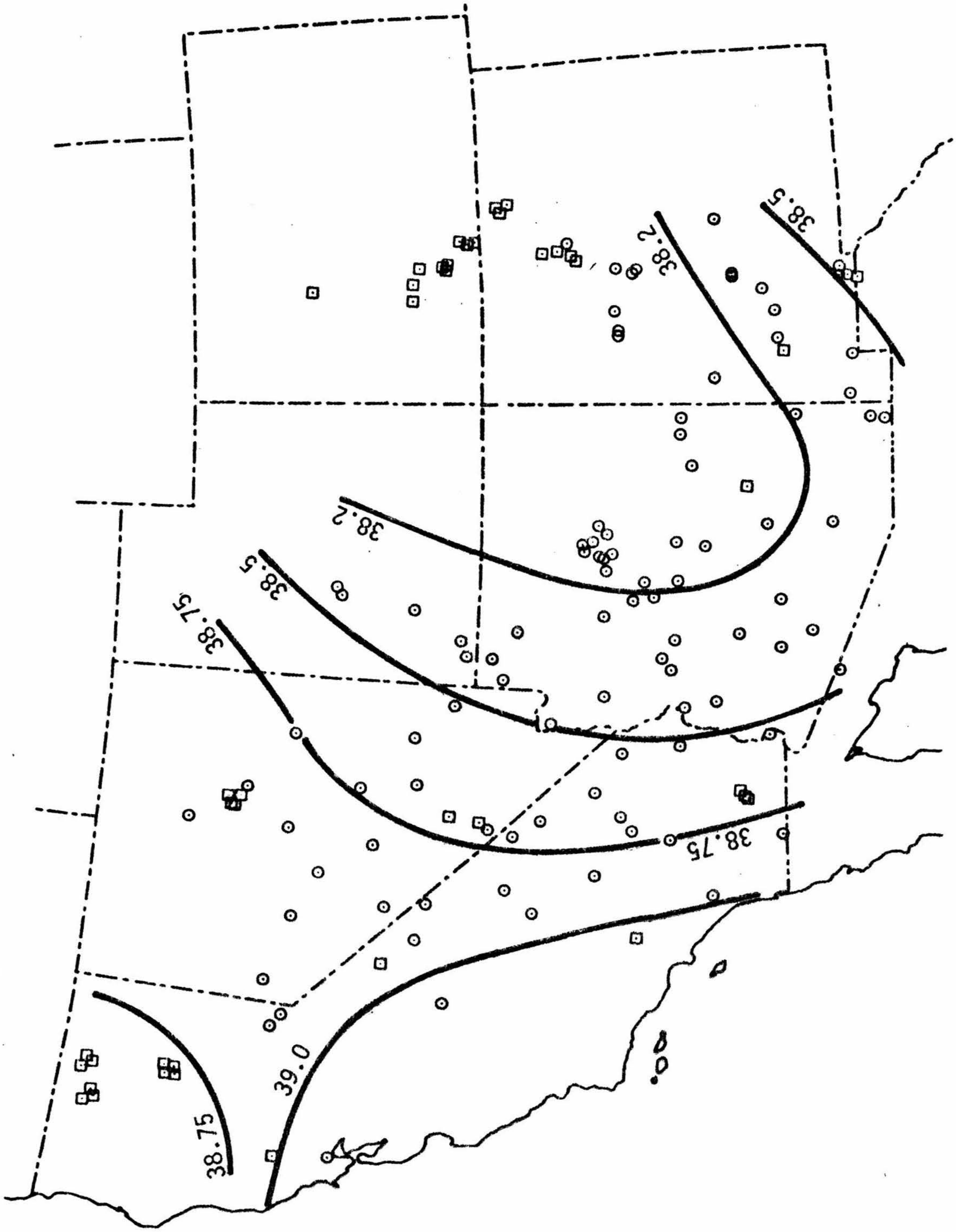


Figure 4.5b

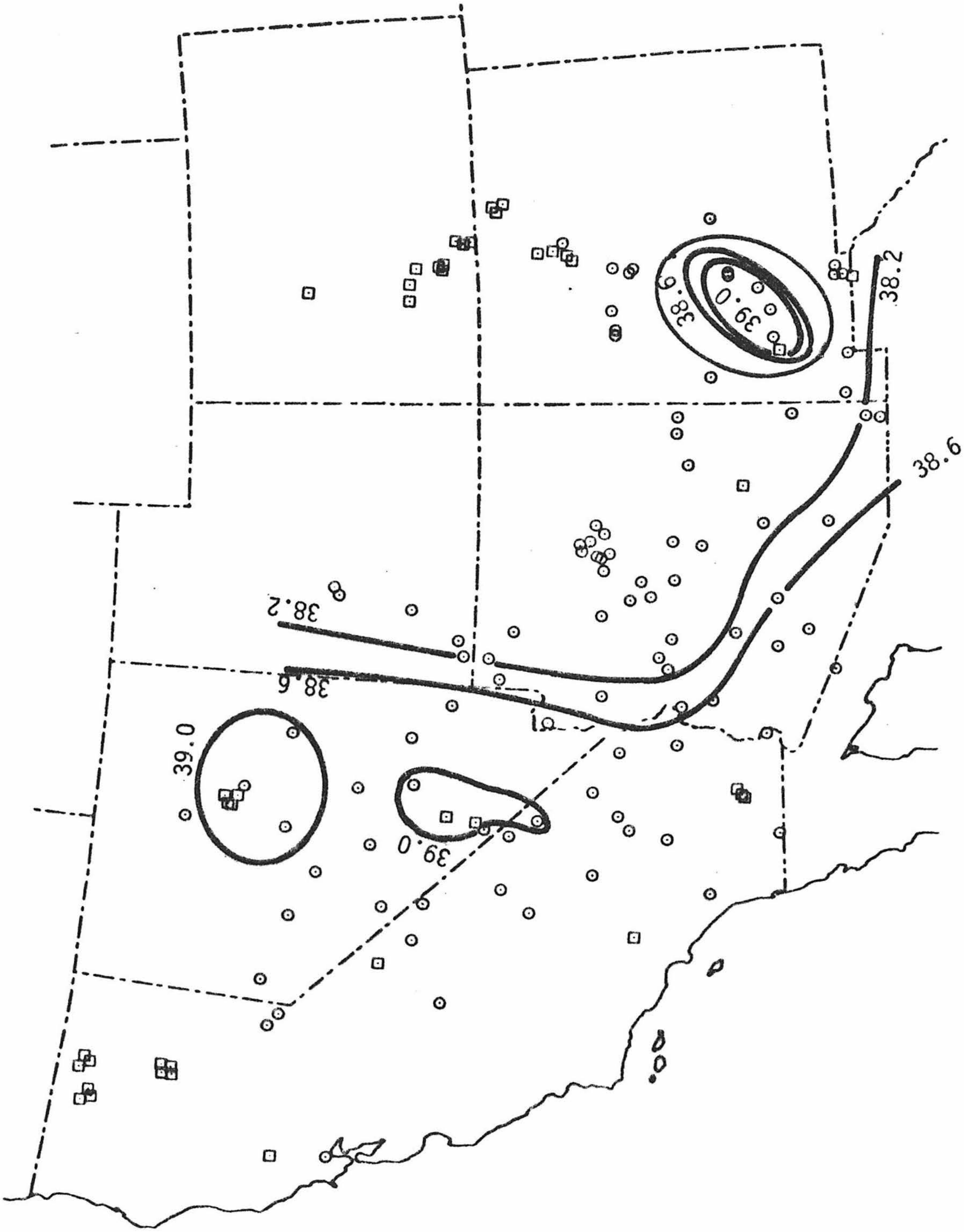


Figure 4.5c

ignore other parameters and covariations significant to the understanding of regional isotopic systematics. Figure 4.4b and 4.5c show hand-contoured $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratio isopleths, which are perhaps better approximations of the regional trends. But these diagrams, too, neglect some attributes which distinguish Colorado Plateau and Basin and Range samples, and gloss over the special characteristics and complexities of data from southern Nevada and southern New Mexico.

4.4 Major Provincial Isotopic Characteristics

The lead isotopic characteristics observed for late Cenozoic basalts can be said to be of two major types, one characteristic of the southwestern Colorado Plateau, and the other more typical of the Basin and Range province. Several criteria can be used to distinguish Colorado Plateau (CP) and Basin and Range (BR) type isotopic systematics. Contrasts in the magnitudes of $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios are most apparent. CP samples are generally less radiogenic than BR samples. Basalts with characteristics typical of Basin and Range samples have $^{206}Pb/^{204}Pb \geq 18.7$ and $^{208}Pb/^{204}Pb \geq 38.5$. On the other hand, Colorado Plateau samples usually have $^{206}Pb/^{204}Pb < 18.7$ and $^{208}Pb/^{204}Pb < 38.5$. The general decrease in radiogenic character toward the Plateau is illustrated by Figure 4.6, where $^{206}Pb/^{204}Pb$ values are plotted against sample locality distance from the southwestern edge of the Colorado Plateau. This figure shows that the Colorado Plateau does have a few samples as radiogenic as BR samples. However, it also indicates that

Figure 4.6. The variation in $^{206}Pb/^{204}Pb$ as a function of sample distance from the southwestern edge of the Colorado Plateau in Arizona. Similar trends are also expressed in the $^{208}Pb/^{204}Pb$ data for the same area.

Figure 4.6

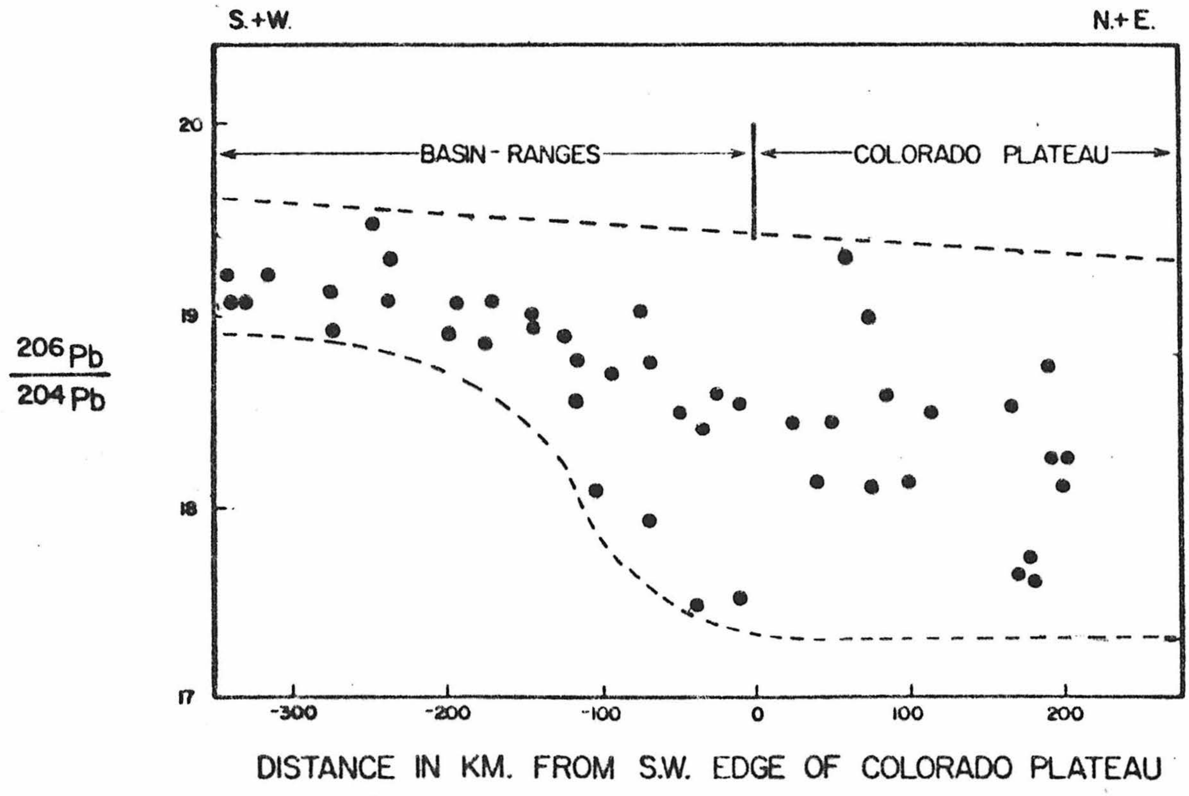

S.+W.
N.+E.
BASIN - RANGES
COLORADO PLATEAU
20
19
18
17
^{206}Pb / ^{204}Pb
-300
-200
-100
0
100
200
DISTANCE IN KM. FROM S.W. EDGE OF COLORADO PLATEAU

Figure 4.7. Subsets of data plotted in various figures of this and other chapters. Solid symbols represent data from Basin and Range province samples which appear to have isotopic characteristics intermediate between those of typical BR and CP samples; these are the points plotted as open circles in Figure 4.12. A = samples from northern and central Nevada and adjacent regions in eastern California (Fig. 4.9b, Fig. 4.12d). B = samples from southern Nevada and adjacent regions in eastern California (Fig. 4.15, Fig. 4.12d). C = data from southern California and southwestern Arizona (Fig. 4.9a, Fig. 4.12c). D = samples along the western margin of the Colorado Plateau in northern Arizona and southern Utah; this area is centered around St. George, Utah (Fig. 4.8b, Fig. 4.12a). E = samples from the San Francisco volcanic field (Flagstaff, Arizona) and south and west toward Prescott, Arizona (Fig. 4.8a, Fig. 4.12a). F = samples from near the margin of the Colorado Plateau in central Arizona, including points in the Tonto section of Hayes (1969) (Fig. 4.16). G = data from the Mexican Highlands (Hayes, 1969) of southeastern Arizona and southwestern New Mexico (Fig. 4.13, Fig. 4.14). H = Colorado Plateau type samples bordering on the Mexican Highlands (Fig. 4.14). I = samples from the southern Rio Grande rift area between Socorro and Las Cruces, New Mexico (Fig. 4.12c). J = samples from northern and central New Mexico (Fig. 4.12b). K = samples from the San Juan volcanic field of southwestern Colorado (Fig. 4.12e). San Juan data from Lipman *et al.* (1978).

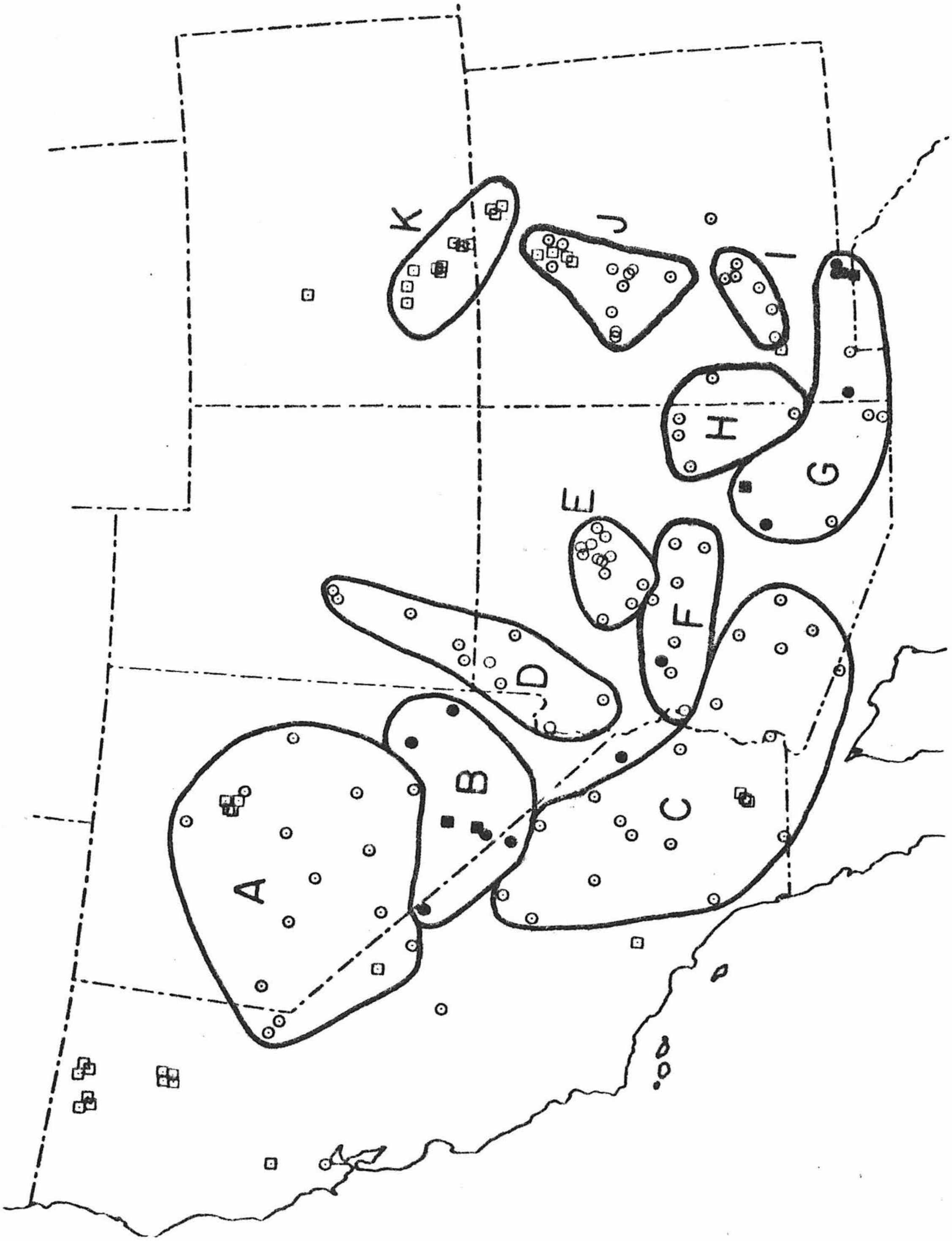


Figure 4.7

the average and lower limit of CP $^{206}Pb/^{204}Pb$ ratios are considerably less than the average and lower limit of BR sample ratios. According to Figure 4.6 the onset of this decrease in radiogenicity occurs as much as 100 km outside the structural boundary of the Plateau.

Figure 4.6 also illustrates a second distinction between CP and BR type data. Within local areas Basin and Range samples have a limited variability in isotopic ratio. Local areas in the Colorado Plateau, on the other hand, show a much wider range in $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios. For example, data from the San Francisco volcanic field on the Colorado Plateau, a region roughly 50 km in diameter, shows a 7% variation in $^{206}Pb/^{204}Pb$, and a 4% variation in $^{208}Pb/^{204}Pb$ ratios. Samples from the Mohave desert, a Basin and Range region roughly 150 by 300 km in size, give $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios which display only a 1% variation.

Total $^{207}Pb/^{204}Pb$ variation in local areas on the Colorado Plateau is also greater than the variation of $^{207}Pb/^{204}Pb$ in local areas of the Basin and Range province. However, for a given $^{206}Pb/^{204}Pb$ ratio, the corresponding $^{207}Pb/^{204}Pb$ ratio can be predicted within ±0.1-0.2% for CP samples. Basin and Range $^{207}Pb/^{204}Pb$ values have a 0.5-1.0% variation at a given $^{206}Pb/^{204}Pb$ ratio. This suggests a useful criterion for discriminating between CP and BR behavior - Colorado Plateau type data describe well-defined linear arrays on a $^{206}Pb/^{204}Pb$-$^{207}Pb/^{204}Pb$ (α-β) diagram; Basin and Range data do not. Figures 4.8 and 4.9 illustrate this distinction. Figures 4.8a and 4.8b show data from two Colorado Plateau areas: the San Francisco volcanic field near Flagstaff, Arizona; and an area along the western margin of the Colorado Plateau centered at St. George, Utah (see Figure 4.7 for locations of plotted data). Both the generally unradiogenic nature and large range in CP isotope ratios can be observed in these diagrams. However, it is most pertinent to see that, within experimental error, α-β data from each area fall on a single line, an "isochron." Compare this pattern to data from two areas exhibiting normal Basin and Range characteristics - the Great Basin of northern Nevada and the Mohave-Sonoran desert of southern California and southwestern Arizona (Fig. 4.9). The $^{206}Pb/^{204}Pb$ (α) and $^{207}Pb/^{204}Pb$ (β) data from these areas describe radiogenic, globular shaped fields of limited dimensions. If the BR data fields have an elongation, it is at best poorly defined.

A comparative homogeneity of lead isotopic compositions is considered good evidence for BR style isotopic systematics, even in transitional or special areas where isotopic ratios approach low values otherwise characteristic of the Colorado Plateau. Alternately, extended linear arrays on α-β diagrams are taken to be characteristic of CP type behavior even when the sampling area lies somewhat outside the physiographic or structural boundary of the Colorado Plateau.

Colorado Plateau data do not fall on a large number of distinct, linear α-β arrays. More than 95% of the data identified as Colorado Plateau type lie, within 2σ analytical error ($\sim$0.14% of each isotope ratio), either on the "isochron" defined by the Flagstaff data or the "isochron" defined by the St. George data (see Fig. 4.10). Since both linear arrays are similar in position and slope, CP data as a whole

Figure 4.8a. Lead isotopic data on late Cenozoic volcanics from the San Francisco volcanic field near Flagstaff, Arizona and adjacent, generally older fields to the south and west toward Prescott, Arizona (Area E in Figure 4.7). Error bars indicate a 0.1% error. The regression line on the $^{206}Pb/^{204}Pb$-$^{207}Pb/^{204}Pb$ plot has a slope of 0.093 ±0.006, corresponding to a secondary isochron age of 1500 ±125 my. The $^{208}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ regression has a slope of 0.99 ±0.13, which might be interpreted in terms of a source region Th/U value of approximately 3.4.

Figure 4.8b. Lead data on late Cenozoic, generally mafic, volcanics from the western margin of the Colorado Plate in northern Arizona and southern and central Utah (Area D in Figure 4.7). This area is roughly centered about St. George, Utah. Error bars indicate a 0.1% error. The $^{207}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ regression line has a slope of 0.098 ±0.007, corresponding to a secondary isochron age of 1600 ±130 my. The $^{208}Pb/^{204}Pb$ regression has a slope of 1.33 ±0.13. This number might be interpreted in terms of a source region Th/U ratio of approximately 4.6.

Figure 4.8a

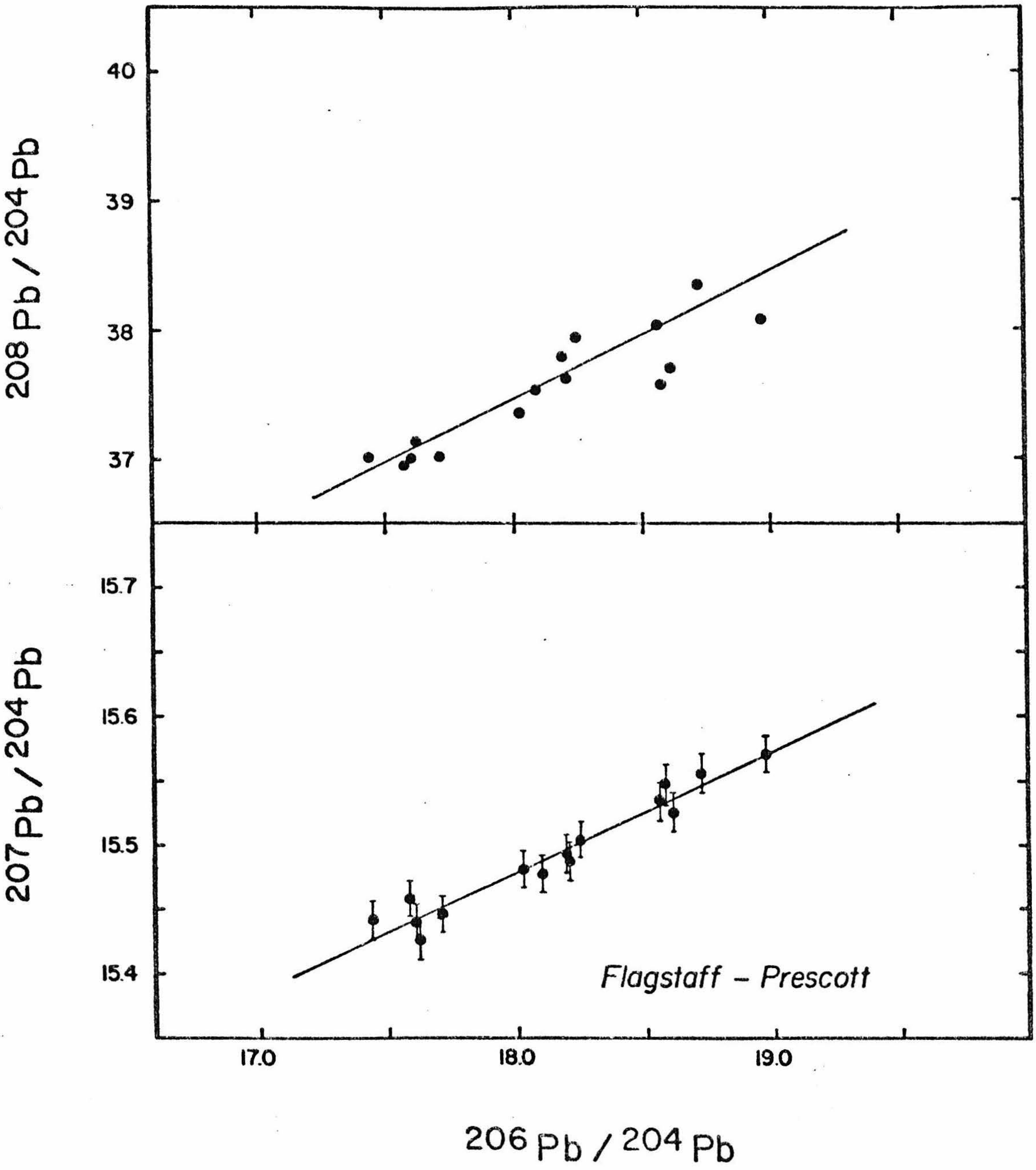

40
39
38
37
208Pb/204Pb
15.7
15.6
15.5
15.4
207Pb/204Pb
Flagstaff - Prescott
17.0
18.0
19.0
206Pb/204Pb

Figure 4.8b

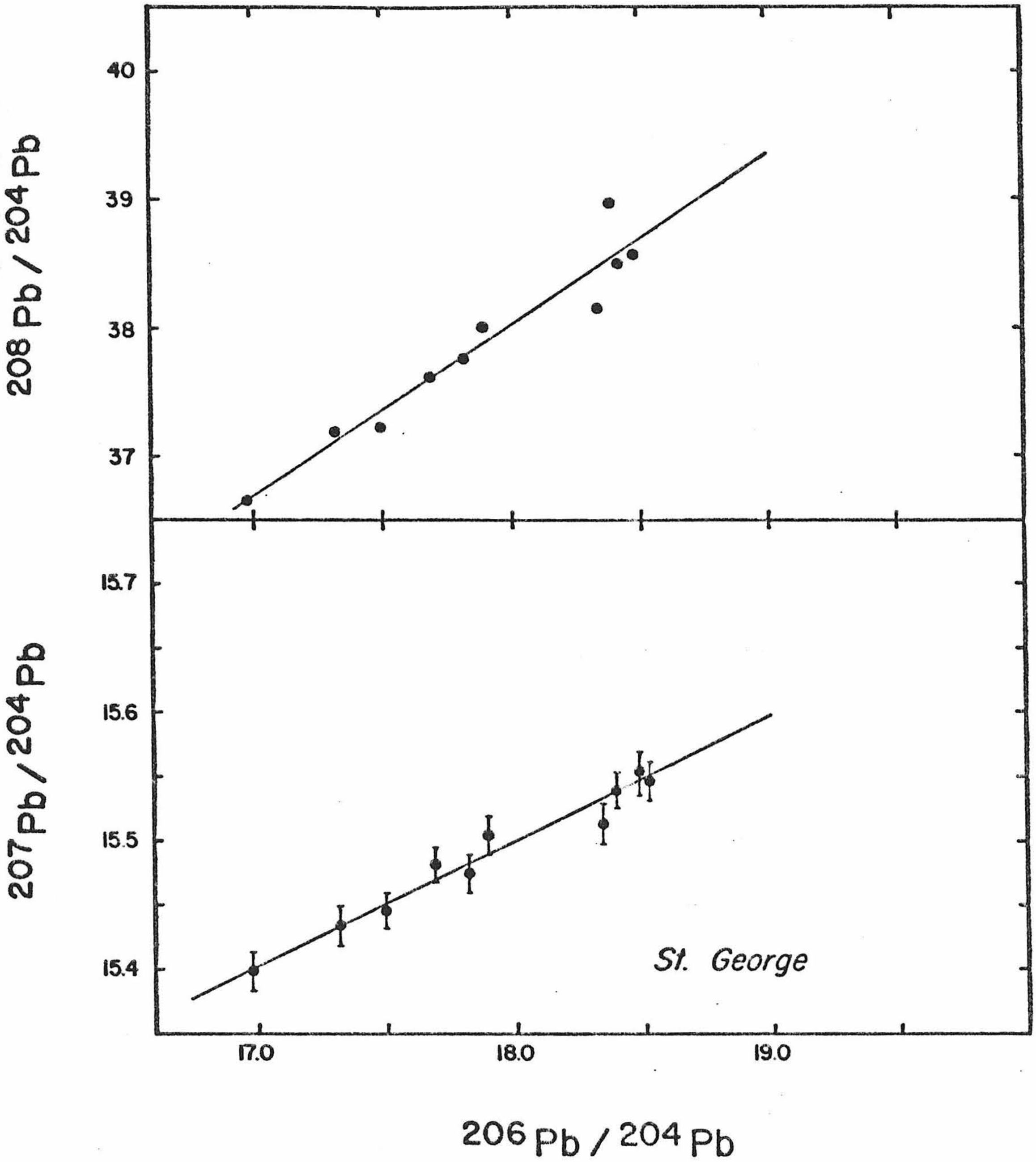

40
39
38
37
208 Pb / 204 Pb
15.7
15.6
15.5
15.4
207 Pb / 204 Pb
St. George
17.0
18.0
19.0
206 Pb / 204 Pb

Figure 4.9a. Lead isotopic data on late Cenozoic, generally basaltic volcanic rocks from southern California (circles) and southwestern Arizona (squares). Error bars indicate a 0.1% error. Area C in Figure shows the sample localities for plotted data.

Figure 4.9b. Lead isotopic data on Cenozoic volcanics from the Great Basin of northern and central Nevada (Area A in Figure 4.7). Open diamonds represent published data points from Rye *et al*. (1974). Filled circles denote analyses performed for this work.

Figure 4.9a

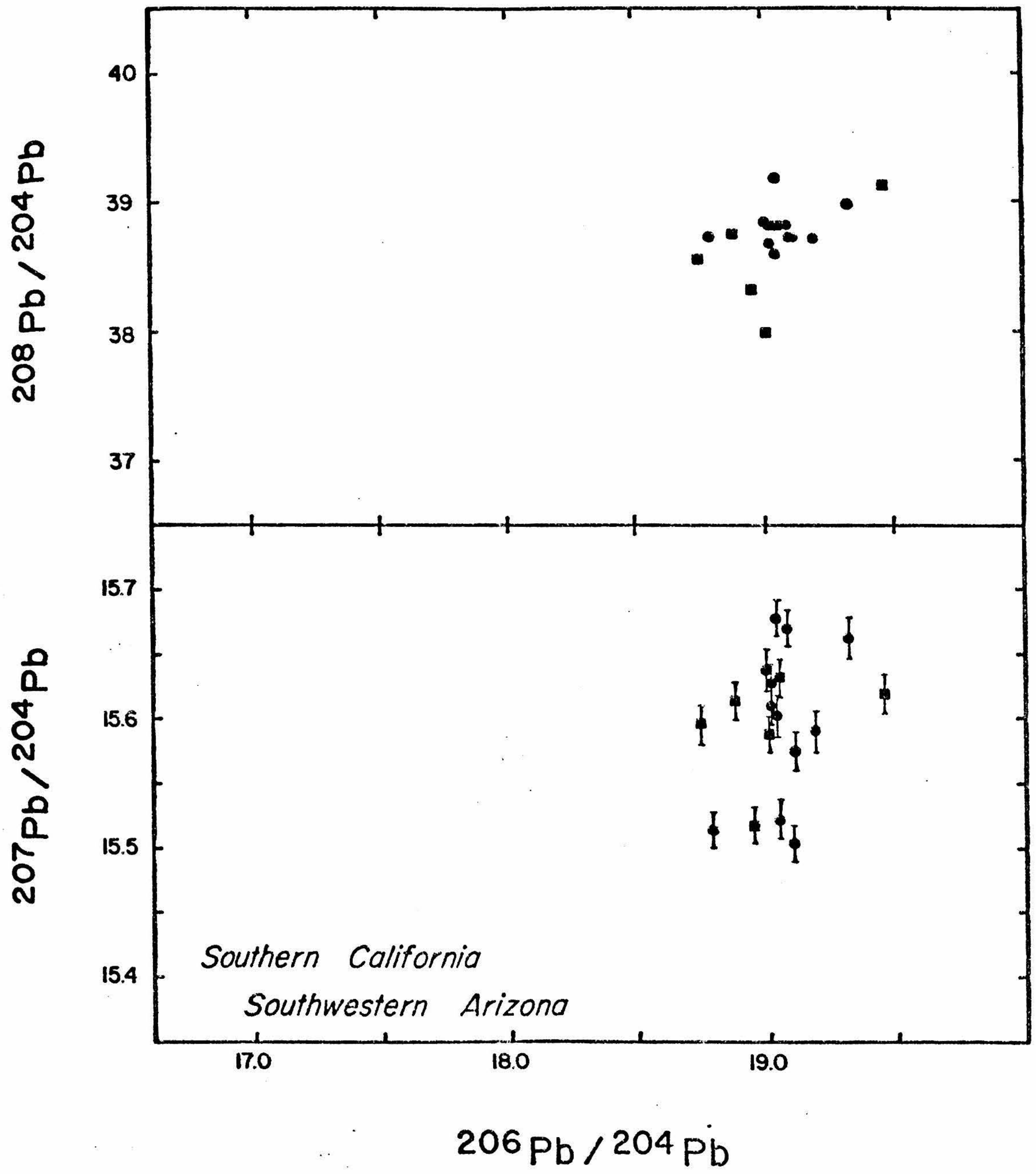
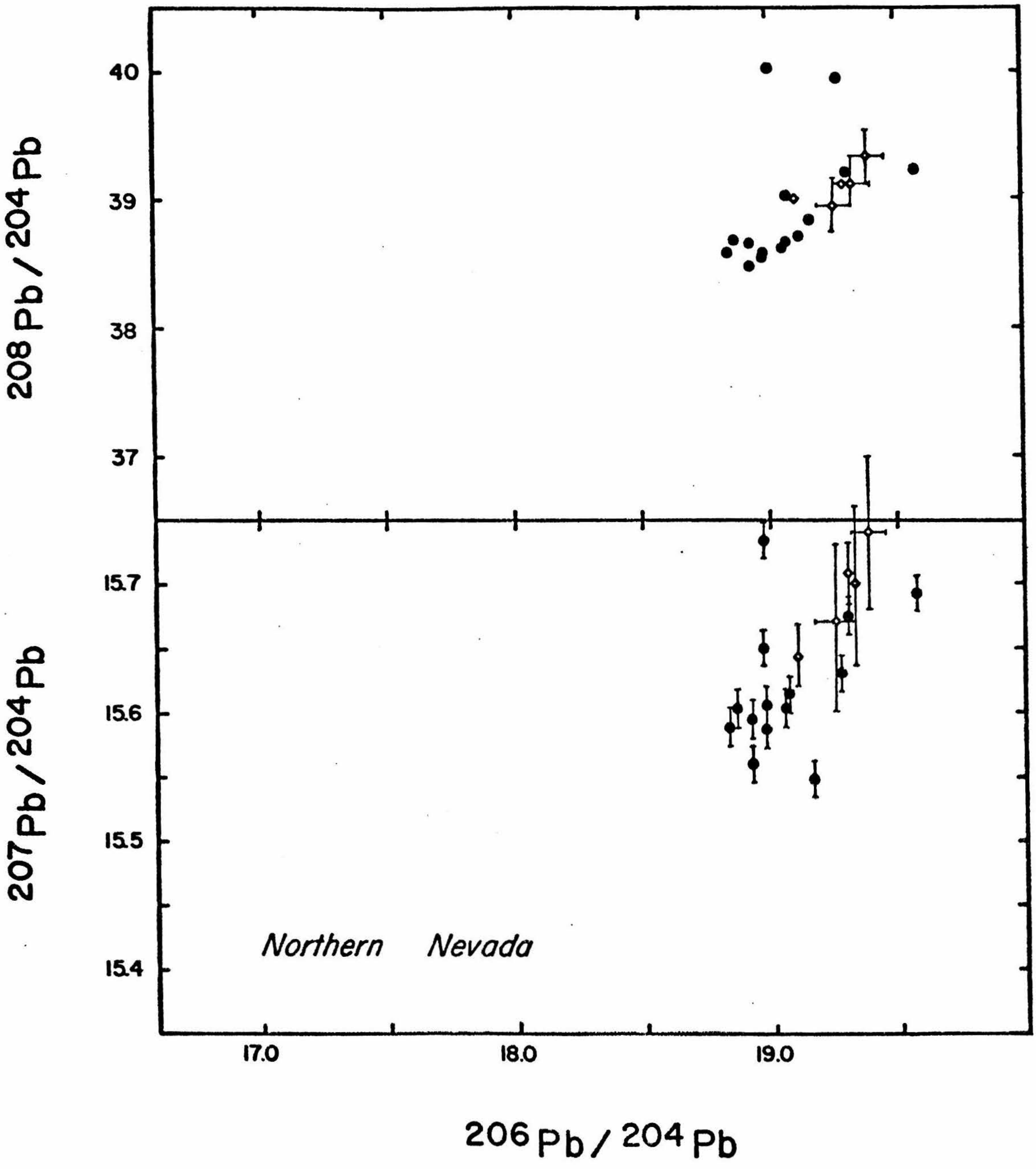

40
39
38
37
208 Pb / 204 Pb
15.7
15.6
15.5
15.4
207Pb / 204Pb
Southern California
Southwestern Arizona
17.0
18.0
19.0
206 Pb / 204 Pb

Figure 4.9b

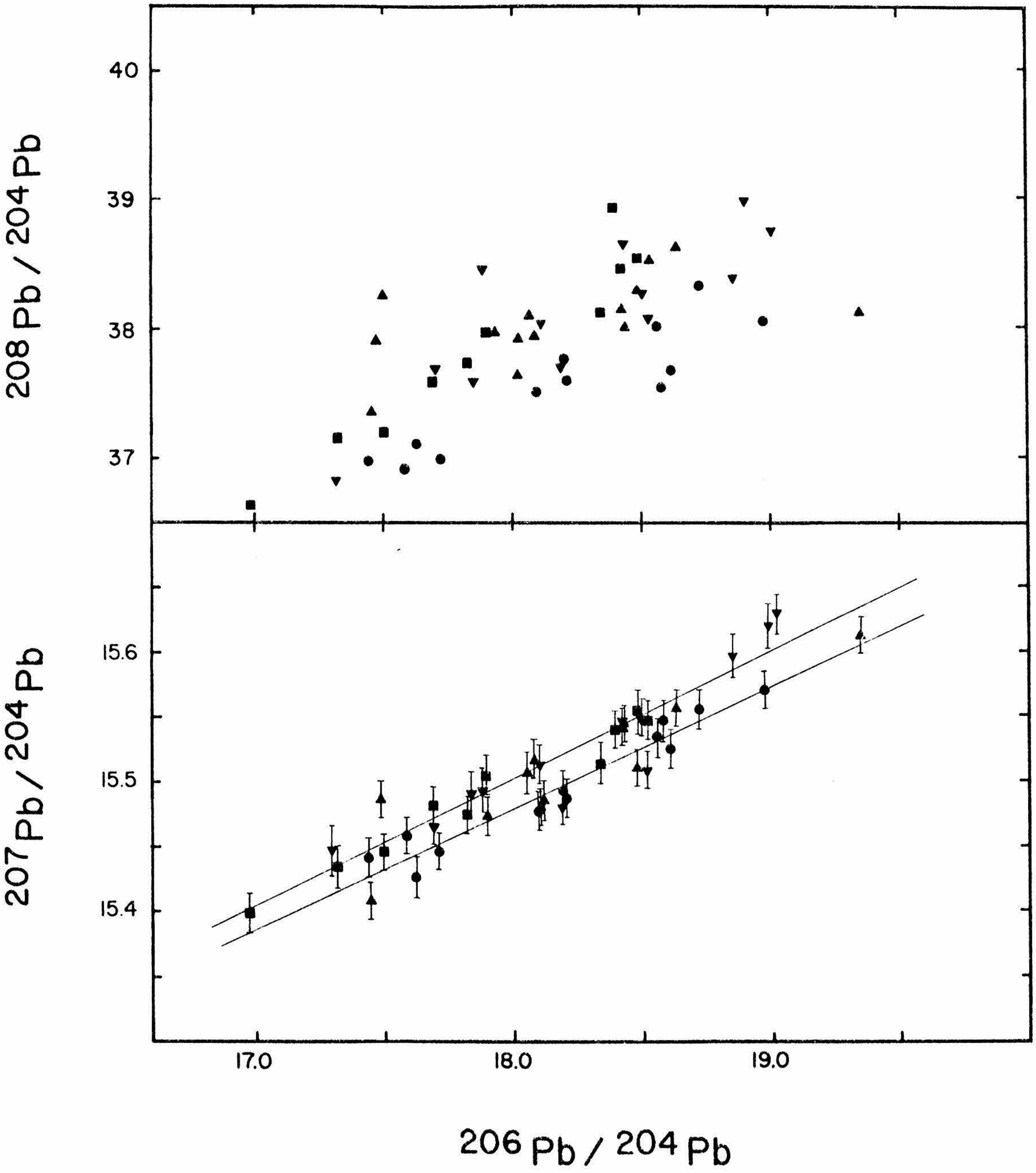

208Pb/204Pb
40
39
38
37
207Pb/204Pb
15.7
15.6
15.5
15.4
Northern Nevada
17.0
18.0
19.0
206Pb/204Pb

describe a fairly restricted linear field on the $^{206}Pb/^{204}Pb-^{207}Pb/^{204}Pb$ diagram. Consequently, it is not often necessary to sample extensively in a local area to tell if that area is characterized by CP behavior. A few unradiogenic data points lying on the Flagstaff or St. George lines adequately identify the data as CP type. On the other hand, location of a data point distinctly off the CP isochrons strongly suggests a sample of BR type. It might be noted, however, that some radiogenic, otherwise typical Basin and Range data points fall on the CP isochrons. Consequently, the occurrence of data points (especially radiogenic ones) on the CP isochrons does not necessarily require these data to be CP type.

It should be noted at this point that Zartman (1974) has proposed a twofold distinction in ore leads from the western United States similar to the CP-BR classification discussed here (see Fig. 1.4). Specifically he notes that the data from Cortez, Nevada (Rye _et al._, 1974) - an area in the Basin and Range province - is radiogenic and fills a small, unelongated area on an α-β diagram. In contrast, lead data from Milford, Utah ores, a district in the St. George area of Figure 4.8b, produce an extended linear array when plotted on an α-β diagram, as do leads from other mining districts bordering on the Colorado Plateau in Utah (see Stacy _et al._, 1968). Zartman's classification differs from the one suggested here on three counts: It is based on ore and related rock leads, which may not be derived from the same sources as basalt leads; he includes rocks as old as Mesozoic in his classification, while this work only considers later Cenozoic

Figure 4.10. Lead data on all samples from the Colorado Plateau and neighboring areas displaying similar isotopic characteristics. Error bars show the magnitude of a 0.1% error. The lower line in the figure is the regression line calculated from the Flagstaff-Prescott area data of Figure 4.8a. The upper line is taken from Figure 4.8b, and represents the $^{206}Pb/^{204}Pb$-$^{207}Pb/^{204}Pb$ regression line calculated on data from the western margin of the Colorado Plateau around St. George, Utah. Circles are data points from the Flagstaff-Prescott area. Squares are data from the St. George area. Data points from the Colorado Plateau of New Mexico, together with data points from the Rio Grande rift north of Socorro, New Mexico, are indicated by downward pointing triangles. All other CP data points are indicated by upward pointing triangles; these samples lie near the margin of the Colorado Plateau in central Arizona.

Figure 4.10


40
39
38
37
208 Pb / 204 Pb
15.6
15.5
15.4
207Pb / 204Pb
17.0
18.0
19.0
206 Pb / 204 Pb

volcanic rocks; and he interprets his data in terms of the inferred absence or presence of Precambrian basement rather than in terms of Cenozoic structural provinces.

Besides a $^{206}Pb/^{204}Pb$-$^{207}Pb/^{204}Pb$ covariance, Figure 4.8 shows a positive correlation between $^{208}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ in both Flagstaff area and St. George area data. This correlation is not quite as well defined as the α-β interrelationship; the divergence of $^{208}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ data points from a single straight line is more than analytical errors allow. In comparison, the Basin and Range data of Figure 4.9 exhibit a less pronounced covariance between $^{208}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$, if a significant correlation does indeed exist.

Differences between CP type and BR type data can be displayed in still another way. Figure 4.11 shows all the lead analyses of this work plotted on a triangular diagram similar to those employed by Cannon _et_ _al_. (1961). This diagram shows the relative proportions of ^{206}Pb, ^{207}Pb and ^{208}Pb in CP samples to be clearly distinguished from normal BR proportions. Typical BR type data are relatively rich in ^{206}Pb and lie toward the ^{206}Pb-^{208}Pb rich or Joplin lead side of a line joining the Stacey and Kramers (1975) value of modern terrestrial lead to the Tatsumoto _et_ _al_. (1973) value of primordial lead. In addition, most of the BR data field appears to lie towards the uranogenic side of the Stacey and Kramers (1975) growth curve. Colorado Plateau data, on the other hand, lie to the left or "old" lead side of the Stacey and Kramers-Tatsumoto _et_ _al_. modern "geochron." Also, the bulk of the

Figure 4.11a. Triangular diagram showing the relative proportions of ^{206}Pb, ^{207}Pb, and ^{208}Pb, assuming ^{206}Pb + ^{207}Pb + ^{208}Pb = 1.0. Point PL shows the locus of primordial lead - the isotopic composition of lead 4.57 by ago (Tatsumoto _et_ _al_., 1973). Point MTL is the Stacey and Kramers (1975) estimate of modern terrestrial lead. GC is the terrestrial lead growth curve of Stacey and Kramers (1975). For reference a line has been drawn between MTL and PL. The small triangular area is shown expanded in Figure 4.11b.

Figure 4.11b. Expanded triangular field from Figure 4.11a. Open triangles indicate data from the Colorado Plateau and immediately adjacent areas with distinctive CP type leads. Solid dots are data on samples from the Basin and Range province and coastal areas of California which display isotopic characteristics typical of BR type leads. Open circles represent data on Basin and Range province samples which display isotopic characteristics intermediate between or unlike either those considered typical of Basin and Range or Colorado Plateau provinces. The sample localities of these anomalous data points are indicated in Figure 4.7.

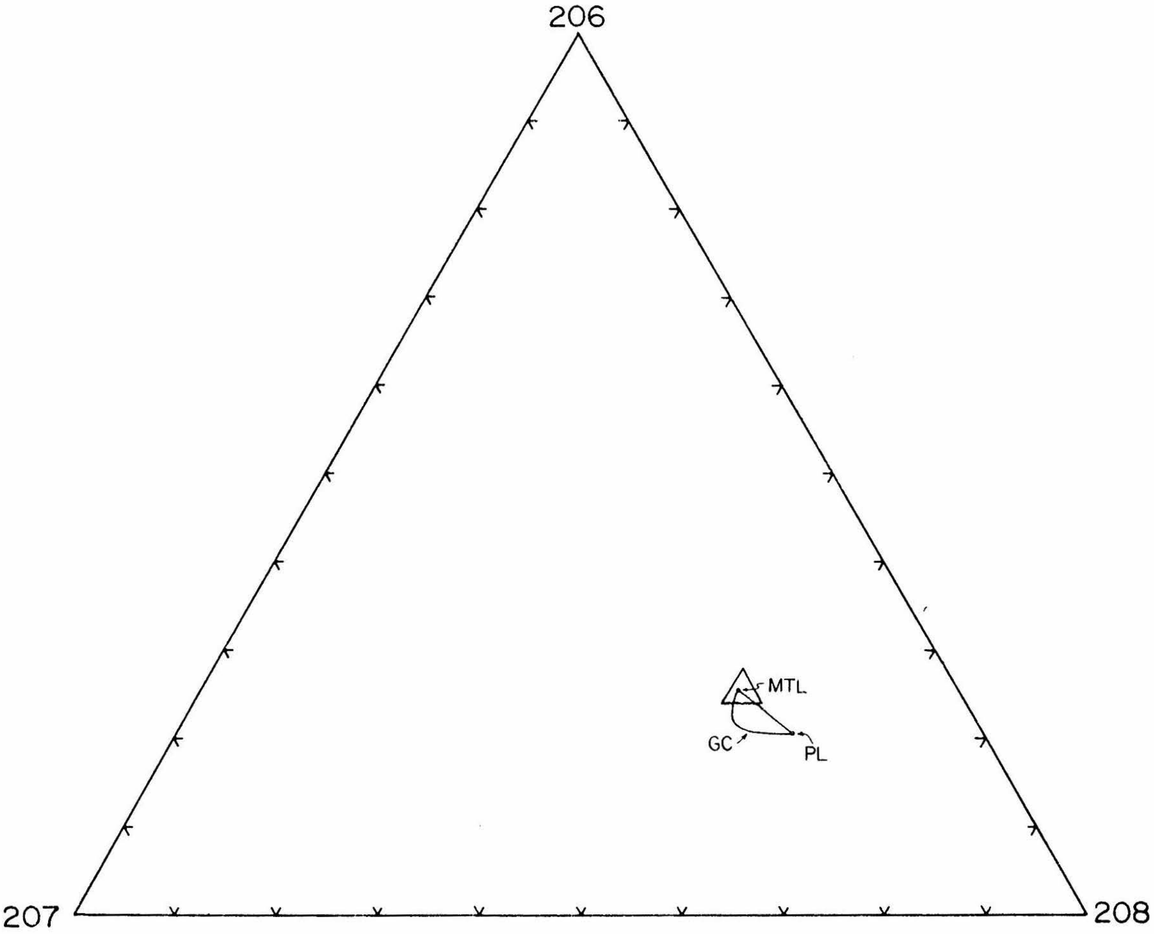


Figure 4.11a

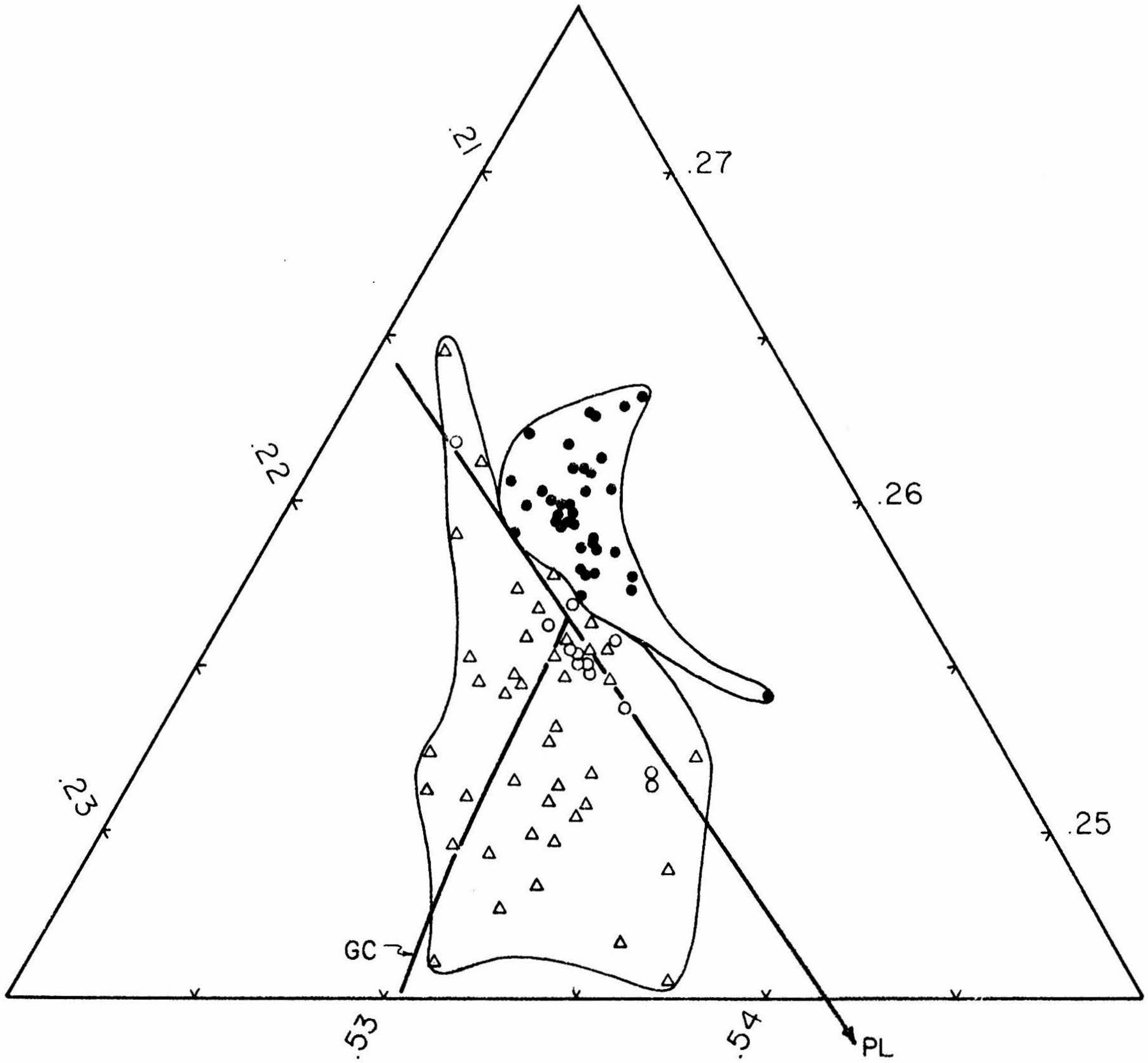


Figure 4.11b

Figure 4.12a. Data from two southwestern Colorado Plateau areas plotted in the expanded triangular field of Figure 4.11. Open triangles indicate data from the area around St. George, Utah (Area D in Figure 4.7). Solid circles indicate data from an area around Flagstaff, Arizona, which extends to the southwest toward Prescott, Arizona (Area E in Figure 4.7). The data from each region appear to describe completely distinct fields on the triangular diagram. Note also that the elongation of each field is roughly parallel to the terrestrial lead growth cruve (GC) of Stacey and Kramers (1975).

Figure 4.12b. Data from central New Mexico (CNM), Area J in Figure 4.7, plotted on the expanded triangular field of Figure 4.11. Data from the Mt. Taylor volcanic field on the Colorado Plateau, as well as data from a segment of the Rio Grande rift marginal to the Colorado Plateau are included. Three data points from this area plot in the BR field of Figure 4.11 and six plot in the CP field on the same Figure. The CNM data field has an elongation similar to that displayed by the Flagstaff-Prescott area data from the southwestern Colorado Plateau, but is somewhat displaced toward the thorogenic side of the diagram.

Figure 4.12a

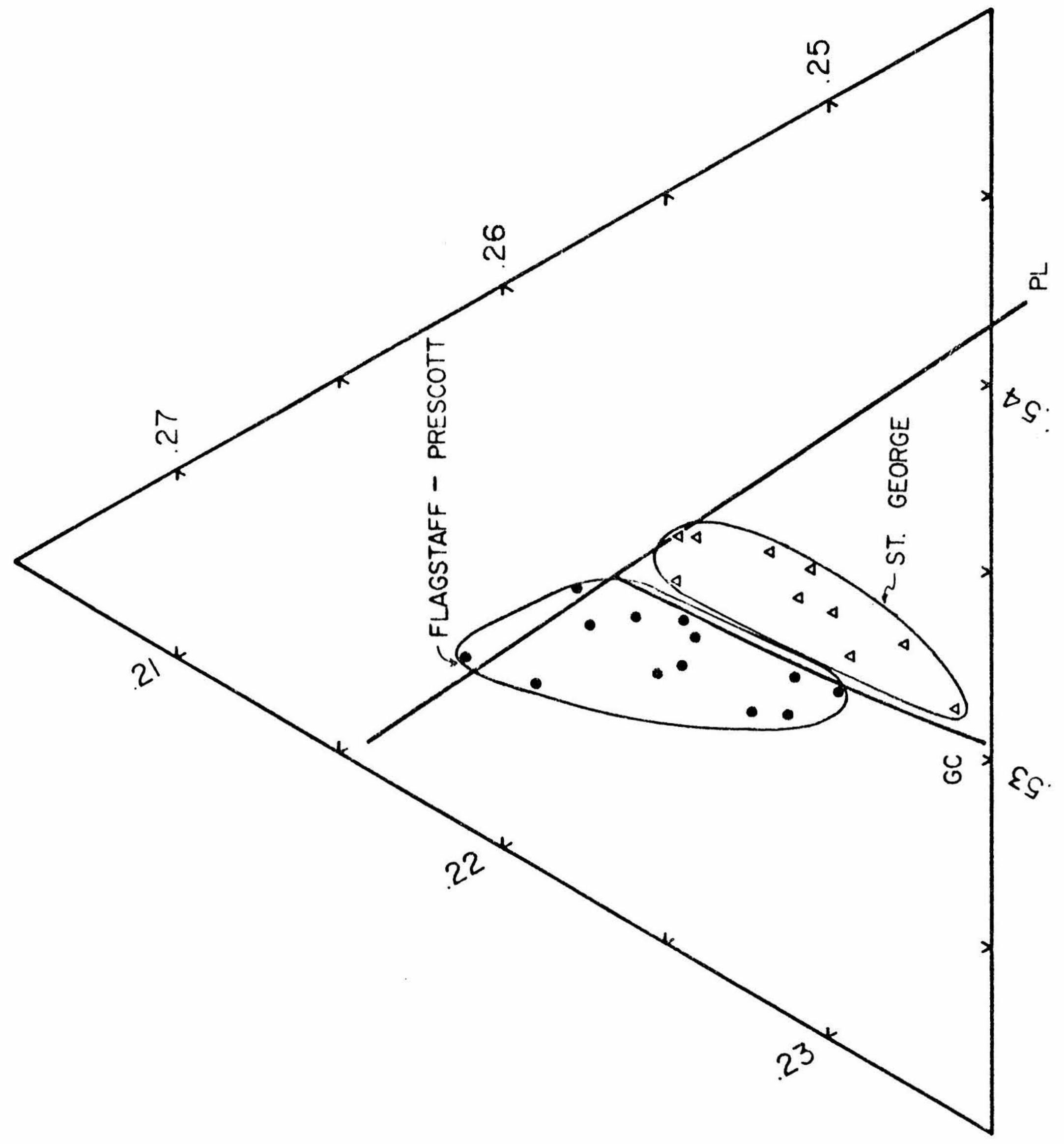


Figure 4.12b

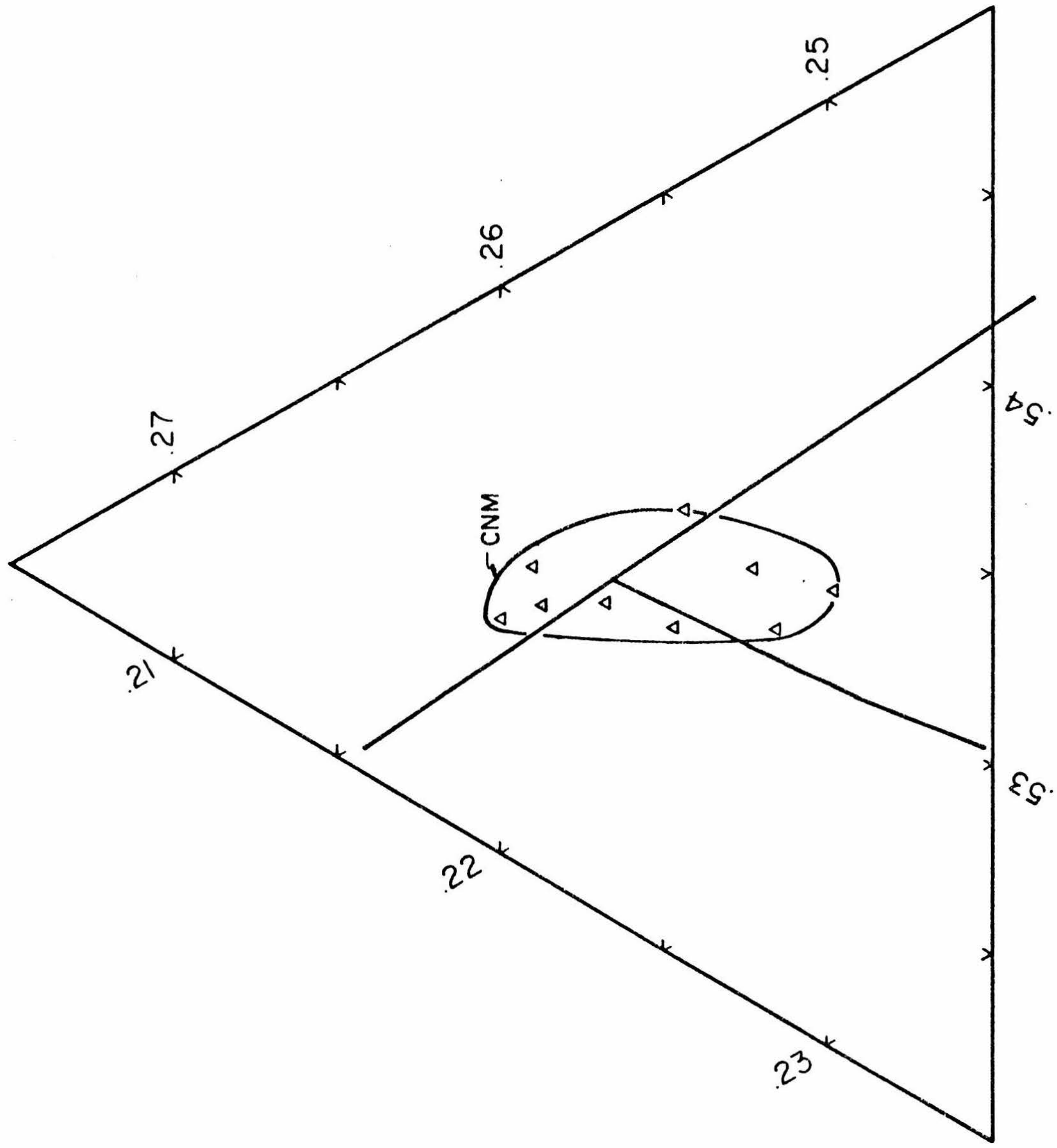


Figure 4.12c. Data from two areas characterized by BR type leads. Filled circles in the field labelled SC-SWA are data points from the southern California and southwestern Arizona (Area C in figure 4.7), while open diamonds in the SRG field are data points from a segment of the southern Rio Grande rift. Data points from both areas lie in the BR field of Figure 4.11b, and appear to define areas more compact than the southwestern CP fields of Figure 4.12a. In addition, the SC-SWA data field appears to display an elongation different from the southwestern Colorado Plateau data fields - its major axis points roughly towards primordial lead (PL) rather than along the modern terrestrial lead growth curve (GC).

Figure 4.12d. Data from northern and central Nevada (Area A in Figure 4.7) are shown as solid circles in the field labelled "NN." Data from a southern Nevada area (Area B in Figure 4.7) are represented as open circles in the field labelled "SN." Data from both Basin and Range areas show an elongation roughly parallel to the geochron pointing toward PL; these elongations appear different than those for the southwestern Colorado Plateau data fields of Figure 4.12a.

Figure 4.12c

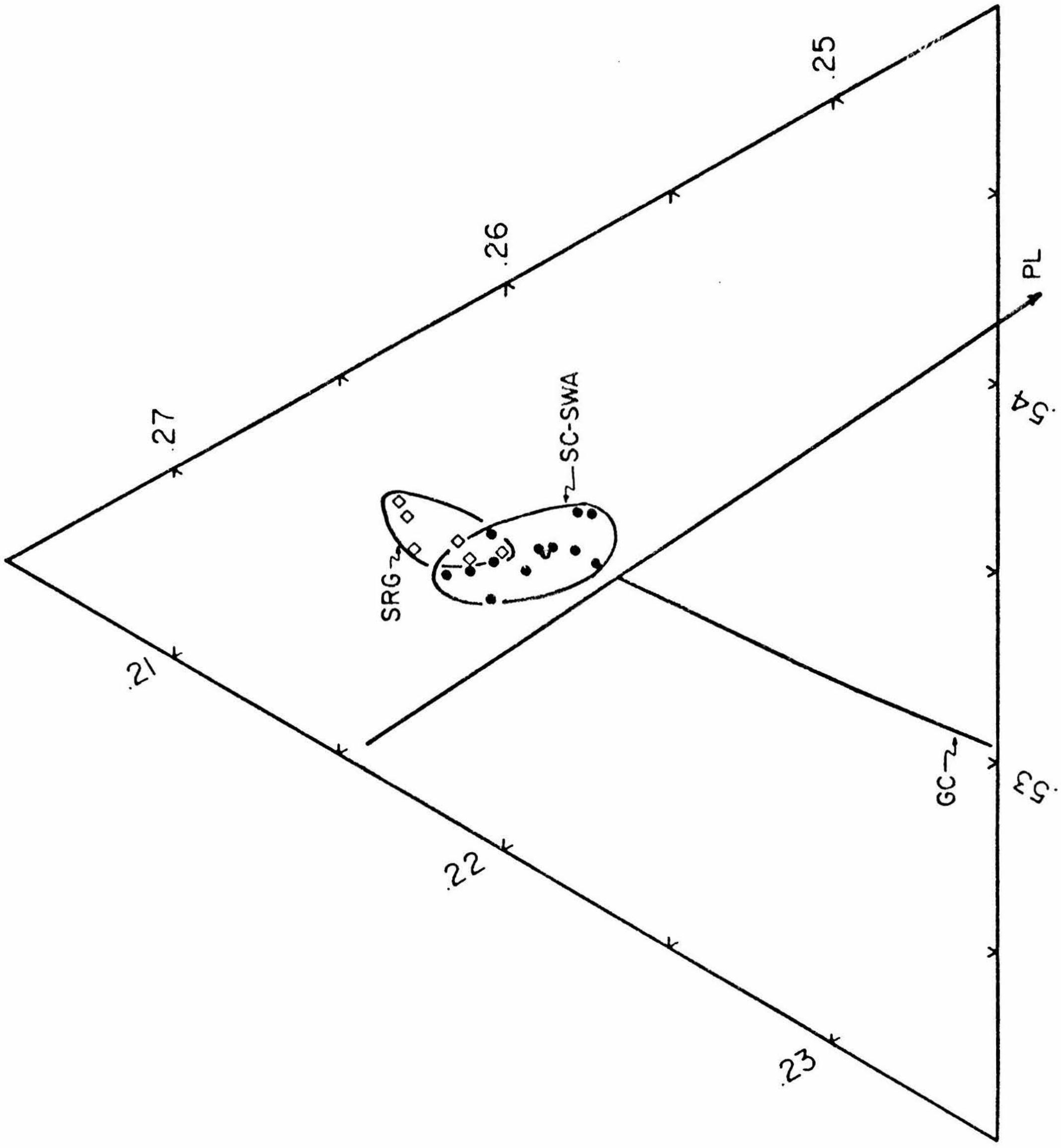


Figure 4.12d

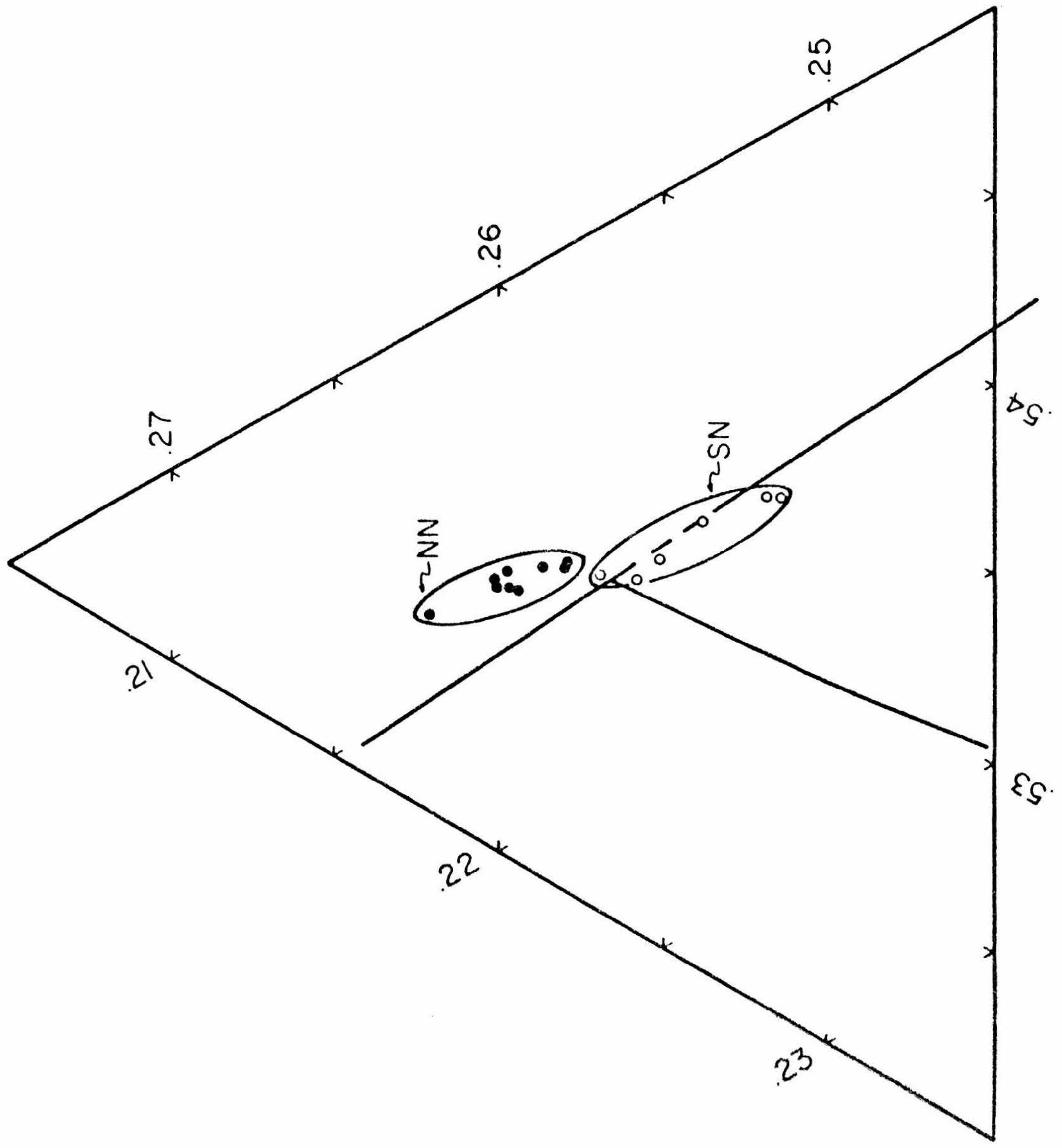
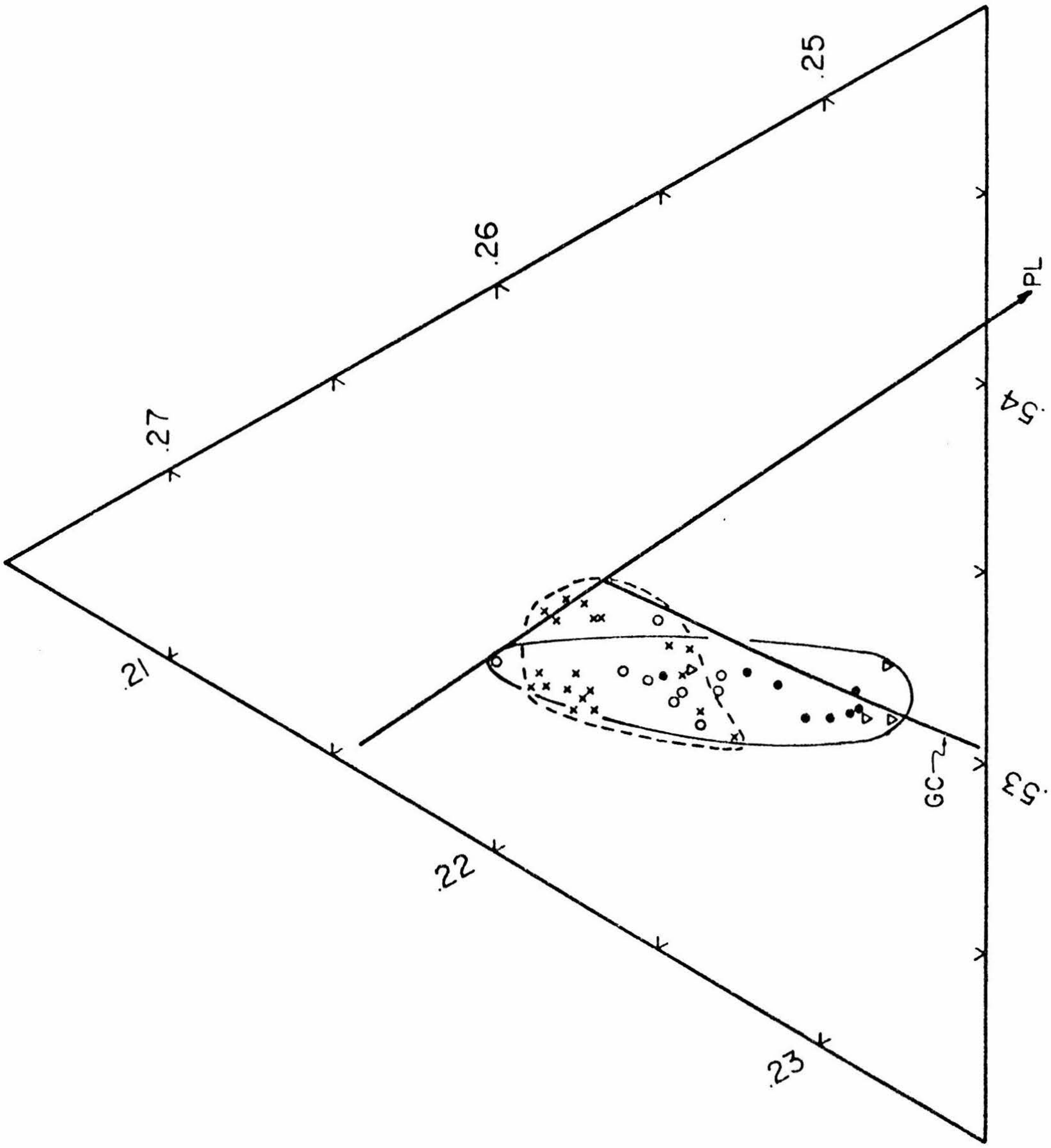


Figure 4.12e. Lead isotopic data from the San Juan volcanic field of southwestern Colorado (Lipman *et al.*, 1978). Early intermediate composition volcanics are shown as solid circles; analyses on caldera-related rocks are shown as X's; and late basalts and rhyolites of the Hinsdale formation are shown as open circles. Isotopic data on several basalts from the Pliocene Servilleta formation near Taos, New Mexico are shown as open triangles (Doe *et al.*, 1969; and this work). The general position and elongation of the San Juan data field is similar to that of the Flagstaff-Prescott field of Figure 4.12a. The data points lying outside the area marked by a solid line seem, in general, to have higher $^{87}Sr/^{86}Sr$ ratios than their counterparts within the field. The dashed line encloses data from caldera-related rocks, which Lipman *et al.* (1978) suggest may have experienced significant interaction with upper crustal materials.

Figure 4.12e



CP data appears to lie toward the ^{208}Pb or thorogenic side of the Stacey and Kramers growth curve.

Data from individual CP areas tend to describe different trends on the triangular diagram than do individual BR areas. Fields of CP data tend to be elongate in directions roughly parallel to the modern terrestrial growth curve. The variations expressed in CP data occur mainly in the ^{206}Pb fraction, with lesser variation in the proportions of ^{207}Pb and ^{208}Pb. In contrast, data fields from BR localities appear to be elongated in a different direction on the diagram. Populations of BR data tend to point roughly toward primordial lead and to be perpendicular to the modern terrestrial growth curve. Thus the variation in the ^{208}Pb fraction appears to be most pronounced while variations in the proportions of the ^{207}Pb and ^{206}Pb are subordinate for BR data from individual areas. These different characteristics of BR and CP data on triangular diagrams are illustrated in Figure 4.12.

4.5 Areas of Anomalous or Transitional Isotopic Characteristics

There are several areas where samples display isotopic characteristics transitional between BR and CP characteristics, or where samples display some attributes characteristic of BR samples and other attributes characteristic of CP samples. For example, Figure 4.11 distinguishes 16 non Colorado Plateau data points which plot near the geochron and just within the CP data field. Geographically many of these samples come from Basin and Range areas bordering on the Colorado

Plateau, especially from the Mexican Highlands region of southeastern New Mexico. Another group comes from the southern Great Basin of southern Nevada and eastern California (see Fig. 4.7 for more precise localities).

Let us first consider in more detail the lead data on the Mexican Highlands samples of southeastern Arizona and southwestern New Mexico (Area G in Figure 4.7). Figure 4.13 indicates that these samples display a rather extended range in $^{206}Pb/^{204}Pb$ - from 18.86 to 17.89. This large range would normally be suggestive of an affinity to the Colorado Plateau style of data. However, the data do not describe a well-defined linear array on a α-β diagram, and are in this way similar to BR type data. Most of the samples (8 of 11) have $^{206}Pb/^{204}Pb$ ratios below 18.7 - below that considered normal for BR data. Ten of the eleven samples have $^{208}Pb/^{204}Pb$ ratios below the 38.3 lower limit for BR type samples. None of the southeastern Arizona samples fall on the two CP reference isochrons, but almost all of the New Mexico samples lie close to an isochron. This observation might suggest that the Arizona samples be considered Basin and Range type, while the volcanics from New Mexico would be best interpreted as CP type. This seems a reasonable conclusion for the Arizona rocks, but there are some difficulties in unequivocally classifying the basalts from New Mexico as either BR or CP type. It might be noted, for example, that four of the five New Mexico data points have very similar isotopic compositions. This homogeneity of isotopic composition is usually considered a characteristic of Basin and Range data.

Figure 4.13. Lead isotopic data on volcanics from the Mexican Highlands section of the Basin and Range province in southeastern Arizona and southwestern New Mexico (Area G in Figure 4.7). Circles are New Mexico data points and triangles are Arizona data points. Filled symbols are data points taken from Zartman and Tera (1973). The two Colorado Plateau regression lines from Figure 4.8 are shown for reference.

Figure 4.13

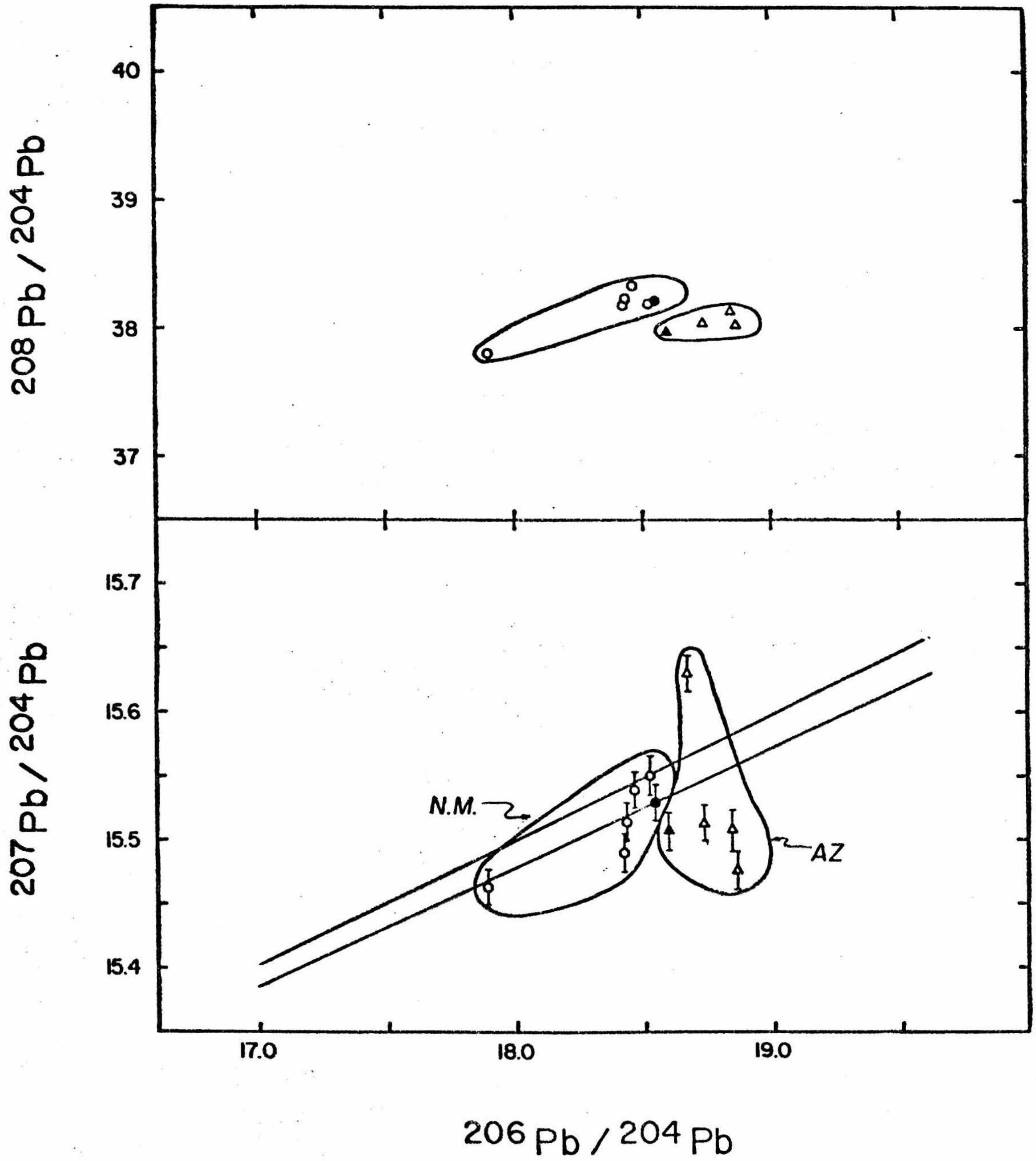
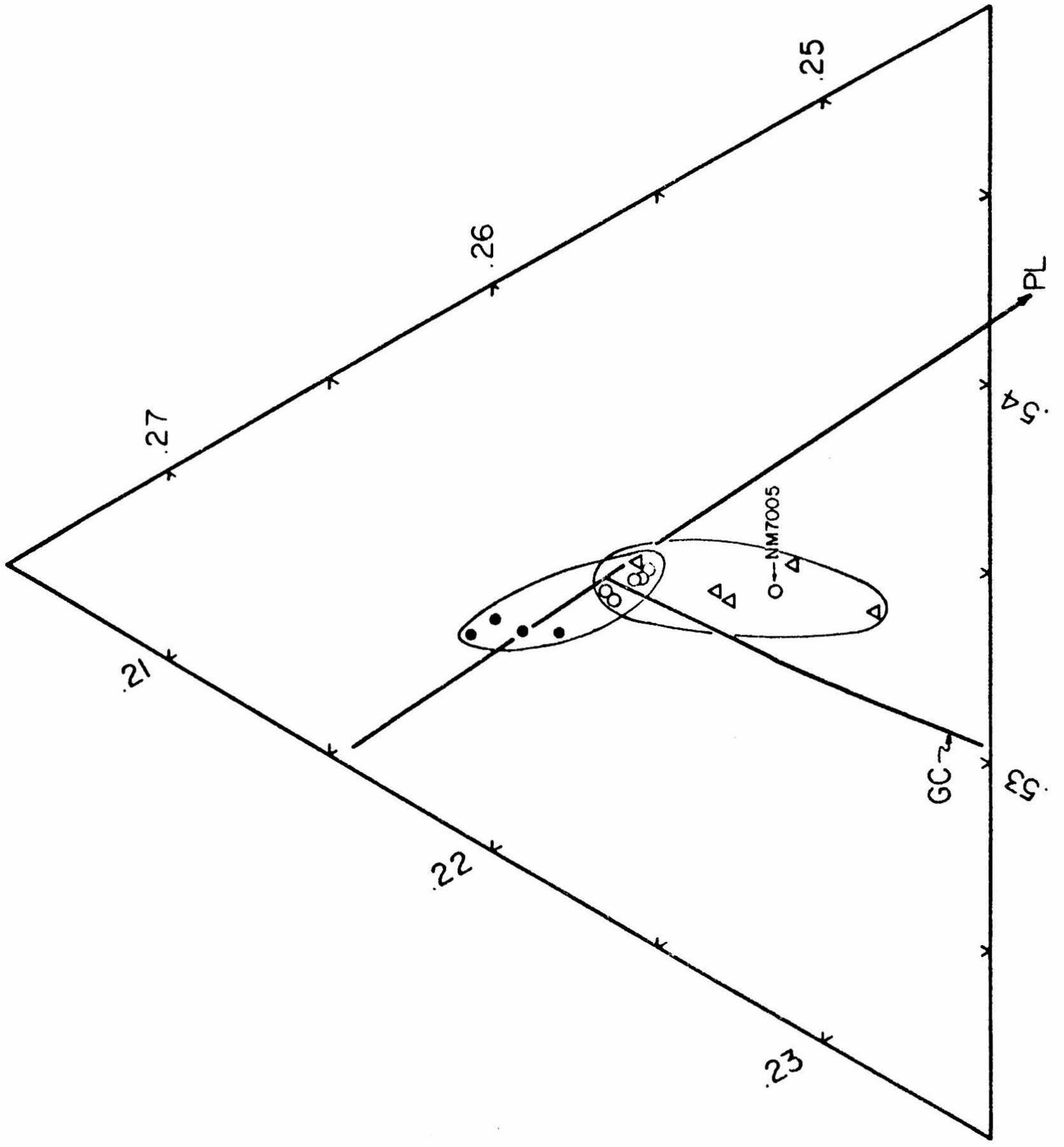

40
39
38
37
208 Pb / 204 Pb
15.7
15.6
15.5
15.4
207 Pb / 204 Pb
N.M.
AZ
17.0
18.0
19.0
206 Pb / 204 Pb

Figure 4.14. Expanded triangular field from Figure 4.11, on which data from the Mexican Highlands (Area G in Figure 4.7) are shown as circles. Filled circles represent data on Arizona samples; open circles represent data on New Mexico samples. Open triangles indicate data points on samples from nearby regions of the Colorado Plateau (Area H in Figure 4.7). If the data from the two Mexican Highlands areas are grouped together (and sample NM7005 is excluded from consideration), the result is a data field whose elongation is similar to the BR data fields of Figures 4.12c and 4.12d. If the open circles (New Mexico samples) are taken alone or grouped with samples from the nearby Colorado Plateau, the result is a data field whose position and elongation is similar to data fields from the southwestern Colorado Plateau (Fig. 4.12a).

Figure 4.14

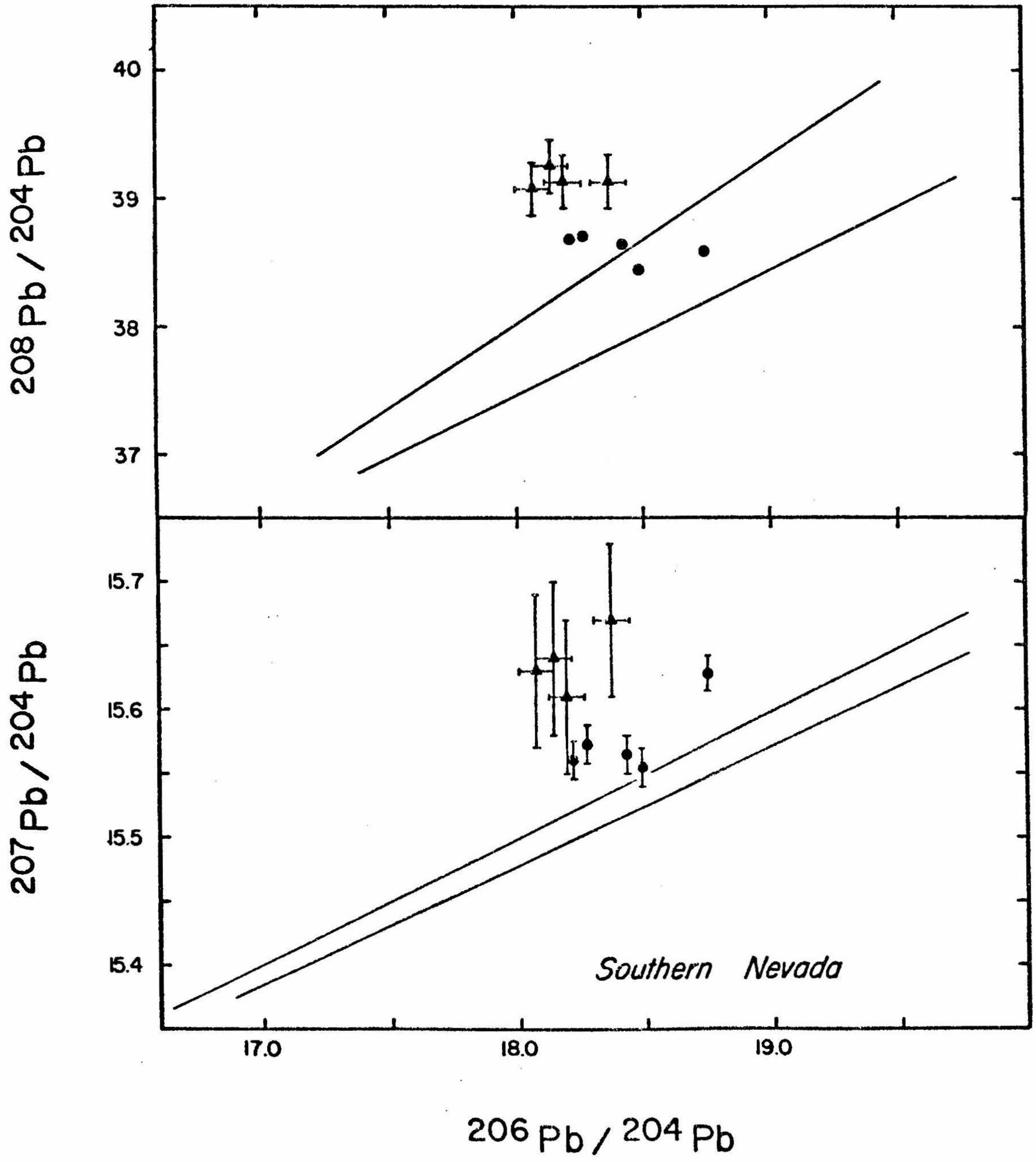


The difficulty in classifying these New Mexico samples can also be observed on a ^{206}Pb-^{207}Pb-^{208}Pb triangular diagram (Fig. 4.14). All of the New Mexico data points fall in the CP field, but all but one (NM7005) are located in an area intermediate between the BR and CP data fields. If the Mexican Highlands samples from both Arizona and New Mexico are grouped together, and the NM7005 data point is excluded from consideration, the result is a data field with a typical BR type elongation. The data field points toward primordial lead. However, if the New Mexican samples are taken independently, and NM7005 is not excluded, the resulting data field has a elongation and a position virtually identical with that described by data from the neighboring Colorado Plateau. Thus the lead isotopic characteristics of basalts from southern New Mexico appear to be transitional between BR and CP type data, just as the physiographic characteristics of the region are transitional between that typical of Basin and Range and Colorado Plateau areas.

Although southern Nevada (Area B in Figure 4.7) has physiographic and geologic features indisputably characteristic of the Basin and Range province, its volcanics possess leads not uniquely characteristic of either BR or CP categories. As shown in Figure 4.15, eight of the nine samples from this area have ^{206}Pb/^{204}Pb ratios less than 18.7, the lower limit of normal BR type data. On the other hand, eight of these samples have ^{208}Pb/^{204}Pb values above the 38.5 "upper limit" for CP samples. The data show a variability in ^{206}Pb/^{204}Pb somewhat intermediate between CP and BR type data. Two of the analyses

Figure 4.15. Lead data on late Cenozoic volcanics from southern Nevada and nearby areas in eastern California. Triangles are data on silicic tuffs reported by Doe (1970). Circles are data from basalts analyzed in this report. The two Colorado Plateau regression lines from Figure 3.11 are shown for reference.

Figure 4.15

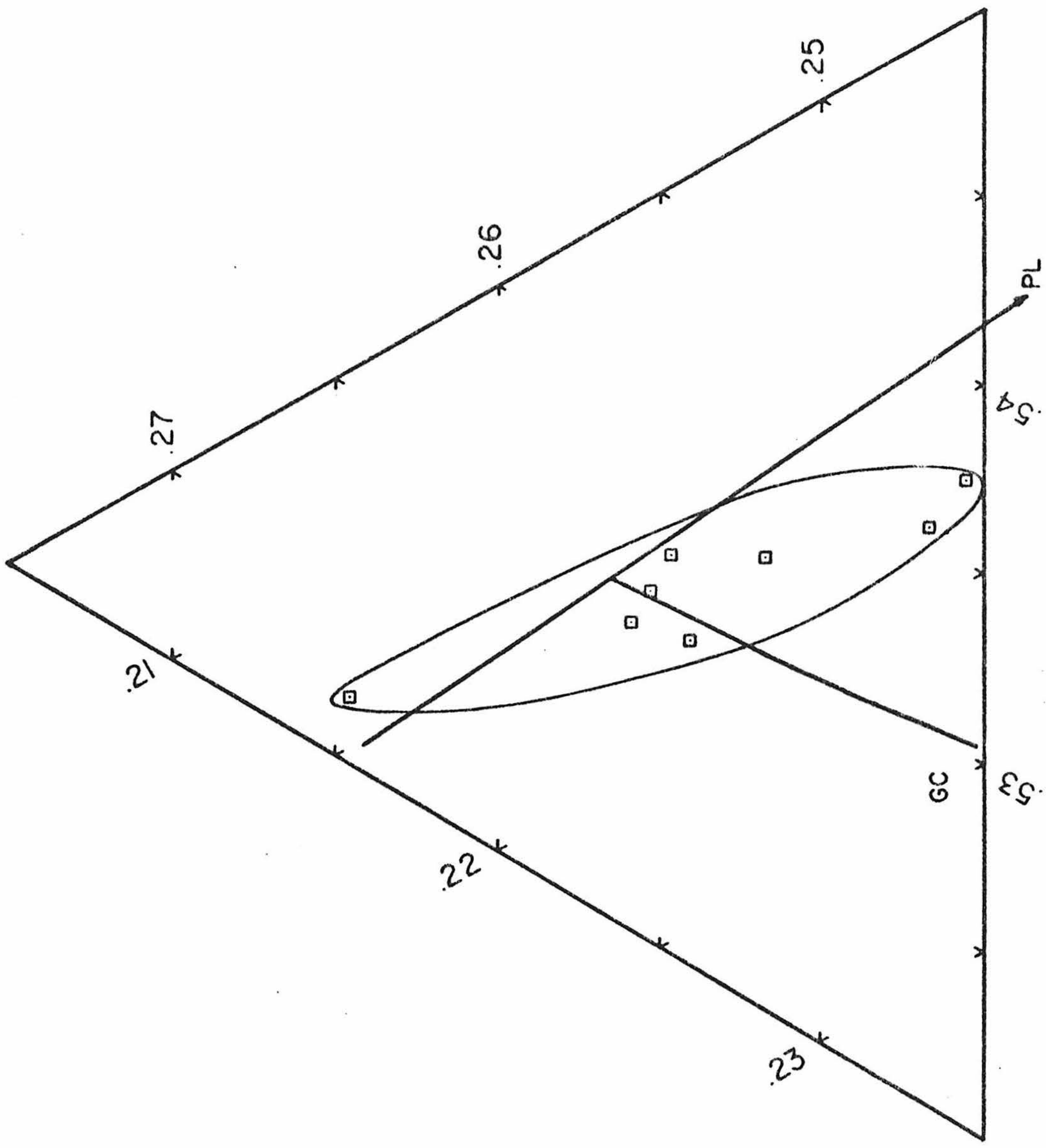

40
39
38
37
208 Pb / 204 Pb
15.7
15.6
15.5
15.4
207 Pb / 204 Pb
Southern Nevada
17.0
18.0
19.0
206 Pb / 204 Pb

fall near the CP reference isochrons, but seven do not. On a triangular diagram the southern Nevada (SN) leads fall within the CP data field, but as a group display an elongation which is typical of Basin and Range data (see Fig. 4.12d). Thus the leads from this area in the southern Great Basin, like those of the Mexican Highlands, do not fall easily into either the Basin and Range or Colorado Plateau categories. As will be discussed in later sections, the strontium isotopic ratios of volcanics from southern Nevada (Leeman, 1970; Hedge and Noble, 1971) also distinguish this area from typical BR or CP areas.

A third area in the southwestern United States appears to have lead isotopic characteristics not quite typical of its physiographic setting. This area is found along the margin of the Colorado Plateau in central Arizona, with many of the questionable data points from an area between the physiographic boundary and what is sometimes considered the structural boundary of the Plateau (see Area F in Figure 4.7 for location). As far as α and β data are concerned, these samples appear to be more or less typical of CP type rocks. There are one or two samples which are more radiogenic (e.g., $^{206}Pb/^{204}Pb = 19.4$) than is normal for CP type data, but then again CP data do typically display a wide range in their isotopic ratios. However, when the data are plotted on a triangular diagram, several unusual features are revealed. Rather than bunching into a tight, elongated field, the data spread over a larger region of the diagram than is usual. In addition, the data field shows an elongation which is more typical of BR data than CP data. These considerations suggest that it might not be appropriate

Figure 4.16. Data on samples from an area along the margin of the Colorado Plateau in central Arizona (Area F in Figure 4.7) plotted on the expanded triangular field of Figure 4.11.

Figure 4.16



to consider some or all of the leads from this area to be typical CP type data.

4.6 Geographic Extent of BR and CP Systematics

The isotopic systematics characteristic of volcanic rocks from the Colorado Plateau do not appear to be strictly confined within the physiographic or even within what is often considered the structural boundary of the Colorado Plateau. Similarly, Basin and Range isotopic characteristics appear to extend beyond the limits of the Basin and Range province. For example, all of the data points from the Sierra Nevada and coastal regions of California appear to display BR type systematics. In addition, "Basin and Range" leads are not found in every area of the Basin and Range province. Volcanics from southern Nevada, for instance, seem to have their own special (SN) isotopic characteristics. It is therefore useful to consider the geographic extent of the different types of isotopic behavior independently of the extent of the different physiographic provinces. The terms BR and CP will be retained, however, to indicate the similarity of an area's rock leads to data from the type areas used to define Colorado Plateau type and Basin and Range type isotopic styles - the St. George and Flagstaff areas in the southwestern Colorado Plateau for CP type data, and the northern Great Basin and Basin and Range province of southern California and southwestern Arizona for BR type data.

4.6.1. Classification of CP and BR type data

Before the geographic extent of BR and CP type isotopic behavior can be displayed, it is first necessary to establish a set of criteria which distinguish, sample by sample, the two types of behavior. One simple algorithm used previously (Everson and Silver, 1976) is shown in Figure 4.17. In this scheme a data point is classified variously as Colorado Plateau type, probably Colorado Plateau type, probably Basin and Range type, or normal Basin and Range type depending on the value of the sample's $^{206}Pb/^{204}Pb$ ratio, and whether the data point lies, within analytical error, on one of the two CP reference isochrons. This algorithm works satisfactorily for the most part but suffers occasionally from its discrete classification limits. For instance, the samples from the Potrillo volcanic field of southern New Mexico constitute an extremely homogeneous set of data. However, because their $^{206}Pb/^{204}Pb$ ratios cluster around a value of 18.5, and because several points lie just outside the 0.1% error allowance for being on the CP isochrons, Potrillo data is classified as both CP and BR type. Another objection to the Figure 4.17 algorithm is that it completely ignores $^{208}Pb/^{204}Pb$ ratios in its classification.

These defects can be overcome by a classification procedure which employs a discriminant function. As discussed by Davis (1973) and Anderson (1958), a discriminant function is a linear, multivariate function, the terms of which are weighted in such a way as to maximize the difference between two populations of data. The numerical value

Figure 4.17. A classification scheme used by Everson and Silver (1976) to categorize individual data points as Basin and Range or Colorado Plateau type. The judgment between the two categories was based on (1) the magnitude of the $^{206}Pb/^{204}Pb$ ratio (α), and (2) whether or not the data point fell, within experimental error, on one of the two Colorado Plateau $^{207}Pb/^{204}Pb$-^{206}Pb-^{204}Pb regression lines of Figure 4.8.

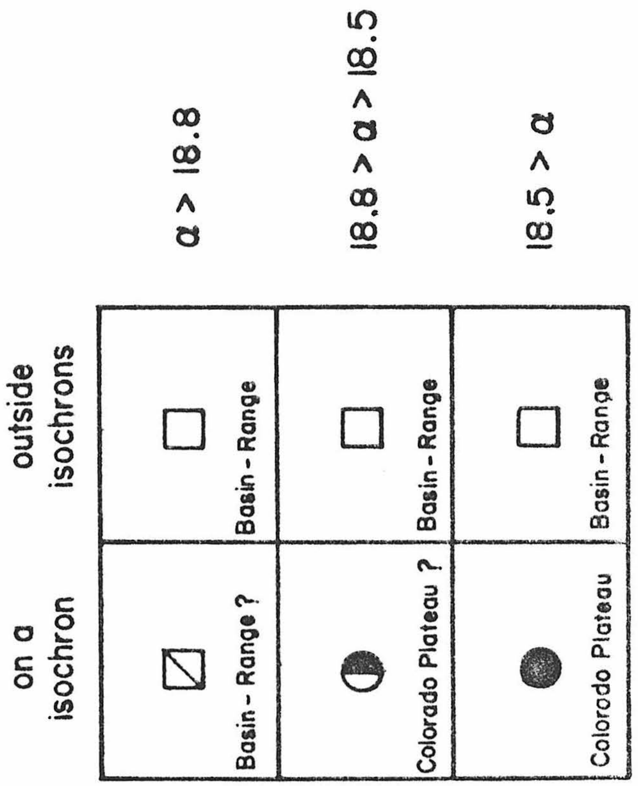

on a isochron
outside isochrons
α > 18.8
18.8 > α > 18.5
18.5 > α
Basin - Range ?
Basin - Range
Colorado Plateau ?
Basin - Range
Colorado Plateau
Basin - Range

Figure 4.17

of the function, whether it is greater or less than a reference value, is used to classify each data point into one of the two population sets.

In calculating a function which would discriminate CP and BR type data, analyses from the southwestern Colorado Plateau (specifically the regions surrounding St. George, Utah, and Flagstaff, Arizona) were used to define the Colorado Plateau population. The type BR data set was defined by samples from the Basin and Range province of northern and central Nevada, southern California, and southwestern Arizona. The variables considered potentially the most useful in classifying the two data sets were the $^{206}Pb/^{204}Pb$ ratio, the $^{208}Pb/^{204}Pb$ ratio, and the difference between the measured $^{207}Pb/^{204}Pb$ ratio and the β predicted by the Colorado Plateau "isochron." The discriminant function calculated by the Davis procedure is:

$$F = 137.47 - 7.180\alpha - 1.014\delta - 0.0586\gamma$$

where α = measured $^{206}Pb/^{204}Pb$ ratio

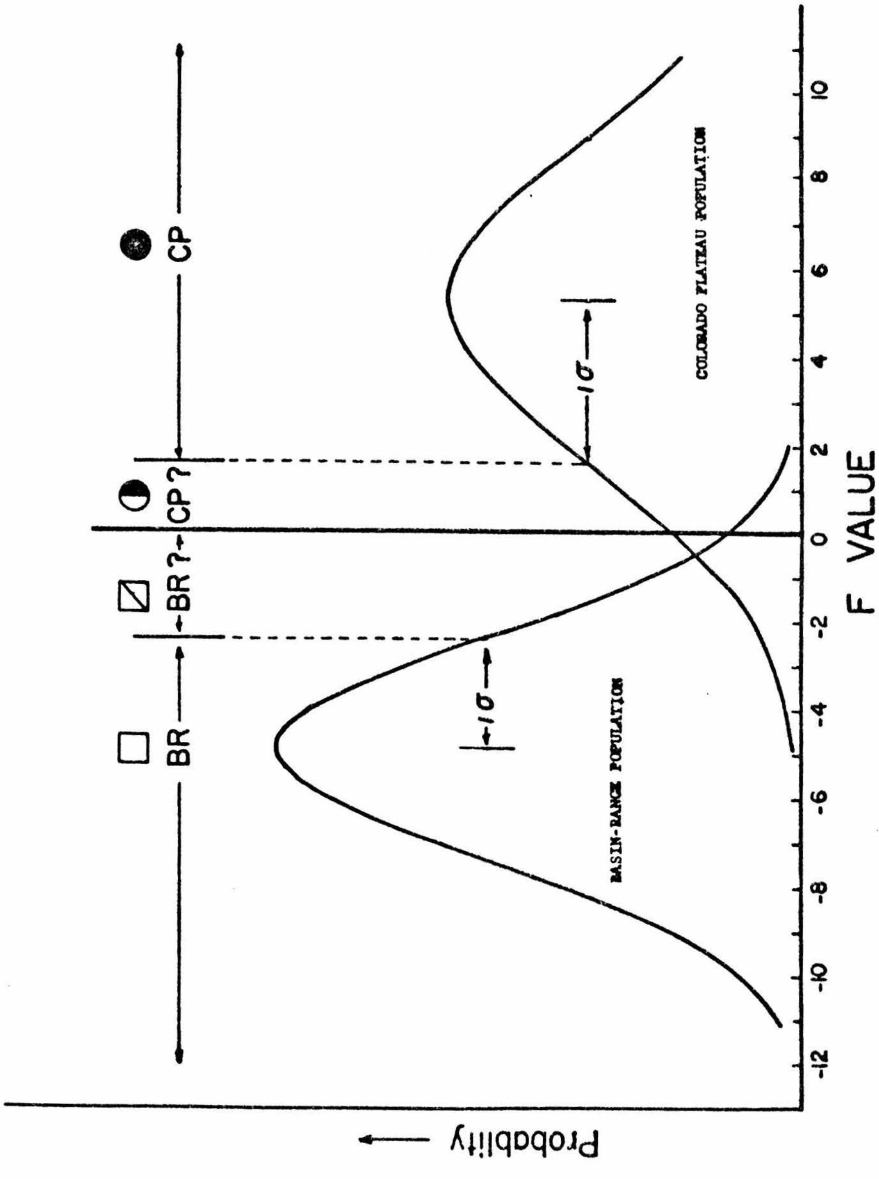
δ = measured $^{208}Pb/^{204}Pb$ ratio

$\gamma = |(\beta - A - B\alpha)/\sigma|$; β being the measured $^{207}Pb/^{204}Pb$ ratio; A and B are coefficients of the line defined by the type CP data (A = 13.961, B = 0.084828); σ = the estimated standard deviation of CP data from the CP isochron. For samples run with the silica gel procedure $\sigma = 0.0162$. For PbS analyses σ was assumed = 0.06.

A positive value of F indicates that a sample belongs in the CP

Figure 4.18. The discriminant function classification scheme used in this report to categorize individual data points as Basin and Range (BR) or Colorado Plateau (CP) type. A value of the discriminant function F less than zero indicates that it is more probable that a sample belongs in the Basin and Range population. An F value above zero is indicative of a CP type lead. F values near zero have been denoted as CP? and BR? in order to specially display those leads which would be most subject to misclassification. See text for further details.

Figure 4.18


BR
BR?
CP?
CP
1σ
1σ
BASIN-RANGE POPULATION
COLORADO PLATEAU POPULATION
-12
-10
-8
-6
-4
-2
0
2
4
6
8
10
F VALUE
Probability

population while a negative value indicates that it belongs in the BR population (see Fig. 4.18). The type CP population has a mean F of 5.28 and a sigma of 3.67. The type BR population has a mean of -4.86 with a standard deviation of 2.48.

Rather than strictly classifying each sample into only BR and CP categories, it would be useful to specially denote those samples having F values near zero. These samples would be the ones having transitional characteristics and the ones most likely to be misclassified. With this in mind the classification scheme shown in Figure 4.18 was devised. Samples were considered unambiguously of the BR type if they had F values less than -2.40 (the Basin and Range mean plus the Basin and Range standard deviation). Similarly, samples were considered probably "Basin and Range" if they had F values less than zero but greater than -2.40. In the same way samples were considered unambiguously of the CP type if F was greater than 1.61 and probably of the CP type if F was between 1.61 and 0.0.

The spatial distribution of CP and BR points based on this classification is shown in Figure 4.19. A number of conclusions can be drawn after examining this figure:

1. The F function adequately classifies members of the two populations. Of the twenty-four samples used to define the normal Basin and Range population, all are correctly classified as BR type. Of the samples defining the type Colorado Plateau isotopic characteristics twenty-one of the twenty-two are correctly classified.

Figure 4.19. The geographic distribution of Colorado Plateau (CP) type and Basin and Range (BR) type data points, using the discriminant scheme of Figure 4.18 to judge between the two types of data. Filled circles were judged to be unambiguous CP type data; half filled circles were considered somewhat more likely to be CP type than BR type. Open squares represent data classified as BR type, and squares with a diagonal cross bar are borderline cases more likely to belong to the BR population than the CP population. Triangles represent data points considered on the basis of additional criteria not used in the discriminant function scheme to be neither BR nor CP type data. The dotted pattern denotes the approximate limits of these anomalous, SN type data points. The cross hatched pattern represents the approximate boundary of the CP isotopic province.

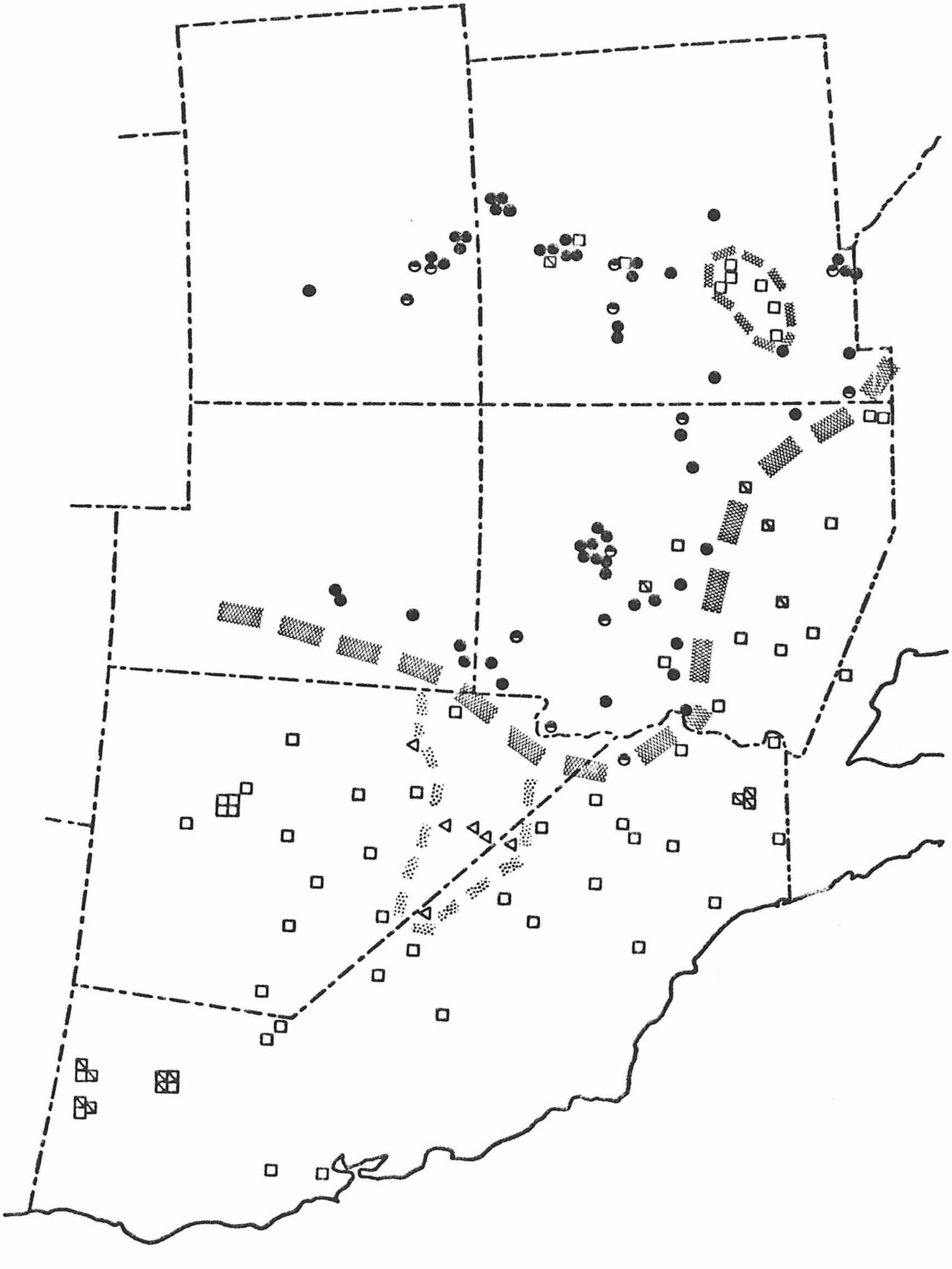


Figure 4.19

2. Discriminant function values indicate that the isotopic characteristics of the southwestern Colorado Plateau, the type area, extrapolate to other areas of the Plateau. Samples from the White Mountain volcanic field of central, eastern Arizona, from the Mt. Taylor volcanic field of New Mexico, as well as the other parts of the Colorado Plateau on which data were taken exhibit CP characteristics according to the discriminant function.

3. CP leads extend beyond the physiographic and even structural boundaries of the Plateau. Data from the Tonto section of Hayes (1969), the region between the physiographic and structural boundaries of the Plateau in central Arizona, has, with two possible exceptions, CP type characteristics. In addition, samples from some western Arizona and eastern California areas within the Basin and Range province also exhibit CP isotopic characteristics. Samples from southernmost New Mexico are uniformly classified as CP type even though the region has Basin and Range structures. Data from the northern Rio Grande rift, an area structurally similar to the Basin and Range province, display isotopic characteristics similar to those found on the Colorado Plateau, as does one sample bordering on the Great Plains.

4. According to the discriminant function, the data from southern Nevada (SN) samples appear to have lead characteristics resembling the Colorado Plateau type more than the Basin and Range type of data. However, the volcanics from this area have attributes which are not normal for either the Basin and Range province or the Colorado Plateau. Despite low $^{206}Pb/^{204}Pb$ ratios, samples from this region

have high $^{208}Pb/^{204}Pb$ and $^{87}Sr/^{86}Sr$ ratios, and α and β ratios which do not define linear arrays. Data from this area should probably be regarded as belonging to a population distinct from both normal BR and CP data sets.

5. BR type data is not limited to true Basin and Range areas. Samples from the Sierra Nevada, the Cascades, and the near-coast regions of California have isotopic characteristics which are indistinguishable from normal BR type data.

6. Rocks from an area along the southern portion of the Rio Grande rift have isotopic characteristics which are distinctly BR in character. This BR area appears to lie completely surrounded by areas characterized by CP type isotopic behavior.

4.6.2. Areal extrapolation of regional lead patterns

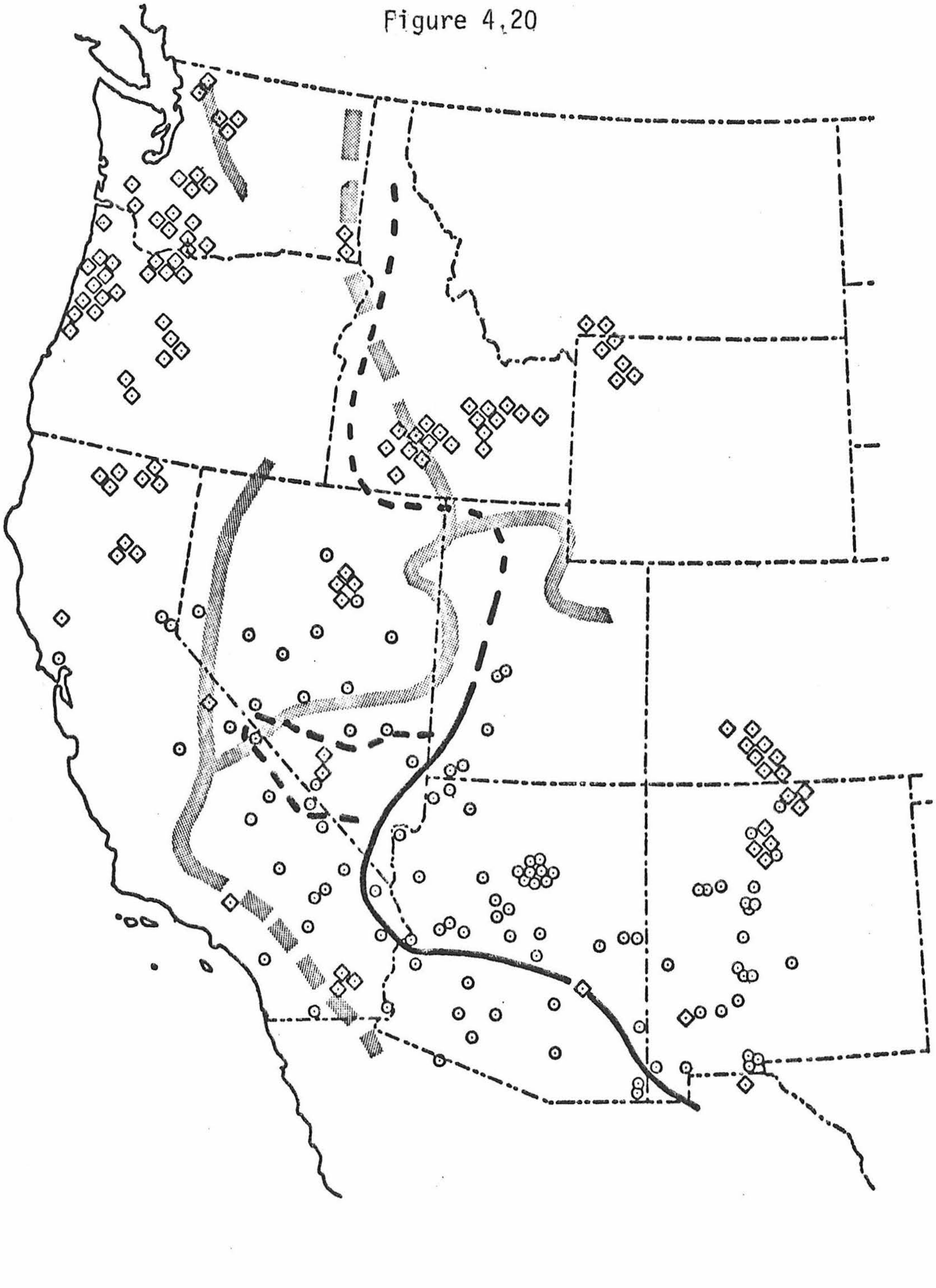
The data on late Cenozoic basalts presented in this work describe the lead isotopic provincialism of only a limited portion of the western United States. With the help of published data on Cenozoic volcanics, it is possible to see that the isotopic patterns which characterize the Southwest extend in a general way to a much larger area (Fig. 4.20). In the Pacific Northwest, the geographic boundary between "CP" and "BR" volcanic rock leads appears to approximately follow Zartman's (1974) Area I-Area II boundary, which was based on both Mesozoic and Cenozoic rock and ore leads. The major difference is that the Zartman boundary cuts the Snake River Plain; recently published data from Leeman (1975) indicate that the "BR"-"CP" boundary should bend around this region.

4.6.3. Comparison between different descriptions of lead provinces in the western United States

Figure 4.20 compares the isotopic provinces identified in this report with those proposed by Zartman (1974). As has been mentioned previously, Zartman's Area I leads have characteristics similar to what has been called CP type data in this report. BR type leads appear to be analogous to Area II and/or Area III leads. Several divergences can be noted between the two models. Firstly, the data of this work do not appear to support a distinction between Area II and Area III leads. According to Zartman, leads from both areas show a small range in local isotopic composition but Area II has somewhat more radiogenic leads than Area III. Area II has a normal isotopic range of 19.1 to 19.7 for $^{206}Pb/^{204}Pb$ and 38.9 to 40.3 for $^{208}Pb/^{204}Pb$, while Area III leads range from 18.7 to 19.4 in $^{206}Pb/^{204}Pb$ and 38.2 to 39.1 for $^{208}Pb/^{204}Pb$. Figure 4.4 shows, however, that a number of data points from the Great Basin of Nevada - Zartman's Area II - are less radiogenic than the criteria for Area II would allow. On the other hand, volcanic samples from other, scattered areas in the southwest have leads as radiogenic as any of those observed in Area II. For example, sample C3032 from the Sierra Nevada, C5003 from the Mohave desert, M3012 from the Pinacate volcanic field, and a number of samples from the southern

Figure 4.20. Extrapolation of the CP-BR isotopic boundary (heavy black line) to other geographical areas not studied in this investigation. Circles are data points from this study. Diamonds are data points from published sources, including those tabulated in the caption to Figure 3.1, and Tatsumoto and Snavely (1969), Davis _et al_. (1964), Leeman (1974), and Peterman _et al_. (1970). The lead province boundaries of Zartman (1974) (hatched pattern) are shown for comparison.

Figure 4.20



Rio Grande rift have leads as radiogenic as the more radiogenic samples of Area II.

A second difference occurs about the association of CP or Type I isotopic behavior with geologic features of the crust. Zartman has indicated that his Area I coincides with those regions possessing Precambrian basement. Although every area found in this report to have CP characteristics has a Precambrian basement, the converse is not true. Large areas in southwestern Arizona and southern California are characterized by Precambrian basement and display unequivocal BR type isotopic systematics. The lead data in these areas possessing Precambrian outcrops and BR leads appear to be identical to data from areas without a known Precambrian crystalline basement - the coastal areas of California and the Great Basin of Nevada.

A third difference between the two models, shown in Figure 4.20, occurs over the nature of leads from southern Nevada. Zartman classified this region as an Area I area. The discriminant function discussed in the previous section concurred that leads from this area should be assigned to the CP population. However, as discussed in Section 4.5, the leads from this area show properties not typical of CP type data. Consequently, it is this report's opinion that the leads from southern Nevada belong to neither the CP-Area I or BR-Area II type systematics, but should be regarded as belonging to a separate southern Nevada (SN) lead province.

The differences between Zartman's and this report's descriptions of lead provinces in the southwestern United States can be rationalized in several ways. For instance, Zartman's work is based at least partially on ore leads and Mesozoic, generally granitic, igneous rocks, while this work is based wholely on data from late Cenozoic volcanic, generally basaltic, rocks. Basaltic volcanic rocks are most likely to be derived from mantle source regions and probably experience in many cases little interaction with crustal rocks. Consequently, basalt leads would be likely to reflect characteristics of source regions in the mantle. On the other hand, mineralization associated with ores often involves considerable interaction with crustal rocks and meteoric waters. Consequently, ore leads might be expected to display in some form the characteristics of the local crust. Having a galena from a Basin and Range area with a Precambrian basement with Type I lead isotopes might indeed be compatible with a nearby basalt having BR characteristics. The ore might be recording crustal characteristics while the basalt might be reflecting properties of the underlying mantle.

It is also plausible that the great Mesozoic granitic batholiths of the western United States were derived from different source regions than the late Cenozoic basalts. Their different chemical and mineralogic properties could reflect different modes of petrogenesis. In addition, major changes in the style of igneous activity and tectonism have developed since the Mesozoic, and it is conceivable that these changes were reflected in changes in the igneous rock source regions. Modifications of source region characteristics in time might well be mirrored in modifications of the lead isotopic characteristics of the derivative igneous rocks.

Divergences between the two lead province descriptions might also be attributed to deficiencies in the coverage provided by available data. For example, Zartman's limited data in southern California and Arizona make location of his province boundaries difficult in this area. Similarly, the current lack of data in critical areas of the Pacific Northwest makes this work's suggested BR-CP boundary there highly conjectural. Zartman's establishment of a separate lead province in northern Nevada (Area II) could conceivably be the result of his extrapolation of the lead characteristics of a local area around Corte , Nevada to a much larger region. The few ore leads reported by Zartman for areas west and south of Cortez appear to be comparable with this work's rock leads from the same area. More analyses of both rocks and ores would certainly clarify the situation. It might be noted, however, that the distribution of Zartman's data allows him to separate his Area I into two parts: Area Ia with $\sim$2.7 by isochron ages, and Area Ib with secondary isochron ages $\leq$1.8 by. Lack of data prohibits this report from making that distinction on the basis of basalt leads. It can be seen, however, that Leeman's data on the Snake River Plain is consistent with Area Ia behavior, while samples from the southwestern Colorado Plateau have leads that are consistent with Area Ib systematics.

It is also notable that this work's explanation for the occurrence of lead provinces in the Southwest is different than the model proposed by Zartman. The two models will be discussed in later sections.

CHAPTER 5: INTERPRETATION OF COLORADO PLATEAU TYPE LEAD ISOTOPIC DATA

5.1 Overview

The intent of this chapter is to interpret the lead isotopic data on late Cenozoic volcanic rocks from the southwestern Colorado Plateau in light of observations on their petrologic and chemical characteristics, and to examine constraints on petrogenetic models for these volcanic rocks from the isotopic data.

5.2 Location and History of Colorado Plateau Volcanism

Cenozoic volcanism has been extensive along the margins of the Colorado Plateau, but only sparse volcanic activity has occurred deep within the Plateau's interior. The earliest volcanism marginal to the Plateau was Oligocene in age and calc-alkaline in nature. The San Juan volcanic field in southwestern Colorado, the Marysvale area in central Utah, and the Mogollon-Datil volcanic province of southwestern New Mexico were important localities for this mid-Tertiary andesitic to rhyolitic volcanism (see Figure 1.2 for the geographic localities of these and other volcanic fields mentioned in the text). In comparison, late Cenozoic volcanism associated with the Colorado Plateau has been dominantly basaltic in nature. The Mt. Taylor volcanic field of west-central New Mexico, the White Mountains of eastern Arizona, the San Francisco and Mt. Floyd volcanic fields of north-central Arizona, the western Colorado Plateau field of northwestern Arizona and southwestern Utah, and the High Plains and Black Rock desert areas of central Utah all include areas of abundant late Cenozoic basaltic volcanism. In addition to basalts, the San Francisco Peaks, Mount Taylor, and the Jemez Mountains include substantial amounts of young, intermediate to silicic volcanics. Although each of these areas is deserving of careful, detailed study, the bulk of the data presented in this report comes from late Cenozoic volcanic rocks of the southwestern Colorado Plateau, especially the areas around St. George, Utah, and Flagstaff, Arizona. Consequently, the following discussions emphasize the volcanism found in this limited portion of the Plateau.

5.3 Petrology of Basaltic Rocks from the Southwestern Colorado Plateau

A number of workers have studied the petrologic characteristics of volcanic rocks from different areas of the southwestern Colorado Plateau. Included among these are Robinson (1913), Moore *et al.* (1976), Best and Brimhall (1974), Lowder (1973), Hausel and Nash (1977), and McKee and Anderson (1971). Although their observations are uniformly apropos, each of these authors have described and categorized their samples using different terminologies. Moore *et al.* (1976), for example, distinguished three types of basalts (alkali olivine basalt, high alumina basalt, and basaltic andesite) for the San Francisco volcanic field, while Best and Brimhall (1974) divided the basaltic rocks near St. George, Utah into seven categories (hawaiite, basanite, alkali olivine basalt, ankaramite, sodic hawaiite, basaltic andesite, and analcime hawaiite). This diversity in terminology has tended to hinder comparisons between the volcanism of different areas.

In order to more easily compare and categorize basaltic rocks from the different volcanic fields of the southwestern Colorado Plateau, this author has found it useful to borrow from and to modify, in some instances, classification schemes from a number of different sources, including several of the papers listed above. The petrographic and chemical attributes of Colorado Plateau basaltic rocks have each been characterized according to different schemes, although the results of both schemes are correlative.

5.3.1. Petrographic description of Colorado Plateau basalts

A preliminary attempt was made to apply the classical petrographic descriptions of Kuno (1960) for Japanese basalts to the mafic volcanics of the Colorado Plateau. This attempt did not meet with great success. Kuno used the presence or absence of olivine reaction rims, plagioclase compositions, the occurrence of titanaugite, and the appearance of alkali feldspar or silica minerals as late crystallizing ground mass phases to classify basalts as alkali basalts, high alumina basalts, or tholeiites. No obvious olivine reaction rims have been observed in any Colorado Plateau basaltic rocks, even those with substantial (> 10%) quantities of normative hypersthene, or those in which olivine and orthopyroxene are found together in the groundmass. In addition, no systematic variations in plagioclase compositions have become apparent during the course of this study, although the common, extensive zoning of plagioclase and the relatively inaccurate optical methods for measuring An contents utilized here might possibly have obscured significant differences. The An content of basalt plagioclases appears to fall consistently in the range An50 to An65, with only a few exceptions. Furthermore, titanaugite appears to be very rare in Colorado Plateau basalts (only two of the more than forty Colorado Plateau basalts examined here appear to contain titanaugite), although alkaline basalts with normative nepheline are not uncommon. Moreover, mesostasis silica phases and alkali feldspars have often proved difficult to positively identify in thin section, especially in basalts which are fine-grained or which contain interstitial, often opaque glass. It is difficult, therefore, to classify many Colorado Plateau basalts as either alkaline or subalkaline solely on petrographic grounds.

It is possible, however, to differentiate between the more mafic and the felsic basalts, a distinction that might plausibly separate the relatively "primitive" basalts from those that are more "differentiated." Consequently, this report has somewhat modified the characterizations of Moore _et_ _al_. (1976) and divided the continuum of Colorado Plateau basalts into three broad groups: olivine-augite basalts, feldspathic basalts, and basaltic andesites. Olivine-augite (OA) basalts have high color indices, contain a total modal content of olivine and clinopyroxene of $\sim$35% or more, and possess abundant olivine phenocrysts. Calcium-rich clinopyroxene is commonly found only in the groundmass, where it is plentiful. OA basalts do not, by definition, contain orthopyroxene or calcium-poor clinopyroxene, or phenocrysts of plagioclase. Many olivine-augite basalts have subophitic textures - an indication of the abundance of clinopyroxene relative to feldspar in the groundmass. In contrast, feldspathic basalts often have trachytic or pilotaxitic textures, reflecting an abundance of groundmass plagioclase. Feldspathic basalts always contain at least 40% modal plagioclase, and occasionally have plagioclase modes up to 60%. Feldspathic basalts commonly contain olivine phenocrysts but they are usually smaller and considerably less abundant than those in OA basalts. Plagioclase phenocrysts occur with some frequency in feldspathic basalts, and orthopyroxene or calcium-poor clinopyroxene may be present (usually as groundmass phases) with or without groundmass olivine or augite. Basaltic andesites are generally similar to feldspathic basalts in their petrographic characteristics, but contain reacting quartz and "wormy" plagioclase megacrysts. "Wormy" plagioclases appear to be oligoclase-andesine crystals (Best and Brimhall, 1974) containing minute glass and oxide inclusions - giving them their mottled, black and white sieve-like texture. These plagioclase megacrysts are often embayed. The quartz megacrysts found in basaltic andesites are typically rounded, embayed, and rimmed by clinopyroxene coronas.

All three types of basaltic rocks (olivine-augite basalt, feldspathic basalt, and basaltic andesite) have been observed in every volcanic field where more than a few samples were taken (see Appendix E). No special characteristics appear to distinguish the basalts of any particular area. These observations suggest that the mafic volcanics are essentially similar in every area of the southwestern

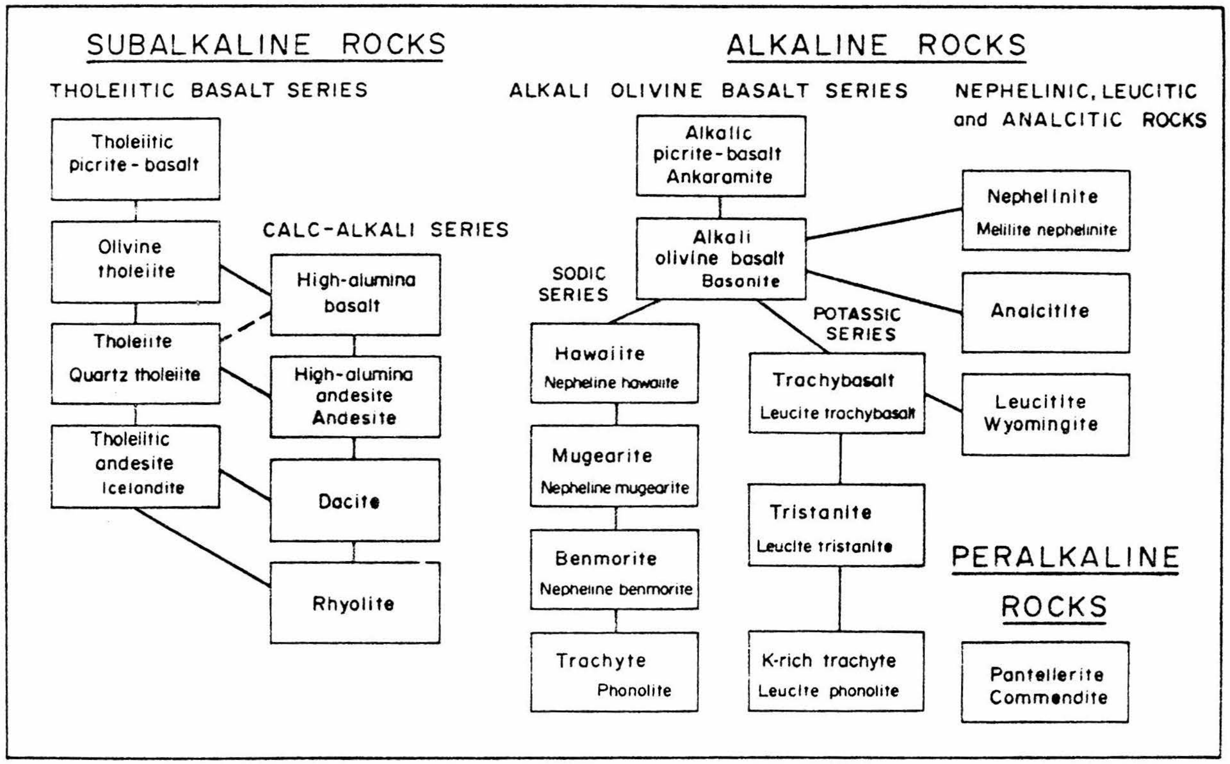
Colorado Plateau, despite the different terminologies used by different workers in different volcanic fields.

It is interesting to note, however, that not every Colorado Plateau volcanic field contains the same intermediate and silicic volcanic rock types. For example, the area around St. George, Utah seems to lack both intermediate and silicic volcanics (Hamblin and Best, 1975), while the White Mountain volcanic field contains some rhyolitic rocks (Merrill and Pewe, 1977). The San Francisco volcanic field contains basalts, andesites, dacites and rhyolites (Robinson, 1913; Moore *et al.*, 1976).

5.3.2. Chemical description of Colorado Plateau basalts

Chemical analyses were available for the majority of samples collected for isotopic study from the southwestern Colorado Plateau (see data in Appendix E). However, many of these chemical analyses came from published sources, and it was not always possible to confirm that chemical and lead isotopic samples came from exactly the same outcrop or even the same flow. Nonetheless, published petrographic and chemical descriptions have appeared to be consistent with the petrographic characteristics of the matched lead isotopic samples in every case.

The algorithm proposed by Irvine and Baragar (1971), which sorts chemical data into the categories diagramatically shown in Figure 5.1, has been used to characterize and to categorize the chemical attributes of Colorado Plateau volcanic samples. The results of this classification



General classification scheme for the common volcanic rocks. The lines joining boxes serve to outline common associations. The rocks indicated by small print within the boxes are variants of the main rock.

Figure 5.1

procedure are displayed in Table 5.1. Despite the small number of rocks involved, several inferences can be drawn from this table.

Table 5.1 shows that both subalkaline and alkaline volcanic rocks are present on the Colorado Plateau. Some samples have obviously alkaline or subalkaline chemistries. For example, A6021 has ~13% normative nepheline and A4028 has ~5% normative quartz (see Appendix E). However a larger number are considerably less extreme in their characteristics - having, for example, less than 3% normative nepheline, or with hypersthene, diopside, and olivine together in the norm. The abundance of these intermediate or transitionally subalkaline to alkaline rocks might explain why clear-cut alkaline or subalkaline characteristics (e.g., olivine reaction rims or titanaugite) are usually not well developed in thin section. It might also be mentioned that these observations are compatible with the conclusions of several authors (e.g., McKee and Anderson, 1971; Lowder, 1973; Wenrich-Verbeek, 1974; and Hausel and Nash, 1977) who have emphasized the transitional calc-alkalic (or tholeiitic) to alkalic nature of southwestern Colorado Plateau volcanism.

Table 5.1 confirms that the same types of basalts are present in every volcanic field on the southwestern Colorado Plateau. Each area has relatively mafic and relatively silicic basalts, alkaline and subalkaline rock types, and basaltic andesites. This suggests that the mafic volcanic rocks from every field on the southwestern Colorado Plateau are essentially similar in their chemical characteristics, and that it is appropriate to group data from different Colorado Plateau areas together in the arguments presented in the following sections.

Table 5.1.

Sample No.	Chemical Classification			Petrographic Classification
	Type	Series	Name	
San Francisco volcanic field				
A4029	subalkaline	tholeiitic	olivine tholeiite	OA basalt
A4030	subalkaline	calc-alkalic	andesite	basaltic andesite
A4031	alkaline	sodic	hawaiite	feldspathic basalt
A5014	subalkaline	calc-alkalic	andesite	basaltic andesite
A6014	alkaline	sodic	hawaiite	feldspathic basalt
A6015	subalkaline	calc-alkalic	rhyolite	rhyolite
A6018	subalkaline	calc-alkalic	dacite	dacite vitrophere
A6021	alkaline	sodic	basanitoid	OA basalt
A6022	subalkaline	calc-alkalic	high alumina basalt	feldspathic basalt
A6023	alkaline	sodic	alkali olivine basalt	OA basalt
A6053	subalkaline	calc-alkalic	andesite	feldspathic basalt
A6054	subalkaline	calc-alkalic	dacite	glassy dacite
A6058	subalkaline	calc-alkalic	andesite	feldspathic basalt
St. George area				
U5016	alkalic	sodic	hawaiite	basaltic andesite
U5017	alkalic	sodic	hawaiite	feldspathic basalt
A6030	alkaline	sodic	hawaiite	feldspathic basalt
A6031	alkaline	sodic	ankaramite	OA basalt

Table 5.1 (continued)

Sample No.	Chemical Classification Type	Series	Name	Petrographic Classification
U6032	subalkaline	calc-alkalic	high alumina basalt	feldspathic basalt
Tonto Section* (of Hayes, 1969)				
A4027	alkalic	sodic	alkali olivine basalt	OA basalt
A4028	subalkaline	tholeiite	quartz tholeiite	feldspathic basalt
A6025	subalkaline	calc-alkalic	high alumina basalt	feldspathic basalt?
A6026	subalkaline	calc-alkalic	andesite	basaltic andesite
A6063	alkaline	sodic	alkali olivine basalt	olivine-augite basalt
A6064	alkaline	sodic	olivine tholeiite	OA basalt
White Mountains				
A4033	subalkaline	calc-alkalic	high alumina basalt	basaltic andesite
A6060	alkaline	sodic	alkali olivine basalt	OA basalt?
A6062	alkaline	sodic	alkali olivine basalt	OA basalt

*The Tonto Section, as defined by Hayes (1969), is the mountainous area on the southwestern side of the Colorado Plateau between the physiographic boundary and what is commonly considered the structural boundary of the Plateau.

Table 5.1 and Appendix E also indicate that there is a correlation between the chemical and petrographic properties of Colorado Plateau volcanic rocks. Appendix E shows that olivine-augite basalts have relatively low SiO_2 concentrations ($\leq$50%), Al_2O_3 concentrations from 14 to 16%, Na_2O+K_2O usually $\leq$4.5% and average MgO contents somewhere around 8.5%. Feldspathic basalts, on the other hand, usually have SiO_2 contents between 50 and 54%, Al_2O_3 concentrations sometimes as high as 18%, Na_2O+K_2O concentrations typically $\geq$4.5%, and average MgO concentrations around 6.3%. Basaltic andesites show a wide range in SiO_2 contents from 51-59%; Al_2O_3 values are usually around 15-16%, Na_2O+K_2O contents are usually about 6%, as are MgO concentrations.

In addition, Table 5.1 indicates that olivine-augite basalts correspond to relatively mafic, "undifferentiated" volcanic rocks: basanite, ankaramite, alkali olivine basalt, and olivine tholeiite. Basalts petrographically labelled as feldspathic may represent somewhat more "differentiated" categories. Those feldspathic basalts lacking orthopyroxene are categorized as hawaiites (alkaline, sodic series). Those with orthopyroxene in the mode were variously classified as quartz tholeiite, high alumina basalt and (mafic) andesite. Three basaltic andesites were called andesite by the Irvine and Baragar classification scheme. Another was alkaline enough to be called a hawaiite, and a fourth was poor enough in silica to be called a high alumina basalt.

It is also interesting to note from Table 5.1 that the alkaline volcanics from the southwestern Colorado Plateau seem to belong to the sodic series. In contrast some basalts from the nearby Basin and Range province have potassic chemistries (refer to Chapter 6).

5.4 Interpretation of α-β Diagrams

One distinctive feature of the Colorado Plateau lead data set is that it generates linear arrays on a $^{206}Pb/^{204}Pb$ (α) versus $^{207}Pb/^{204}Pb$ (β) diagram (see Figure 4.8 and 4.10). Two models may be called on to explain this behavior. First, the linear arrays on the α-β diagram can be interpreted to be secondary isochrons. This model assumes: 1) the Colorado Plateau volcanics have been derived from a system that was originally homogeneous in its lead isotopic composition at some time T; 2) at time T this system chemically fractionated into a number of subsystems having different μ values; and, 3) since T each subsystem has evolved separately as a closed system to its own, distinctive isotopic composition. In this model the slope of the regression line through the Colorado Plateau α-β data can be used to calculate the differentiation age, T.

The alternate hypothesis is that the linear arrays on the $^{206}Pb/^{204}Pb$-$^{207}Pb/^{204}Pb$ diagram are mixing lines. Here, for example, it might be assumed that pristine magma from an isotopically homogeneous reservoir is contaminated with isotopically distinct material in transit to the earth's surface. In this case the position of a data point on the α-β diagram can be taken to be a measure of the amount of foreign lead added to the original magma.

There is one circumstance where the conclusions of both models may be valid simultaneously. This circumstance occurs when the leads of two systems with different μ values but having the same history (the same initial isotopic composition and differentiation age, T) are mixed. The slope of the mixing line is then the same as that of the secondary isochron of age T, and the isotopic ratios of each sample are measures of the degree of mixing taking place.

5.5 Plausibility of the Secondary Isochron Model

The secondary isochron model is not directly amenable to being independently tested. However the ages implied by the isochron model appear to be geologically reasonable. The St. George isochron indicates a 1600 ±130 my age for the source region generating volcanic rocks in that area, while the Flagstaff-Prescott isochron implies a 1500 ±130 my age. For comparison Silver and others (1977) have recorded three major episodes of Precambrian igneous activity in the southwestern Colorado Plateau - one from 1700 to 1740 my bp, another from 1610-1700 my bp, and a third 1410-1465 my ago. Thus, the secondary isochron ages implied by the Colorado Plateau basalt lead data fall within a period of major igneous activity associated with the formation of the oldest Precambrian crystalline basement in the southwestern United States. It is reasonable to hypothesize that the inferred Precambrian chemical fractionation of the Colorado Plateau basalt source regions relates in some way to the generation of Precambrian granitic rocks and to the differentiation of continental lithosphere.

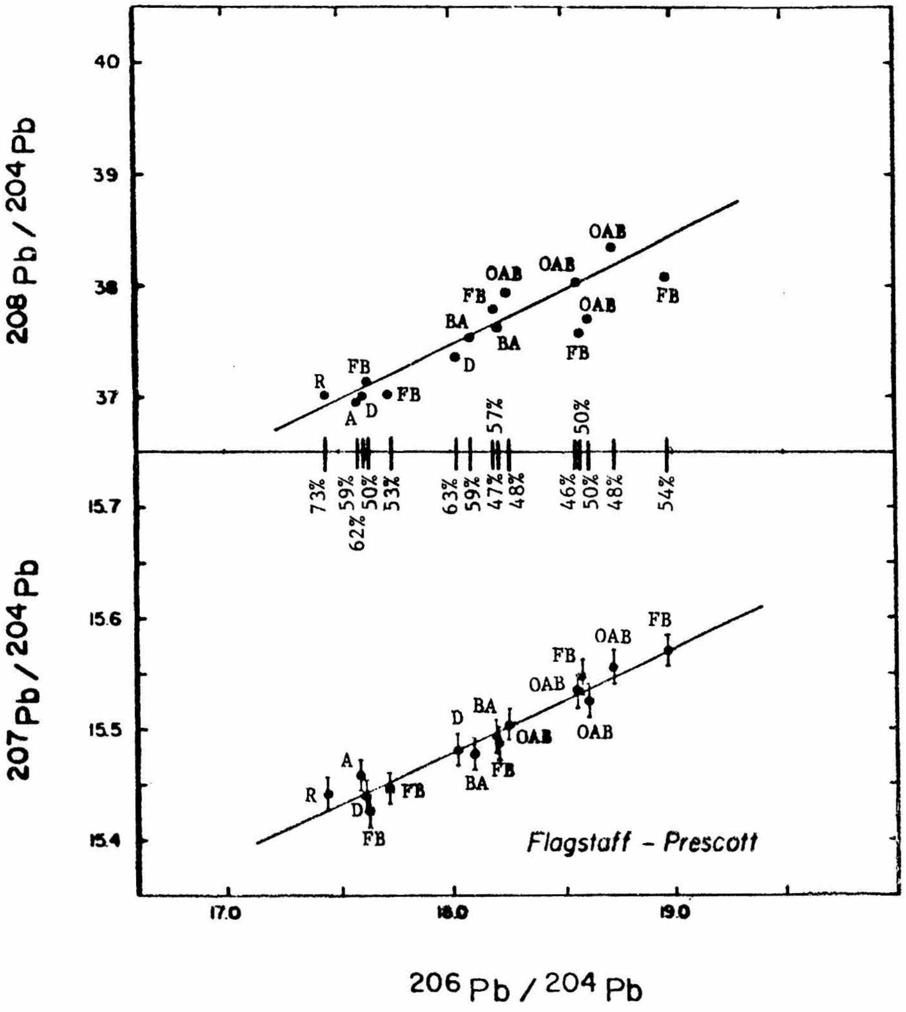
Even if mixing, or contamination, is an important petrogenetic process, there are considerations which suggest that the calculated secondary isochron ages may still be meaningful numbers. In each local area of the southwestern Colorado Plateau (e.g., the San Francisco volcanic field) α-β data appear to lie on a single straight line within analytical error. On the Colorado Plateau as a whole data points seem to fall on one of two very similar lines. This restricts potential mixing end-members to an extremely limited portion of the α-β diagram. It is difficult to understand how two unrelated mixing components could be so restricted in their isotopic compositions over an area as large as the southwestern Colorado Plateau (some 400,000 km^2). One obvious way of getting mixing components with acceptably limited isotopic compositions over a region of such a size is to derive them from two systems with the same history - the same age of origin. In such a circumstance the implied isochron age may still be a valid reflection of the age of the system.

5.6 Testing the Simple Mixing Model

Mixing models used to interpret the Colorado Plateau α-β diagrams are potentially testable. The following sections examine what constraints can be placed on the chemical and isotopic compositions of potential mixing components, and attempt to estimate what fraction of "contaminating" material is required to make up the various volcanic rock types. The aim here is to examine the likelihood that contamination is an active petrogenetic process on the Colorado Plateau, and to

Figure 5.2: $^{206}Pb/^{204}Pb$ - $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ - $^{208}Pb/^{204}Pb$ diagrams for the San Francisco volcanic field, showing rock type and silica content of each sample. OAB = olivine augite basalt; FB = feldspathic basalt; BA = basaltic andesite; A = andesite; D = dacite; and R = rhyolite. Silica contents are shown on the shared boundary between the two diagrams. Silica concentrations are in weight percent. Refer to Appendix E for chemical data sources.

Figure 5.2


208 Pb / 204 Pb
40
39
38
37
R
FB
A
D
FB
BA
D
FB
OAB
BA
OAB
OAB
OAB
FB
FB
57%
50%
73%
59%
62%
50%
53%
63%
59%
47%
48%
46%
50%
48%
54%
207 Pb / 204 Pb
15.7
15.6
15.5
15.4
A
R
D
FB
FB
D
BA
BA
FB
OAB
OAB
FB
OAB
OAB
FB
Flagstaff - Prescott
17.0
18.0
19.0
206 Pb / 204 Pb

investigate where in the crust or mantle volcanic source materials might reside.

Simple mixing of two well-defined components requires that there be a regular correlation between the chemical and isotopic properties of the resulting mixture. As Figure 5.2 shows, this does not seem to be the case for data from the San Francisco volcanic field. The rocks with the most extreme isotopic properties are not consistently those with the most extreme chemical compositions. For example, several of the more silicic rocks (an andesite, a dacite, and a rhyolite) from one area of the volcanic field have extremely unradiogenic leads (e.g., $^{206}Pb/^{204}Pb \simeq 17.6$) but so does a basaltic rock from the same area. Thus, volcanic rocks with different chemical compositions can have the same isotopic compositions. Furthermore, an andesite and a dacite from another area have leads ($^{206}Pb/^{204}Pb = 18.1$) which are just about average for the field. Thus rocks with similar chemical compositions can have different isotopic compositions. This is most dramatically seen in Figure 5.2 for the feldspathic basalts (FB), which are rather uniform in their chemical compositions but which virtually span the whole range of leads observed in the San Francisco volcanic field. These considerations would seem to argue against simple mixing. Either the mixing process is more complex, with a number of components of different chemical and different but related isotopic compositions participating; or mixing is not the only active petrogenetic process, but acts together with other processes, such as crystal fractionation, to produce the observed range of chemical and isotopic properties; or mixing is not an important petrogenetic process. It is not yet possible to conclusively select one of these three alternatives. It is possible, however, to place some constraints on the various components which might potentially participate in a complex mixing process.

5.7 Olivine-Augite Basalts and Upper Crustal Contaminants

The occurrence of voluminous basaltic volcanism on the Colorado Plateau suggests that one of the components in a hypothetical mixing system must be derived from the mantle. The olivine-augite basalts, especially the ankaramites and basanitoids, should closely approximate this mantle-derived component. Their low silica contents (≤46% for ankaramite and basanitoid samples) would seem to preclude significant sialic contamination. The low $^{87}Sr/^{86}Sr$ ratios (.7030-.7040) reported for these basalts by Leeman (1974) and Brookins and Moore (1975) are also consistent with a derivation from the mantle.

Figure 5.3 shows that, as a group, the OA basalts are relatively radiogenic in lead but exhibit a fairly wide range in isotopic composition. $^{206}Pb/^{204}Pb$ ratios for these basalts run from approximately 18.3 to 19.3. The other volcanic rocks from the Plateau - the feldspathic basalts, basaltic andesites, dacites, and rhyolites - generally tend to be less radiogenic and more silicic than the olivine-augite basalts (although they do overlap the OA basalt range of isotopic compositions). For example, one feldspathic basalt from the St. George area (U6032) has $^{206}Pb/^{204}Pb = 16.98$, $^{207}Pb/^{204}Pb = 15.40$, and $^{208}Pb/^{204}Pb = 36.54$ -

Figure 5.3: $^{206}Pb/^{204}Pb$ ratios for the rocks in each of the different petrographic categories used to describe volcanics from the southwestern Colorado Plateau. Open circles indicate especially mafic olivine-augite basalts. The open square is a rather unique feldspathic basalt; it is the only basaltic sample that has hypersthene phenocrysts and the only one which is quartz normative. It is also older (mid Miocene) than most of the other volcanics sampled from the western Plateau.

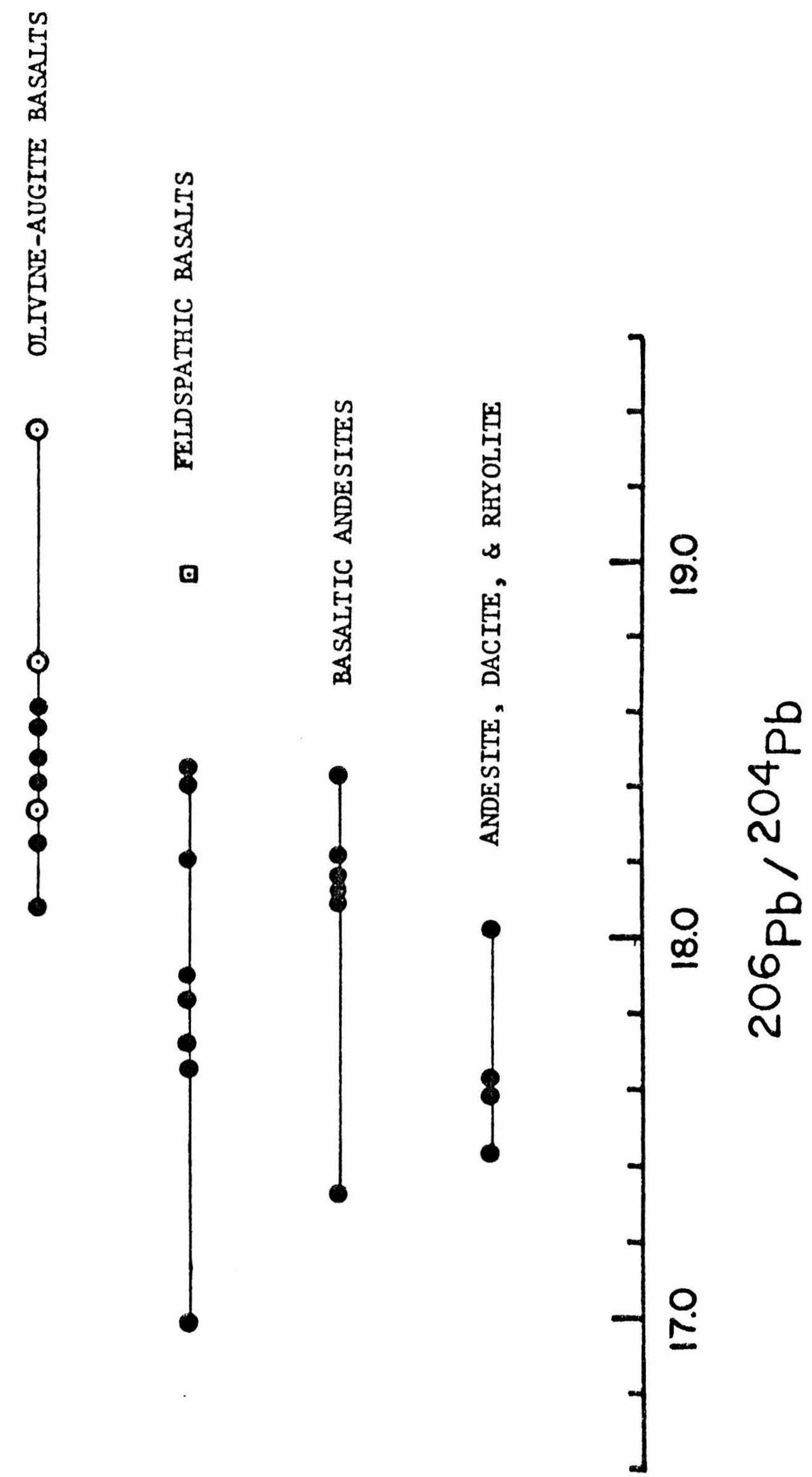

OLIVINE-AUGITE BASALTS
FELDSPATHIC BASALTS
BASALTIC ANDESITES
ANDESITE, DACITE, & RHYOLITE
17.0
18.0
19.0
$^{206}Pb/^{204}Pb$

Figure 5.3

values dramatically below those of any OA basalt. And while the OA basalts have SiO_2 ≤50 weight percent, the other Colorado Plateau volcanics have SiO_2 contents ranging from 47% to 73%. Making these "differentiated" magmas by contaminating mantle derived melts requires a contaminant which is both silica rich and unradiogenic compared to the OA basalts, and to the contaminated lavas themselves.

This restriction prohibits almost all upper crustal crystalline rocks from participating in the contamination process. Precambrian granites, rhyolites, and gneisses from the area around the Colorado Plateau are generally silicic but also tend to be radiogenic in their lead isotopic compositions. Whole rock analyses by Ludwig (1974) and Silver (personal communication) indicate that these crystalline rocks almost always have $^{206}Pb/^{204}Pb$ ratios greater than 18.0, typically greater than 19.0, and occasionally as high as 27.0 (see Figure 5.10). It is difficult to conceive of a process in which generally radiogenic basement rocks contaminate relatively radiogenic mantle-derived melts to generate unradiogenic mixtures. Upper crustal Phanerozoic sedimentary rocks are also unlikely candidates as contaminants, a conclusion supported by their rare, sporadic occurrence as inclusions in mafic lavas.

5.8 Lower Crustal Rocks as Potential Participants in Petrogenesis

Discarding the hypothesis that upper crustal rocks have contaminated mantle-derived melts leaves two possible explanations for the Colorado Plateau lead isotopic data. Either the linear α-β arrays defined by Colorado Plateau data are the result of lower crustal materials mixing with mantle-derived magmas, or the isotopic properties of each volcanic rock directly reflect the characteristics of its source region in the mantle or, possibly, the lower crust.

5.8.1. Possible lower crustal xenocrysts in the basaltic andesites

There are several lines of evidence pertinent to a discussion of the alternatives mentioned above. One involves the interpretation of phenocryst-sized quartz and alkali feldspar crystals which are observed to be in disequilibrium with their host basaltic andesites. Some authors (Best and Brimhall, 1974; Leeman, 1974; Hausel and Nash, 1977; Jones *et al.*, 1974; Laughlin *et al.*, 1974; and Nichols *et al.*, 1971) have concluded that these partially resorbed crystals are high pressure phenocrysts which have become unstable at lower pressures. Others, notably Doe *et al.* (1969) and Lipman *et al.* (1978), have argued that these quartz and feldspar crystals are xenocrysts derived from lower crustal "granitic" rocks, concluding that basalts with xenocrysts are contaminated while those without them are primitive. Those writers favoring no contamination generally cite strontium isotopic evidence (e.g., low $^{87}Sr/^{86}Sr$ ratios compatible with mantle derivation and comparable to ratios of non-xenocrystic basalts) and experimental studies (Cohen *et al.*, 1967; Green and Ringwood, 1968) to support their conclusions. On the other side of the question, Doe *et al.* (1969) present lead isotopic data suggestive of contamination. They report correlations between higher Pb, U, and Th concentrations, less radiogenic Pb isotopic compositions, and greater abundance of "xenocrysts." They also observed that "xenocryst" and groundmass plagioclase separates from a single rock are significantly different in their lead isotopic compositions, an observation difficult to explain without invoking a contamination model of some sort.

Proponents on both sides of this contamination/no contamination argument assume the xenocryst-free rocks are uncontaminated while xenocrystic rocks are potentially contaminated. Lead data from the southwestern Colorado Plateau volcanic rocks do not appear to support an isotopic distinction between xenocrystic basaltic andesites and feldspathic basalts, which lack xenocrysts. As Figure 5.3 shows, basaltic andesites are commonly less radiogenic than the seemingly primitive, non-xenocrystic OA basalts, in agreement with the Doe et al. (1969) data. However, the unxenocrystic feldspathic basalts are commonly less radiogenic than the basaltic andesites. Thus, the presence of xenocrysts does not in itself seem to be definitive about whether or not a rock sample will have an especially unradiogenic lead, and by implication, whether or not the sample is contaminated.

5.8.2. Geochemical data bearing on the origin of the feldspathic basalts and more silicic volcanic rocks from the Colorado Plateau

Figures 5.4 through 5.9 review geochemical evidence relevant to the contamination question. In each of these diagrams contamination (mixing) would be expressed as a correlation between the Y-coordinate ($^{206}Pb/^{204}Pb$ or $^{87}Sr/^{86}Sr$) and the X-coordinate (SiO_2, K_2O, MgO, Pb, or Sr concentration, or $^{206}Pb/^{204}Pb$). The slope of the correlation depends on the chemical and isotopic composition of the two mixing components, and the scatter of the ordinate and abscissa data would be a measure of the heterogeneity of these two end-members. On the other hand, chemical differentiation (for example, by crystal fractionation) would give rise to a horizontal trend on each of these diagrams - isotopic composition would not change in response to changed concentrations of the chemical components.

Figure 5.4 , 5.5 , and 5.6 suggest that there is an apparently significant but obviously rough correlation between the chemical and isotopic compositions of volcanic rocks from the southwestern Colorado Plateau. Figure 5.4 indicates that the olivine augite basalts generally tend to be poorer in SiO_2 and more radiogenic in lead than the other volcanic rocks. Figure 5.5 suggests that the OA basalts tend to be richer in MgO than the other Colorado Plateau volcanics. Figure 5.6 indicates that OA basalts have K_2O concentrations overlapping those of other rock types, but which are in general lower than many of the other types of volcanic samples. In each of these diagrams, the feldspathic basalts are seen to nearly span the total range of $^{206}Pb/^{204}Pb$, without any obvious correlation between isotope ratio and chemical concentration. The basaltic andesites and the more silicic volcanic rocks, on the other hand, may tend to display a somewhat more limited range of $^{206}Pb/^{204}Pb$, and to have leads that are more or less intermediate in

Figure 5.4: SiO_2 concentrations and $^{206}Pb/^{204}Pb$ ratios of late Cenozoic volcanics from the southwestern Colorado Plateau. Circles are olivine-augite basalts. Diamonds are feldspathic basalts. Squares are basaltic andesite, and triangles are andesite, dacite, and rhyolite samples. Lines joining two data points indicate these two samples were derived from the same volcanic vent. Long, heavy dashes surround the OA basalt data points. Short, light dashes indicate the field in which feldspathic basalt data points lie. Sources for the chemical data are listed in Appendix E.

Figure 5.4

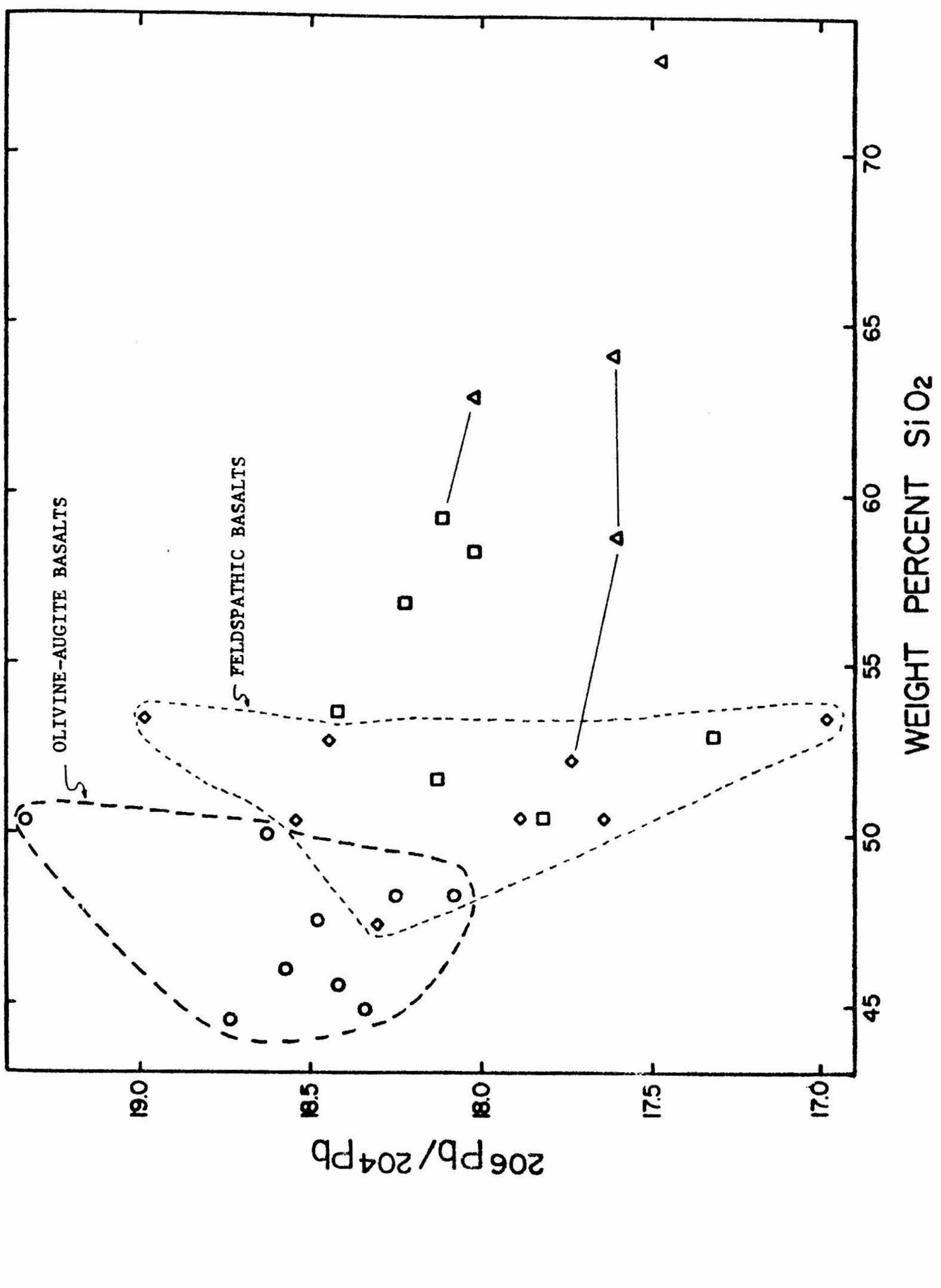

OLIVINE-AUGITE BASALTS
FELDSPATHIC BASALTS
45
50
55
60
65
70
WEIGHT PERCENT SiO_2
19.0
18.5
18.0
17.5
17.0
$^{206}Pb/^{204}Pb$

Figure 5.5: MgO concentrations and $^{206}Pb/^{204}Pb$ ratios of late Cenozoic volcanic rocks from the southwestern Colorado Plateau. Symbols are the same as those used in Figure 5.4. Long, heavy dashes outline the OA basalt data field. Short, light dashes indicate the dimensions of the feldspathic basalt data field. Data points joined by a line indicate samples coming from the same volcanic vent.

Figure 5.5

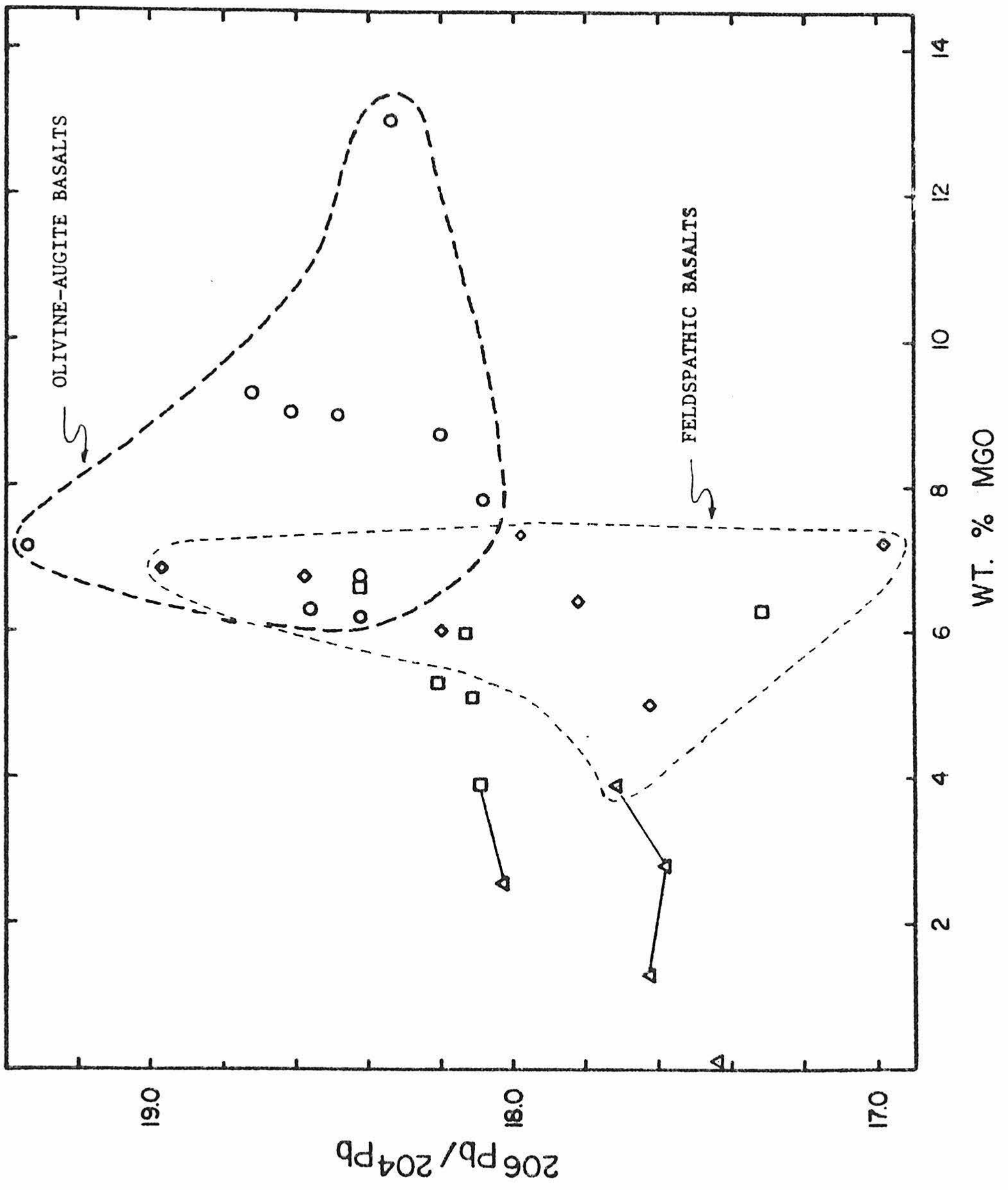
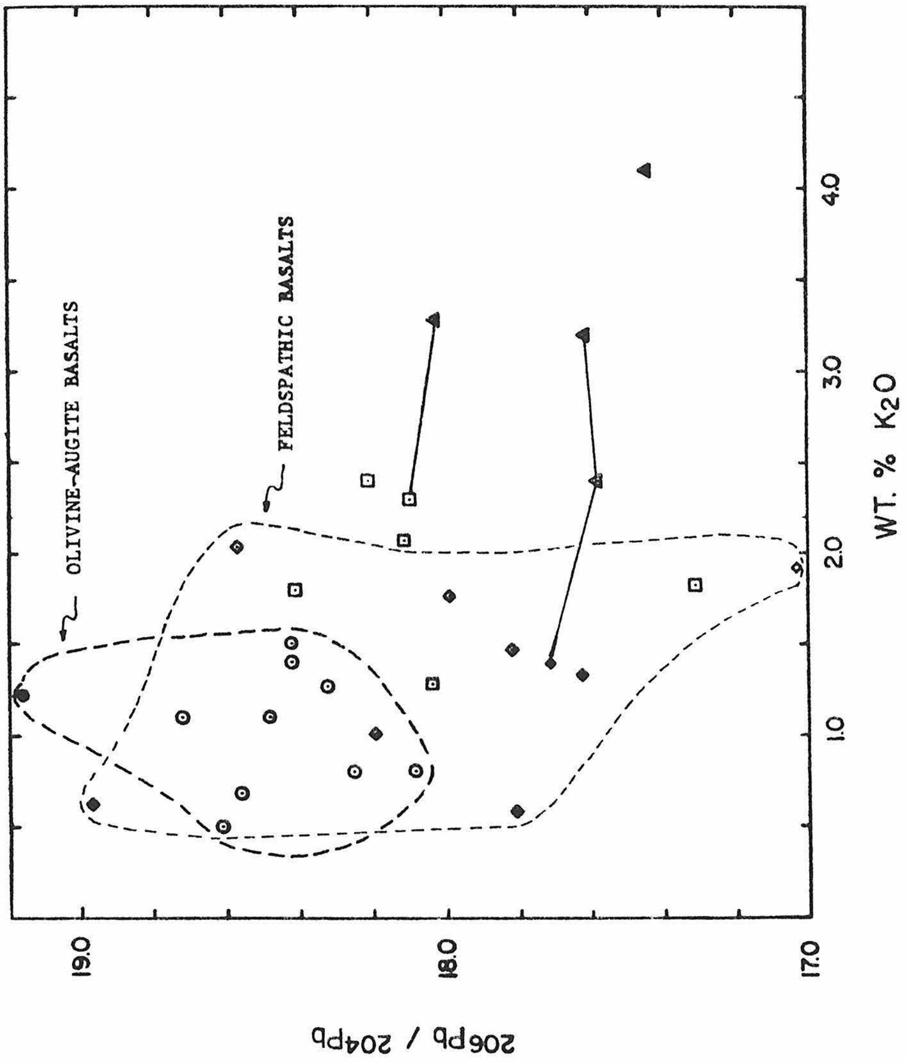

OLIVINE-AUGITE BASALTS
FELDSPATHIC BASALTS
2
4
6
8
10
12
14
WT. % MGO
19.0
18.0
17.0
206Pb/204Pb

Figure 5.6: K_2O concentrations and $^{206}Pb/^{204}Pb$ ratios of late Cenozoic volcanic rocks from the southwestern Colorado Plateau. Symbols are the same as those used in Figure 5.4. Line segments joining two data points indicate that both samples came from the same volcanic vent. Long, heavy dashes outline the OA basalt data field, and short, light dashes outline the feldspathic basalt data field.

Figure 5.6


OLIVINE-AUGITE BASALTS
FELDSPATHIC BASALTS
1.0
2.0
3.0
4.0
WT. % K$_2$O
19.0
18.0
17.0
206Pb / 204Pb

isotopic composition. It can also be noted that rocks coming from the same volcanic vent seem to have similar isotopic compositions despite major differences in chemical composition.

Figure 5.7 shows that the Pb concentrations of volcanic rocks from the southwestern Colorado Plateau range from 2-11 ppm, with the basaltic andesites having the higher Pb concentrations and OA basalts having lower Pb concentrations. The feldspathic basalts appear to have both high and low Pb concentrations, as they have high and low $^{206}Pb/^{204}Pb$ ratios. This diagram suggests a correlation between Pb concentration and isotopic composition. Unfortunately, it is not clear if this correlation would be confirmed should a greater number of data points be available.

Figure 5.8 shows that the Sr concentrations of Colorado Plateau volcanic rocks range from approximately 300 ppm to over 1000 ppm, and that there is considerable overlap in concentration between the more mafic rocks, the basanites and alkali olivine basalts, and the other rock types. $^{87}Sr/^{86}Sr$ ratios range from .7026 to .7069, although all but one of the thirty-three data points have $^{87}Sr/^{86}Sr \leq .7050$. This range in $^{87}Sr/^{86}Sr$ is similar to that exhibited by oceanic basalt samples (Peterman and Hedge, 1971). There does not appear to be a significant correlation between the $^{87}Sr/^{86}Sr$ ratio and strontium concentration. It is perhaps worth special note that the three andesite, dacite, and rhyolite samples have $^{87}Sr/^{86}Sr$ ratios comparable to those of the basalts.

Figure 5.7: Pb concentration and $^{206}Pb/^{204}Pb$ data on late Cenozoic volcanic rocks from the southwestern United States. OAB = olivine augite basalt; FB = feldspathic basalt; BA = basaltic andesite; A = andesite.

Figure 5.7

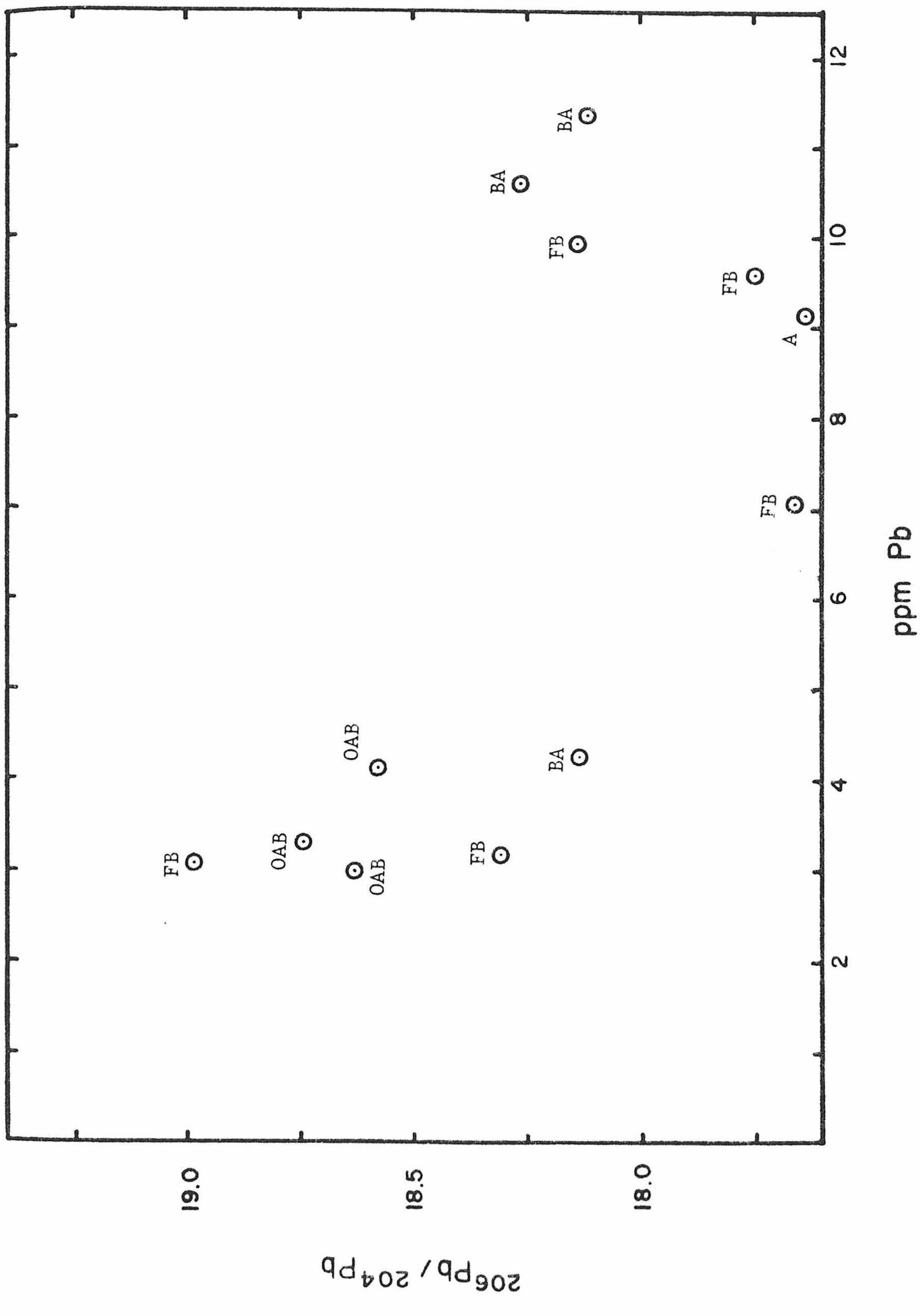

FB
OAB
OAB
OAB
FB
BA
FB
A
FB
FB
BA
BA
19.0
18.5
18.0
$^{206}Pb/^{204}Pb$
2
4
6
8
10
12
ppm Pb

Figure 5.8: Published Sr concentrations and $^{87}Sr/^{86}Sr$ ratios on late Cenozoic volcanic rocks from the southwestern Colorado Plateau. Circles indicate data points from Leeman (1974) on St. George area volcanic rocks. Squares indicate data points from Brookins and Moore (1975) on volcanics from the San Francisco volcanic field. Data on a variety of rock types have been plotted, including basanite and ankaramite (B), alkali olivine basalts (AOB), hawaiites (H), high alumina basalt (HAB), basaltic andesite (BA), andesite (A), dacite (D), and rhyodacite (R). Names shown on the diagram are as they are given in the published sources.

Figure 5.8

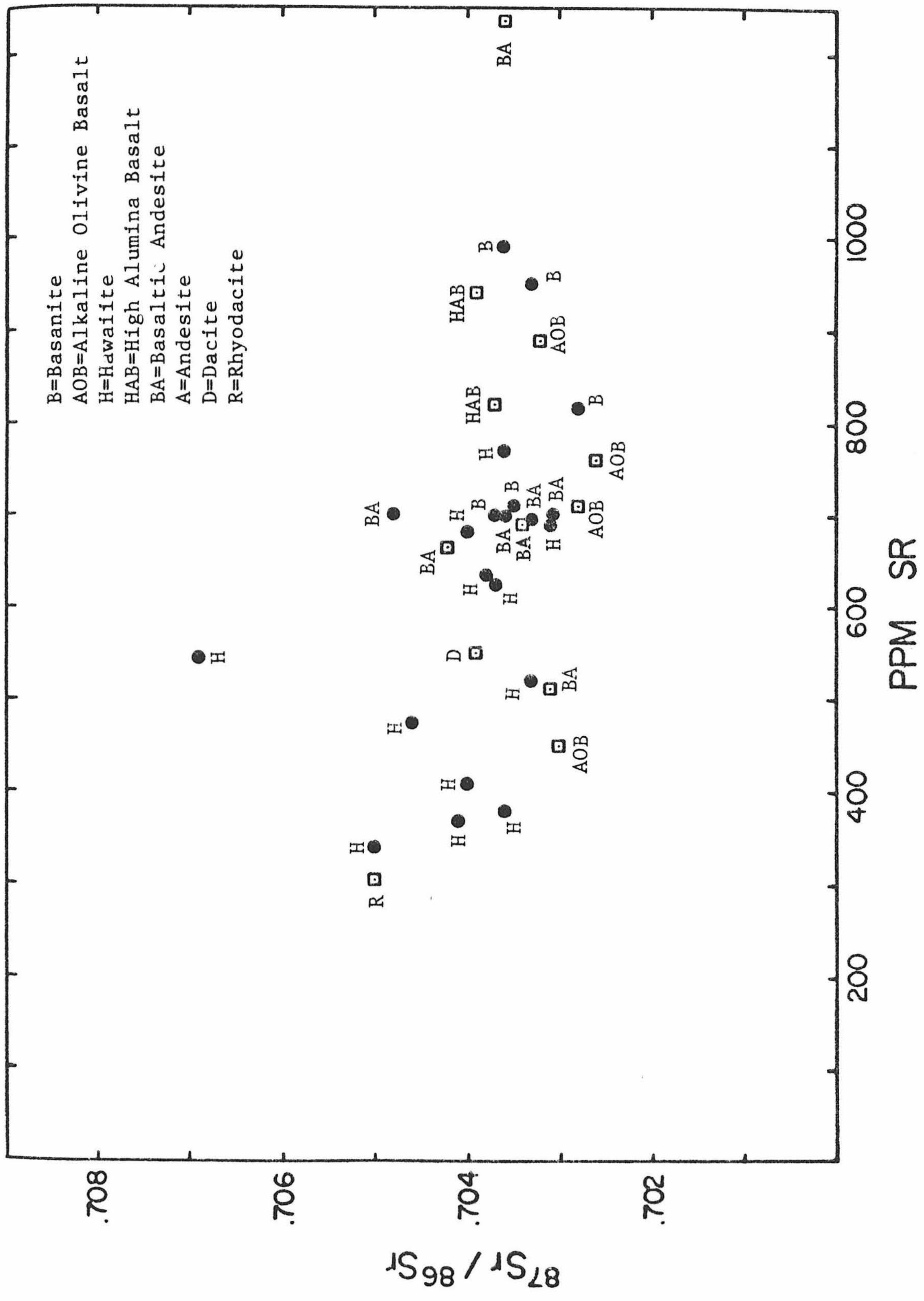

B=Basanite
AOB=Alkaline Olivine Basalt
H=Hawaiite
HAB=High Alumina Basalt
BA=Basaltic Andesite
A=Andesite
D=Dacite
R=Rhyodacite
200
400
600
800
1000
PPM SR
.708
.706
.704
.702
$^{87}Sr / ^{86}Sr$

Figure 5.9: $^{206}Pb/^{204}Pb$ data from this report and published $^{87}Sr/^{86}Sr$ data on late Cenozoic basaltic rocks from the southwestern Colorado Plateau. Circles represent samples from the San Francisco volcanic field (Sr data from Brookins and Moore, 1975). Squares indicate samples from the area near St. George, Utah (Sr data from Leeman, 1974) and from the Black Rock desert of Utah (Sr data point from Pushkar and Condie, 1973). Pb and Sr data were not obtained on exactly the same sample. Pb and Sr samples from the San Francisco volcanic field were usually obtained from exactly the same outcrop locality. Correlations between Pb and Sr samples from the St. George area are generally less well documented. Numbers represent Sr concentrations in ppm. OAB = olivine augite basalt; FB = feldspathic basalt; BA = basaltic andesite; A = andesite; D = dacite.

Figure 5.9

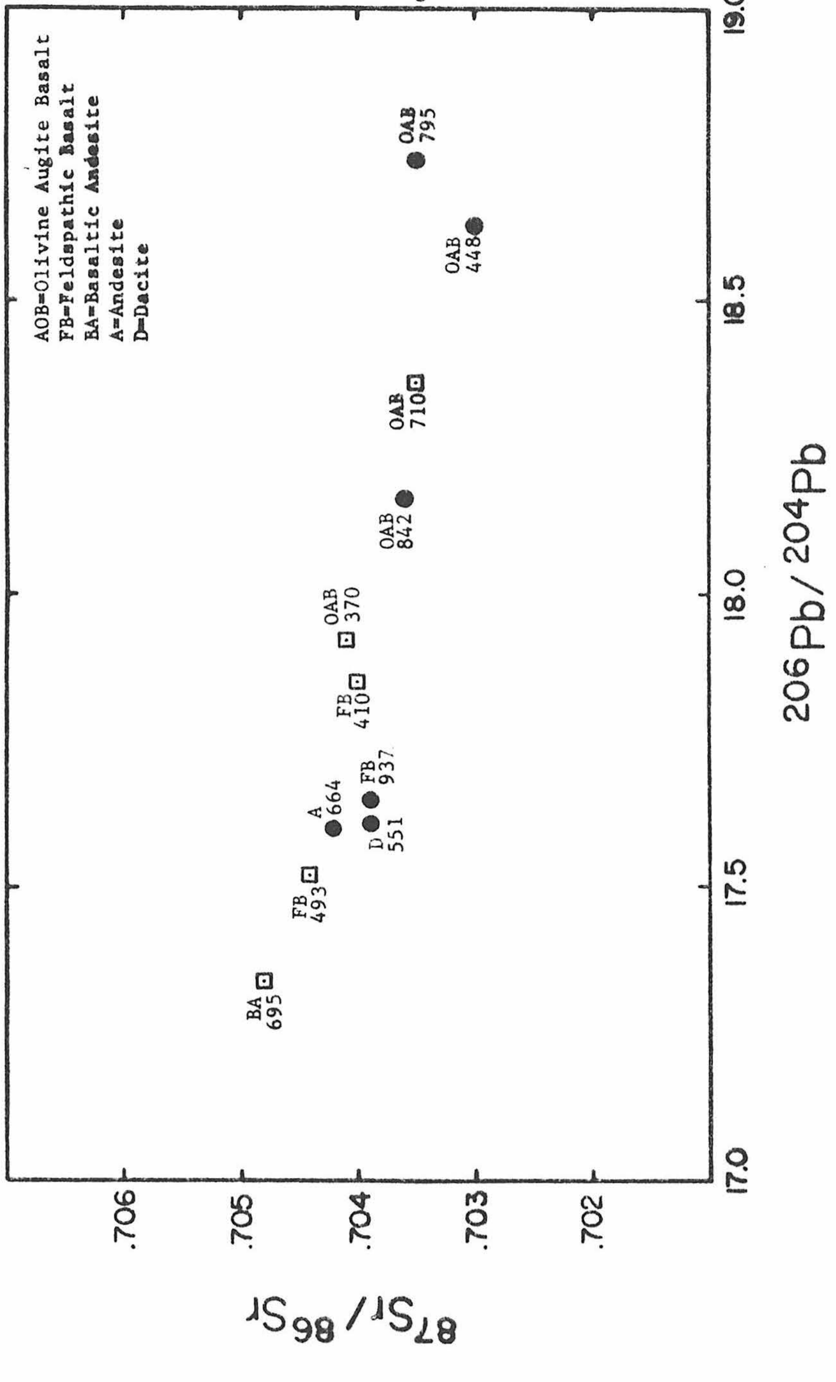

AOB=Olivine Augite Basalt
FB=Feldspathic Basalt
BA=Basaltic Andesite
A=Andesite
D=Dacite
OAB 795
OAB 448
OAB 710
OAB 842
OAB 370
FB 410
FB 937
A 664
D 551
FB 493
BA 695
17.0
17.5
18.0
18.5
19.0
$^{206}Pb/^{204}Pb$
.706
.705
.704
.703
.702
$^{87}Sr/^{86}Sr$

Figure 5.9 appears to indicate that there is an inverse correlation between $^{206}Pb/^{204}Pb$ and $^{87}Sr/^{86}Sr$ for Colorado Plateau rocks. However, it might be noted there does not appear to be any systematic difference in the strontium concentrations of high $^{206}Pb/^{204}Pb$ and low $^{87}Sr/^{86}Sr$ rocks compared to low $^{206}Pb/^{204}Pb$ and high $^{87}Sr/^{86}Sr$ rocks.

The patterns expressed in these five figures might conceivably be interpreted in three ways:

(1) Mantle derived melts have been mixed with a chemically heterogeneous (but isotopically restricted) second component. This component would generally be higher in SiO_2, K_2O, and Pb concentrations, but lower in MgO. It would be less radiogenic in lead but more radiogenic in Sr than the mantle-derived magmas. Feldspathic basalts would be contaminated with relatively mafic material, while andesites, dacites and rhyolites would be contaminated with more felsic material.

(2) Contamination processes have produced the feldspathic basalts and perhaps the basaltic andesites from magmas originally of OA basalt composition. However, the more silicic volcanic rocks were derived from contaminated basaltic rocks by a differentiation process like crystal fractionation;

(3) Feldspathic basalts and basaltic andesites are derived from different source regions than the OA basalts. Feldspathic sources have generally lower μ values than the OA sources, and consequently give rise to basalts less radiogenic in lead. On the other hand, the feldspathic basalt sources would have higher Rb/Sr ratios, which would be consistent with their slightly higher $^{87}Sr/^{86}Sr$ ratios. The chemical

differences between the two rock types might be attributed to chemical differences in source rock, or different conditions of partial melting or crystal fractionation. The more silicic volcanics have been derived from basaltic magmas by chemical differentiation.

In discussing these three alternative models let us first consider whether or not the intermediate and silicic volcanic rocks of the southwestern Colorado Plateau are generated by a mixing process or a differentiation process such as crystal fractionation. In this regard it should be noted that chemical considerations place strong constraints on the amount and composition of the mixing component that can be added to an olivine-augite basalt to make an andesite, dacitic, or rhyolitic mixture. For example, the high SiO_2 content (73%) of the only rhyolite analyzed in this report would indicate that the OA basalt component ($\leq$50% SiO_2) makes up a very small fraction of the rock. The silicic mixing component must then closely resemble the rock itself. This also seems true for andesite and dacite samples. Tables 5.2 and 5.3 show the results of two calculations determining the chemical and isotopic compositions of possible contaminants which could be added to an olivine-augite basalt (samples A6021 or A6023 in these calculations) to produce a mixture like A6053, an andesite from Humphreys Peak. Both calculations indicate that the major fraction of the andesite mixture ($\sim$80%) must be made up of the silicic "contaminant." If the olivine-augite basalt component makes up as much as 40% of the mixture, the MgO concentration of the silicic end-member must be less than zero. This is clearly unreasonable. Because the silicic mixing end-member is

Table 5.2. Mixing calculation[1]

	OA Basalt Endmember	Contaminated Rock	Contaminating Component[2]			
Sample No.	A6021	A6053	F = 0.8	F = 0.6	F = 0.4	F = 0.2
$^{87}Sr/^{86}Sr$[3]	.7035	.7042	.7044	.7048	.7060	.7201
$^{206}Pb/^{204}Pb$	18.721	17.582	17.50	17.39	17.27	17.13
$^{207}Pb/^{204}Pb$	15.555	15.458	15.45	15.44	15.43	15.41
$^{208}Pb/^{204}Pb$	38.351	36.945	36.837	36.71	36.57	36.39
SiO_2[4]	44.6	58.78	62.3	68.2	80.05	$\underline{111.5}$
TiO_2	2.34	1.36	1.12	.71	$\underline{-.11}$	$\underline{-2.56}$
Al_2O_3	14.8	16.9	17.4	18.3	20.05	25.3
FeO	11.2	6.35	5.76	3.95	.33	$\underline{-10.55}$
MgO	9.23	2.75	1.13	$\underline{-1.57}$	$\underline{-6.97}$	$\underline{-23.17}$
CaO	11.59	5.28	3.70	1.07	$\underline{-4.19}$	$\underline{-19.96}$
Na_2O	3.59	5.1	5.48	6.10	7.37	11.4
K_2O	1.1	2.38	2.7	3.23	4.3	7.5
Rb[3]	<20	<20	--	--	--	--
Sr[3]	759	644	631	577	468	140
Pb	3.33	9.06	10.5	12.9	17.7	32.0
U	1.29	1.67	1.77	1.92	2.24	3.19
Th	4.25	4.58	4.66	4.8	5.075	5.9

Table 5.2 (continued)

	OA Basalt Endmember	Contaminated Rock	Contaminating Component[2]			
Sample No.	A6021	A6053	F = 0.8	F = 0.6	F = 0.4	F = 0.2
$^{232}\text{Th}/^{238}\text{U}$[5]	3.40	2.83	2.73	2.57	2.34	1.91
$^{238}\text{U}/^{204}\text{Pb}$[5]	24.6	11.3	10.3	9.10	7.71	6.03
κ[6]	3.97	3.81	3.79	3.76	3.72	3.66
μ[6]	10.6	6.29	5.96	5.57	5.12	4.57

[1] Underlining emphasizes calculated data which are unlikely or impossible for a real contaminant.

[2] F is the weight fraction of contaminant.

[3] Sr and Rb data have been taken from Brookins and Moore (1975).

[4] Sources for chemical data are listed in Appendix E.

[5] Measured values in rock samples.

[6] Calculated from lead isotope ratios (see Section 5.9).

Table 5.3. Mixing calculation[1]

	OA Basalt Endmember	Contaminated Rock	Contaminating Component[2]			
Sample No.	A6023	A6053	F = 0.8	F = 0.6	F = 0.4	F = 0.3
$^{87}Sr/^{86}Sr$[3]	.7035	.7042	.7042	.7049	.7064	.7097
$^{206}Pb/^{204}Pb$	18.248	15.582	17.53	17.47	17.40	17.35
$^{207}Pb/^{204}Pb$	15.504	15.458	15.45	15.45	15.44	15.44
$^{208}Pb/^{204}Pb$	37.934	36.945	36.864	36.77	36.67	36.61
SiO_2[4]	48.2	58.78	61.42	65.83	74.65	83.46
TiO_2	1.91	1.36	1.22	.99	.54	.076
Al_2O_3	14.4	16.9	17.53	18.57	20.65	22.73
FeO	10.78	6.85	5.87	4.23	.96	-2.32
MgO	8.7	2.75	1.26	-1.22	-6.17	-11.3
CaO	10.3	5.28	4.02	1.93	-2.25	-6.43
Na_2O	3.3	5.1	5.6	6.3	7.8	9.3
K_2O	.8	2.38	2.78	3.43	4.75	6.06
Rb[3]	<20	<20	--	--	--	--
Sr[3]	842	664	620	545	397	248
Pb	3.33[5]	9.06	10.5	12.9	17.65	22.43
U	1.29[5]	1.67	1.77	1.92	2.24	2.55

Table 5.3 (continued)

	OA Basalt Endmember	Contaminated Rock	Contaminating Component[2]			
Sample No.	A6023	A6053	F = 0.8	F = 0.6	F = 0.4	F = 0.2
Th	4.25[5]	4.58	4.66	4.8	5.07	5.35
$^{232}\mathrm{Th}/^{238}\mathrm{U}$	3.40	2.83	2.73	2.57	2.34	2.16
$^{238}\mathrm{U}/^{204}\mathrm{Pb}$[6]	24.34	1.31	10.3	9.12	7.73	6.94
κ[7]	4.16	3.81	3.77	3.72	3.65	3.61
μ[7]	8.83	6.29	6.09	5.86	5.59	5.43

[1] Underlining emphasizes calculated data which are unlikely or impossible for a real contaminant.

[2] F is weight fraction of contaminant.

[3] Strontium and rubidium data have been taken from Brookins and Moore (1975).

[4] Sources for sample chemical data are referenced in Appendix E.

[5] Rb, U and Th concentrations were assumed for this particular sample.

[6] Measured values in rock samples.

[7] Calculated from lead isotope ratios (see Section 5.9).

(apparently) required to make up the major portion of the mixture, the composition of this end-member remains remarkably like that of the andesitic mixture. For example, SiO_2 = 59% for the andesite and 62% for the calculated silicic mixing component. Similarly the silicic end-member has an $^{87}Sr/^{86}Sr$ ratio much like that of the andesite (.7044 versus .7042), as well as lead isotope ratios not much different from those measured in the andesite.

Although the calculations in Tables 5.2 and 5.3 involve only one andesite and two olivine-augite basalt samples, similar results are obtained for every intermediate sample for which chemical data are available. In each case the chemical and isotopic properties of the silicic mixing component seem required to closely resemble that of the mixture, the intermediate rock itself. Because the intermediate volcanics of the southwestern Colorado Plateau have different chemical and isotopic compositions, this seems to require a different silicic mixing end-member for each sample. Although this is possible, it does not make mixing a necessary or very attractive process for producing andesitic and other silicic volcanic rocks of the Colorado Plateau.

On the other hand, available data appear to be consistent with the idea that silicic lavas are made by a process like crystal fractionation. For instance, incompatible elements like Pb, U, and Th are enriched relative to the OA basalts in the more felsic volcanics of the Plateau - as would be expected in crystal fractionation. It is also interesting that the μ values calculated from the lead isotopic ratios of the more silicic volcanics (assuming appropriate initial lead ratios as calculated in Section 5.9) are substantially less than the $^{208}U/^{204}Pb$ ratios actually measured in the rocks themselves. For the A6053 sample in Table 5.2 the calculated μ value is 6.1 while the measured $^{238}U/^{204}Pb$ is 10.6, almost twice the calculated μ. Similarly the calculated κ value (3.8) appears to be significantly different from the $^{232}Th/^{238}Ph$ ratio actually measured in this sample (2.8). These observations suggest that trace elements in the andesite have been fractionated relative to a (presumably more mafic) source, perhaps by a process like partial melting or crystal fractionation.

There are additional lines of evidence that are consistent with this conclusion. For example, the curved trends that Colorado Plateau volcanics describe on variation diagrams (Moore _et al._, 1976) also suggest that a differentiation process like crystal fractionation rather than mixing is involved in the genesis of the more evolved volcanics of the Colorado Plateau. Crystal fractionation also seems to be consistent with the available lead isotopic evidence. For every silicic volcanic there appears to be a basaltic rock (often a feldspathic basalt) with equivalent lead ratios. This is true for the Colorado Plateau data as a whole, and for data from individual volcanic vents. For example, a basaltic andesite (A5014) from Strawberry Crater has a very similar isotopic composition to a dacite vitrophyre (A6018) from the same cinder cone. Similarly, three samples from Humphreys Peak in the San Francisco volcanic field (A6053, an andesite; A6054, a dacite; and A6058, a high alumina basalt) display a wide range in petrologic and chemical characteristics, but a very narrow range in lead isotopic composition (see Figures 5.4, 5.5, and 5.6). These results would appear to imply a consanguinity between rocks deriving from the same volcanic vent, even though they may have erupted tens of thousands of years apart and are very different in their chemical compositions. The chemical diversity and isotopic similarity of volcanic rocks coming from the same locality would be consistent with the generation of intermediate rocks by fractional crystallization, quite possibly from a parent magma similar to a feldspathic basalt.

It also appears unlikely that a contamination process is directly responsible for generating the feldspathic basalts of the southwestern Colorado Plateau. The feldspathic basalts nearly span the total range of lead isotope compositions observed for Colorado Plateau volcanics, but do not, as a group, show any clear-cut correlation between their chemical and isotopic compositions (see Figures 5.4-5.6). For example, the most radiogenic feldspathic basalt (and the second most radiogenic sample on the southwestern Colorado Plateau) is also the most silica rich with 53.8% SiO_2. The least radiogenic feldspathic basalt, which is also the least radiogenic Colorado Plateau sample, is the one next richest in silica with 53.5% SiO_2. These observations would tend to discourage the idea that contamination plays a major part in the petrogenesis of the feldspathic basalts.

If contamination were involved in feldspathic basalt genesis, it appears that the contaminating material would tend to have chemical and isotopic properties similar to those of the feldspathic basalt itself. Say, for instance, that some contaminating material is being added to an olivine-augite basalt magma to make a feldspathic basalt mixture. Because the feldspathic and OA basalts both have basaltic chemistries, the mixing component also tends to have a basaltic nature. Mixing a 1:1 mixture of OA basalt (with 47% SiO_2) with a contaminant to make a feldspathic basalt (with 51% SiO_2) requires that the contaminant has only 55% SiO_2. Similarly, feldspathic basalts in general seem to have $^{87}Sr/^{86}Sr$ ratios rather like those of their more mafic basaltic counterparts, as well as Sr concentrations usually similar to and sometimes higher than OA basalt Sr contents. For example, Leeman (1974) gave an average $^{87}Sr/^{86}Sr$ of .7035 for the hawaiites and .7039 for the basanites of the St. George area; hawaiite strontium concentrations average ∿600 ppm for the hawaiites and ∿800 ppm for the basanitoids. As a consequence of these similarities, the strontium isotopic composition of a calculated mixing component would tend to bear a close resemblance to that of the feldspathic basalt. In addition, the Pb concentrations of feldspathic basalts tend to be higher than those of the OA basalts, often by a factor of 2 or 3 (see Figure 5.7). Thus even a small fraction of contaminant contributes a relatively larger proportion of lead to a feldspathic basalt "mixture." The lead isotopic composition of the feldspathic basalt, therefore, tends to approximate that of the contaminant.

The mixing calculations shown in Tables 5.4, 5.5, and 5.6 were performed to get a more quantitative estimate of the chemical and

Table 5.4. Mixing model[1]

	OA Basalt Endmember	Contaminated Rock	Contaminating Component[2]			
Sample No.	A6021	A6022	F = 0.8	F = 0.6	F = 0.4	F = 0.2
$^{87}Sr/^{86}Sr^3$	.7035	.7039	.7040	.7041	.7043	.7047
$^{206}Pb/^{204}Pb$	18.721	17.625	17.51	17.38	17.21	16.99
$^{207}Pb/^{204}Pb$	15.555	15.426	15.41	15.40	15.38	15.35
$^{208}Pb/^{204}Pb$	38.351	37.132	37.01	36.86	36.67	36.43
$SiO_2{}^4$	44.6	50.5	52.0	54.4	59.4	74.1
TiO_2	2.34	1.64	1.47	1.17	.59	-1.2
Al_2O_3	14.8	18.3	19.2	20.6	23.6	32.3
FeO	11.12	9.43	9.00	8.30	6.90	2.7
MgO	9.23	5.1	4.1	2.3	-1.1	-11.4
CaO	11.59	8.1	7.2	5.8	2.9	-5.9
Na_2O	3.59	3.9	4.0	4.1	4.4	5.1
K_2O	1.10	1.3	1.35	1.4	1.6	2.1
Rb^3	<20	<20	--	--	--	--
Sr^3	795	937	973	1032	1150	1505
Pb	3.33	7.03	7.96	9.50	12.6	21.8
U	1.29	1.24	1.23	1.21	1.17	1.04

Table 5.4 (continued)

	0A Basalt Endmember	Contaminated Rock	Contaminating Component[2]			
Sample No.	A6021	A6022	F = 0.8	F = 0.6	F = 0.4	F = 0.2
Th	4.25	4.71	4.83	5.02	5.4	6.55
$^{232}\text{Th}/^{238}\text{U}$[5]	3.40	3.92	4.06	4.30	4.79	5.77
$^{238}\text{U}/^{204}\text{Pb}$	24.65	20.85	9.46	7.76	5.62	3.63
κ[6]	3.97	4.09	4.11	4.14	4.18	4.24
μ[6]	10.64	6.45	6.03	5.52	4.87	4.26

[1] Calculated data believed to be unlikely for reasonable contaminating materials are underlined.

[2] F = the weight fraction of the mixture contributed by the contaminant.

[3] Strontium and rubidium data are from Brookins and Moore (1975).

[4] References for chemical data are cited in Appendix E.

[5] These numbers refer to values calculated from isotope dilution measurements of U, Th, and Pb concentrations.

[6] These values were calculated from Pb isotope ratios.

Table 5.5. Mixing model[1]

	OA Basalt Endmember	Contaminated Rock	Contaminating Component			
Sample No.	A4029	A6022	F = 0.8	F = 0.6	F = 0.4	F = 0.2
$^{87}Sr/^{86}Sr$	.7030	.7039	.7040	.7041	.7043	.7045
$^{206}Pb/^{204}Pb$	18.608	17.625	17.54	17.43	17.30	17.14
$^{207}Pb/^{204}Pb$	15.525	15.426	15.42	15.41	15.39	15.38
$^{208}Pb/^{204}Pb$	37.699	37.132	37.08	37.02	36.94	36.85
SiO_2	50.0	50.5	50.6	50.8	51.3	52.5
TiO_2	1.27	1.64	1.73	1.89	2.20	3.12
Al_2O_3	15.6	18.3	19.0	20.1	22.4	29.1
FeO	10.77	9.43	9.1	8.5	7.4	4.08
MgO	9.0	5.1	4.1	2.5	-.8	-10.5
CaO	9.6	8.1	7.7	7.1	5.9	2.1
Na_2O	2.9	3.9	4.2	4.6	5.4	7.9
K_2O	.5	1.3	1.5	1.8	2.5	4.5
Rb	<20	0	--	--	--	--
Sr	448	937	1059	1263	1671	2893
Pb	2.98	7.03	8.04	9.73	13.1	23.2
U	.47	1.24	1.43	1.75	2.40	4.3

Table 5.5 (continued)

	OA Basalt Endmember	Contaminated Rock	Contaminating Component			
Sample No.	A4029	A6022	F = 0.8	F = 0.6	F = 0.4	F = 0.2
Th	2.17	4.71	5.35	6.40	8.52	14.9
$^{232}Th/^{238}U$	4.77	3.92	3.86	3.77	3.68	3.56
$^{238}U/^{204}Pb$	9.93	10.85	10.94	11.04	11.16	11.31
κ	3.31	4.09	4.20	4.36	4.59	4.95
μ	10.21	6.45	6.11	5.71	5.21	4.59

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[1] See footnotes for Table 5.4.

Table 5.6. Mixing model[1]

	OA Basalt Endmember	Contaminated Rock	Contaminating Component			
Sample No.	A6023	A6022	F = 0.8	F = 0.6	F = 0.4	F = 0.2
$^{87}Sr/^{86}Sr$	.7035	.7039	.7040	.7041	.7044	.7049
$^{206}Pb/^{204}Pb$	18.248	17.625	17.56	17.48	17.38	17.26
$^{207}Pb/^{204}Pb$	15.504	15.426	15.42	15.41	15.40	15.38
$^{208}Pb/^{204}Pb$	37.934	37.132	37.050	36.95	36.82	36.66
SiO_2	48.2	50.5	51.1	52.0	54.0	59.7
TiO_2	1.91	1.64	1.57	1.46	1.24	.56
Al_2O_3	14.4	18.3	19.3	20.9	24.2	33.9
FeO	10.78	9.43	9.09	8.53	7.41	4.03
MgO	8.7	5.1	4.2	2.7	-.3	-9.03
CaO	10.3	8.1	7.6	6.63	4.8	-.7
Na_2O	3.3	3.9	4.1	4.3	4.8	6.3
K_2O	.8	1.3	1.4	1.63	2.05	3.3
Rb	<20	0	--	--	--	--
Sr	842	937	960	1000	1080	1317
Pb	3.33	7.03	7.96	9.50	12.6	21.8
U	1.29	1.24	1.23	1.21	1.17	1.04

Table 5.6 (continued)

	OA Basalt Endmember	Contaminated Rock	Contaminating Component			
Sample No.	A6023	A6022	F = 0.8	F = 0.6	F = 0.4	F = 0.2
Th	4.25	4.71	4.83	5.02	5.4	6.55
$^{232}Th/^{238}U$	3.40	3.92	4.06	4.29	4.79	6.51
$^{238}U/^{204}Pb$	24.34	10.85	9.47	7.78	5.65	2.90
κ	4.17	4.09	4.08	4.06	4.04	4.01
μ	8.83	6.45	6.21	5.41	5.54	5.05

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[1] See footnotes for Table 5.4.

isotopic properties of contaminants that might potentially be involved in making feldspathic basalts. It was found that chemical constraints (low MgO and high Al_2O_3) seemed to prohibit small amounts (<40% of the mixture) of contaminant from being involved in the mixing process. As expected the chemical and isotopic characteristics calculated for plausible contaminants did not diverge greatly from those actually measured in the feldspathic basalt itself. This is an important finding in considering what sources in the mantle or crust the contaminating material used to make feldspathic basalts could be derived from. Any contaminating material used in the petrogenesis of the feldspathic basalts could be derived from basically the same source as that directly generating the feldspathic basalts themselves.

5.8.3. Lower crustal source regions

Lower crustal material could potentially participate in the petrogenesis of Colorado Plateau volcanic rocks either as a contaminant, or as a primary source material for these volcanics. The previous section indicated that contamination does not appear to be an especially attractive model for generating either the feldspathic basalts or the more silicic volcanic rocks of the Colorado Plateau. Even if contamination did occur it would seem that the contaminating material would tend to have a chemical and isotopic composition rather similar to those of the "mixed" rock itself. Thus, possible primary volcanic sources would seem to be similar to sources of possible contaminating material - there seems little to be gained by considering primary volcanic source regions and contaminant source regions separately.

As far as chemical constraints are concerned, feldspathic basalts could derive from a source rock of basaltic composition if a large percentage of partial melting were taking place, or from a more mafic (even ultramafic) source if a lesser percentage of partial melting was occurring. Thus a mantle derivation of these rocks seems consistent with their chemical compositions. However, a study of xenoliths from a Colorado Plateau kimberlite (McGetchin and Silver, 1972) presents evidence that "the middle and lower crust consists of amphibolite and granulite grade metamorphic rocks, mostly high grade meta-gabbroic gneisses." The generally mafic nature of the Colorado Plateau lower crust would seem to allow the lower crust to be a possible source region for feldspathic basalts, at least as far as major element chemistry is concerned.

It is difficult to check if the isotopic characteristics of the feldspathic basalts and the more silicic volcanics are consistent with a derivation from the lower crust. No investigations of the isotopic properties of lower crustal material have been published for the Colorado Plateau region, or for any region in the western United States. It is only possible to surmise the geochemical characteristics of the Colorado Plateau lower crust from published work on high grade metamorphic rocks (i.e., granulites) from other areas.

Studies by Moorbath _et al_. (1969) and Gray and Oversby (1972) indicate that rocks in high grade metamorphic terrains are depleted in U and Th relative to lead. Gray reports $^{238}U/^{204}Pb$ ratios between 0.2 and 1.2 for granulite facies rocks from Australia. Moorbath _et al_. (1969) have found that pyroxene granulites from the Lewisian of Scotland have

$^{238}U/^{204}Pb$ ratios between 0.1 and 4.1; their amphibolite facies rocks have $^{238}U/^{204}Pb$ ratios usually less than 3, but rarely as high as 6.

Although thorium is also depleted in high grade metamorphic rocks, it often appears to be enriched relative to uranium. $^{232}Th/^{238}U$ ratios published by Gray range from 5.5 to 12.0, while the Th/U ratios measured by Heier and Thoresen (1971) run from 5 to 12 also. For comparison, typical Th/U values in igneous rocks are usually around 4.

Granulite facies rocks typically display very radiogenic $^{87}Sr/^{86}Sr$ ratios. Spooner and Fairbairn (1970) measured the $^{87}Sr/^{86}Sr$ ratios of fifty pyroxene granulites having a variety of compositions and from a number of different localities. They report a range of ratios running from .7037 to 1.3158, with the vast majority (41 of 50) greater than .7080, and almost all (48 of 50) greater than .7065. Similarly, Black _et al_. (1971) and Taylor (1975) report $^{87}Sr/^{86}Sr$ ratios for high grade metamorphic rocks between .710 and .840. However, Holland and Lambert's (1975) $^{87}Sr/^{86}Sr$ data on the Lewisian gneisses of Scotland are low with values in these rocks ranging from .701 to .703.

In a general way the geochemical data presented above would appear to be consistent with a derivation of the feldspathic basalts, and perhaps even the intermediate volcanic rocks of the Colorado Plateau, from lower crustal sources. These volcanic rocks do, for instance, have relatively unradiogenic lead ratios, implying low source region μ values, and granulite facies rocks are known to have low μ's. However, if one does a quantitative calculation of the source region μ values implied by the Colorado Plateau data (Section 5.9), one finds that only one Colorado Plateau rock has a μ less than 5.0. Several feldspathic basalts have μ's around 7 and 8, one has a μ of approximately 11. In constrast, the "μ" values actually measured in granulitic rocks were most commonly less than 4.0, and were very seldom greater than 6.0. Similarly, the κ values calculated for Colorado Plateau lead data range from 3 to 5. The granulite $^{232}Th/^{238}U$ data was seen to range from about 5 to about 12. In addition, the $^{87}Sr/^{86}Sr$ ratios measured on Colorado Plateau volcanics were, with one exception, $\leq .7050$ (Leeman, 1974; Brookins and Moore, 1975). In contrast, most of the $^{87}Sr/^{86}Sr$ ratios measured on granulites were $\geq .7065$, and a majority were very radiogenic with ratios $\geq .7080$. One is led either to the conclusion that the lower portion of the Colorado Plateau crust is geochemically a little different from other high grade metamorphic terrains, or that Colorado Plateau volcanic rocks are not derived directly from lower crustal sources. The lower crust in the Colorado Plateau region may indeed be somewhat unusual in its geochemical characteristics, but there is no evidence, as yet, to support this conclusion.

It would seem that the most likely source region for the late Cenozoic volcanic rocks of the Colorado Plateau is in the mantle. As mentioned previously, the chemical compositions and $^{87}Sr/^{86}Sr$ ratios of Colorado Plateau basalts appear to be entirely consistent with this interpretation. It is also pertinent that studies on ultramafic xenoliths from Colorado Plateau volcanic rocks (Stoeser, 1974; Best, 1970) suggest that these ultramafic nodules crystallized as cumulates from alkali basalt magmas at depths often as great as the base of the crust.

This would seem to suggest that the magmas from which the cumulates were crystallized were originally generated at even greater depths - in the mantle.

If Colorado Plateau volcanic rocks are derived from the mantle, the diversity in isotopic composition exhibited by these rocks, as well as the rough but apparently significant correlation between chemical and isotopic properties, presumably relates to the isotopic heterogeneity of the mantle which underlies the Colorado Plateau. It should be emphasized that the mantle from which oceanic and island arc volcanics are (seemingly) derived is different in several ways from the mantle generating Colorado Plateau volcanic rocks (see Section 6.1). Oceanic volcanics tend to be rather uniform in their isotopic characteristics, at least for volcanic rocks of similar composition from the same locality. Moreover, oceanic volcanics do not display isotopic ratios as unradiogenic as those exhibited by some Colorado Plateau volcanic rocks, and therefore do not appear to have experienced such a profound reduction in μ. It is also important that Colorado Plateau volcanics appear to exhibit an ancient, Precambrian time signature which seems to directly relate to the history of the overlying continental crust, perhaps even to the initial formation of the continental crust. Thus, if Colorado Plateau volcanic rocks do derive from the mantle, it appears that this is a mantle that has been associated with the continent almost since its inception - that is, Colorado Plateau volcanics are generated within the continental lithosphere.

5.9 Calculation of μ and κ

The $^{206}Pb/^{204}Pb$-$^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ regression lines defined by Colorado Plateau data can be used to calculate volcanic source region μ and κ values. An "average" κ value can be calculated directly from the slope of the $^{208}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ regression line, if one assumes a constant κ for all volcanic sources and utilizes the secondary isochron age determined from the Colorado Plateau α-β regressions. The slope of the Flagstaff-Prescott $^{208}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ regression is 0.991; this implies a κ of 3.39. The St. George data give a slope of 1.33, which gives a κ of 4.56. However, there is some scatter around the Colorado Plateau $^{208}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ regressions. Consequently, the uniform κ assumption may not be entirely correct, and the two κ values calculated above could be slightly inaccurate.

Mu, kappa, and system ages can be calculated independently for each data point if one knows the values of $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ at the beginning of the second stage of lead growth. It is not often possible to obtain a reliable estimate of a system's initial lead ratios. For Colorado Plateau samples, however, it is possible to estimate the range of initial lead ratios by two different methods, and both methods give reasonably equivalent results. The first method utilizes feldspar leads from Precambrian crystalline rocks in the Colorado Plateau region having ages similar to those inferred for the source regions of Cenozoic Colorado Plateau volcanic rocks. L.T. Silver (personal communication), using his own unpublished data and that of Ludwig and Silver (1977), has estimated that Precambrian feldspars from the Colorado Plateau have initial $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ ratios between 15.20, 15.25, and 34.9; and 16.20, 15.37, and 35.7, respectively. The second method uses the intersection of Colorado Plateau regression lines with the calculated geochrons of appropriate age (1.5-1.6 by) to give the initial second stage lead ratios. The 1.5 and 1.6 by geochrons used here have been calculated in two ways. First a single stage model, which assumes a 4.57 by age for the earth and the primordial lead ratios given by Tatsumoto _et al_. (1973), was employed. The second calculation employed the terrestrial two-stage model of Stacey and Kramers (1975).

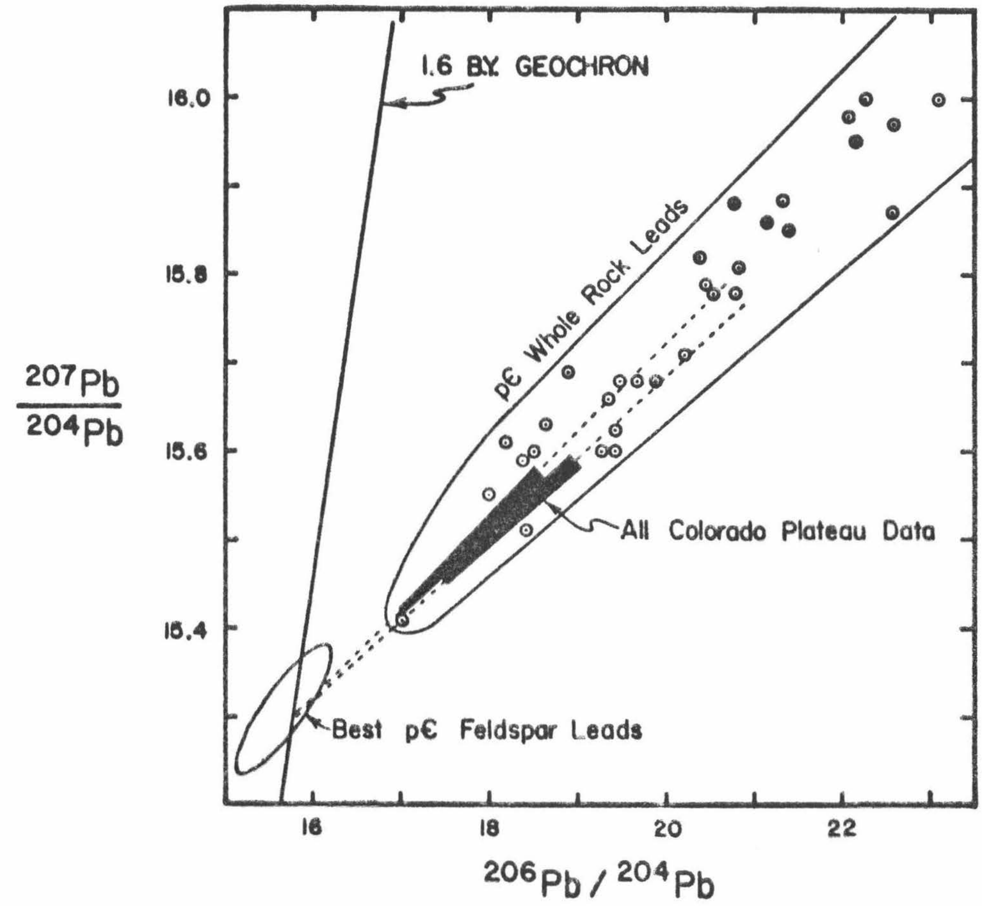
Table 5.7 shows the initial second stage leads calculated by the methods discussed above. Estimates of initial leads from feldspar data and estimates calculated using the intersection method are similar. For example, feldspar leads indicate a range of initial $^{206}Pb/^{204}Pb$ ratios between 15.20 and 16.20. The minimum α calculated by the intersection method is 15.34, and the maximum is 15.93. However, Figure 5.10 shows that the initial ratios inferred from the intersection of Colorado Plateau isochrons and calculated geochrons have somewhat lower $^{207}Pb/^{204}Pb$ ratios than most of the feldspar data. In addition, the growth curve for average terrestrial lead preferred by Stacey and Kramers (1975) also gives a 1.5 by lead with a somewhat higher $^{207}Pb/^{204}Pb$ ratio than the Colorado Plateau α-β regression would indicate. These differences might possibly be ascribed to isotopic heterogeneities in the Precambrian earth, although other, alternative explanations are also possible.

Table 5.7. Approximate initial lead ratios for Cenozoic volcanic source regions

Method	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
Feldspar leads from Precambrian granite	15.20-16.20	15.25-15.37	34.9-35.7
Intersection of St. George regression and 1.6 by single stage geochron	15.34	15.24	34.7
Intersection of St. George regression and 1.6 by Stacey and Kramers (1975) two stage geochron	15.82	15.29	35.0
Intersection of Flagstaff-Prescott regression and 1.5 by single stage geochron	15.43	15.24	34.7
Intersection of Flagstaff-Prescott regression and 1.5 by Stacey and Kramers (1975) two stage geochron	15.93	15.29	35.1

Figure 5.10: A diagram showing the intersection of the Colorado Plateau secondary isochrons derived from Late Cenozoic basalt data and the calculated 1.6 by geochron of Stacey and Kramers (1975). Also shown is the best estimate of the range of initial feldspar Pb ratios in 1.4-1.75 by old granites from the southwestern United States (L.T. Silver, personal communication). Open circles represent whole rock lead isotopic compositions of Precambrian granites from the Colorado Plateau and neighboring areas (L.T. Silver and colleagues, in preparation).

Figure 5.10


1.6 B.Y. GEOCHRON
pЄ Whole Rock Leads
All Colorado Plateau Data
Best pЄ Feldspar Leads
16.0
15.8
15.6
15.4
16
18
20
22
$^{207}Pb/^{204}Pb$
$^{206}Pb/^{204}Pb$

Tables 5.8 and 5.9 show the μ and κ values calculated from Colorado Plateau lead data and the initial ratios of Table 4.7. The results calculated from the single stage model consistently give values of μ around 20% higher and values of κ around 30% lower than the Stacey and Kramers two-stage model results. This difference directly reflects the different initial leads used in the two calculations. Because these initial values span the range of reasonable initial lead indicated by the feldspar data, the μ and κ values shown in the tables may bracket the true values of the source region. However, the model two results are perhaps to be slightly preferred; the two-stage model of Stacey and Kramers (1975) was designed to more closely approximate the obviously complex growth history of terrestrial leads.

The μ values of Tables 5.8 and 5.9 show a considerable degree of variation. The lowest μ is around 4 while the highest values are around 12. Stacey and Kramers (1975) estimated the average terrestrial μ to be 9.78. In comparison to this value most Colorado Plateau volcanics come from systems depleted in U/Pb (see Figure 5.10). If source region Pb concentrations are assumed constant, uranium depletions up to 60% are implied for the source regions. Because Pb loss is probably concurrent with U loss, one would expect even higher levels of U depletion. Prior extraction of magma from Cenozoic basalt source regions could explain this U/Pb depletion. The α-β regression lines defined by Colorado Plateau samples indicate that this inferred episode of magma generation took place at the same time that the earliest, Precambrian Colorado Plateau crystalline basement was being formed.

Table 5.8. Flagstaff-Prescott μ and κ values, assuming a 1.5 by source age*

	μ_1	κ_2	Measured $^{238}U/^{204}Pb$	μ_1	κ_2	Measured $^{232}Th/^{238}U$
A4027	12.12	10.21	10.68	3.61	3.78	5.43
A4028	13.49	11.57	6.96	3.24	3.33	3.16
A4029	11.25	9.35	9.93	3.19	3.27	4.77
A4030	9.70	7.80	19.55	3.55	3.74	3.70
A4031	10.18	8.27	14.50	3.79	4.04	3.63
A5014	9.31	7.41	16.67	3.56	3.76	3.15
A6014	13.18	11.28	--	4.20	4.49	--
A6015	7.28	5.37	--	3.87	4.27	--
A6018	9.83	7.92	--	3.47	3.66	--
A6021	13.23	11.32	24.65	3.79	3.98	3.40
A6022	7.05	5.18	10.85	3.71	4.00	3.92
A6023	10.86	8.95	--	3.90	4.17	--
A6025	13.66	11.82	--	3.83	4.06	--
A6053	9.82	7.98	11.31	3.60	3.87	2.83
A6054	8.07	6.16	--	3.57	3.83	--
A6058	8.20	6.29	9.59	3.42	3.63	2.52
Avg.	10.45	8.56		3.64	3.86	
S.D.	±2.21	±2.21		.25	.32	

*Subscript 1 refers to model 1 which uses $^{206}Pb/^{204}Pb = 15.41$, $^{207}Pb/^{204}Pb = 15.239$, and $^{208}Pb/^{204}Pb = 34.7$ for the initial lead isotopic composition. Subscript 2 refers to model 2 which uses $^{206}Pb/^{204}Pb = 15.934$, $^{207}Pb/^{204}Pb = 15.286$, and $^{208}Pb/^{204}Pb = 35.1$ for the initial lead isotopic composition.

Table 5.9. St. George μ and κ values, assuming a 1.6 by source age*

	μ_1	μ_2	κ_1	κ_2
A5006	11.42	9.80	4.22	4.58
U5016	6.93	5.29	4.28	4.95
U5017	8.11	6.48	4.18	4.65
A5019	7.14	5.51	3.97	4.47
U5020	11.09	9.45	4.23	4.61
U5022	9.02	7.40	4.29	4.83
A6011	10.68	9.04	4.78	5.26
A6030	9.92	8.30	4.47	4.94
A6031	9.24	7.62	3.88	4.14
U6032	5.57	3.93	4.04	4.80
Avg.	8.91	7.28	4.23	4.73
S.D.	±1.95	1.95	.26	.30

*Subscript 1 refers to model 1, which uses $^{206}Pb/^{204}Pb = 15.34$, $^{207}Pb/^{204}Pb = 15.24$, and $^{208}Pb/^{204}Pb = 34.7$ for an initial lead isotopic composition. Subscript 2 refers to model 2, which uses $^{206}Pb/^{204}Pb = 15.93$, $^{207}Pb/^{204}Pb = 15.29$, and $^{208}Pb/^{204}Pb = 35.1$ for an initial lead isotopic composition.

This coincidence seems to imply a genetic relationship between the generation of high U/Pb Precambrian granites in the crust and the depletion of U/Pb due to magma extraction, in the mantle below.

Kappa values (from Tables 5.8 and 5.9) range from about 3.3 to 5.3. Colorado Plateau source κ's tend to be, on the whole, higher than the 3.87 average terrestrial value proposed by Stacey and Kramers (1975). The St. George data set, in particular, is characterized by higher than normal κ's (Figure 5.11). This suggests an enrichment of Th relative to U in St. George area volcanic source regions. Since the source regions of Colorado Plateau volcanics are thought to have been depleted in U, the κ data may indicate only that Th has been depleted only to a somewhat smaller degree than uranium.

There appears to be little correspondence between the μ value calculated from a sample's lead isotope ratios and its $^{238}U/^{204}Pb$ ratio measured by isotope dilution. Figure 5.12 shows no simple correlation between these two parameters. The data points in this diagram, with the exception of one unusual hypersthene bearing feldspathic basalt, do indicate, however, an increase in rock $^{238}U/^{204}Pb$ over calculated source region values. This enrichment is not consistent - varying from a 1:1 increase to nearly a 3:1 increase in "μ." The data in Figure 5.12 suggest no clearcut relationship between U/Pb enrichment and the major element chemistry of a sample. Olivine augite basalts, for example, span the whole range of U/Pb enrichment.

The scatter in Figure 5.12 demonstrates the inadvisability of calculating an age from a U-Pb isochron using measured uranium and lead

Figure 5.11: μ (mu) = ($^{238}U/^{204}Pb$) and κ (kappa) = ($^{232}Th/^{238}U$) values calculated for the source regions of Colorado Plateau volcanic samples. The average terrestrial values calculated by Stacey and Kramers (1975) are shown for comparison. Open circles are basaltic andesites, and filled circles are andesites, dacites, and rhyolites. Triangles and squares are feldspathic basalts. Diamonds are olivine-augite basalts.

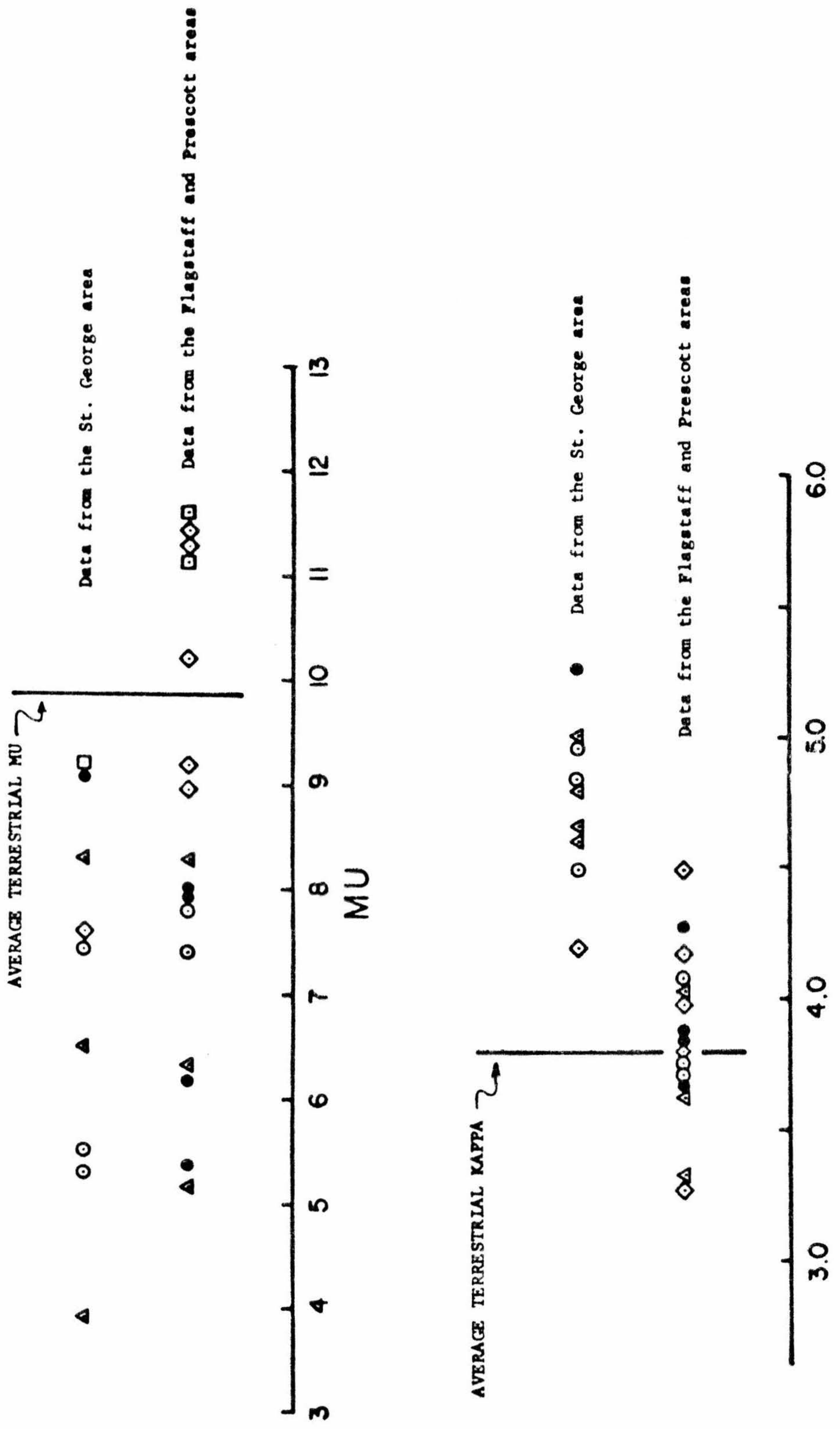
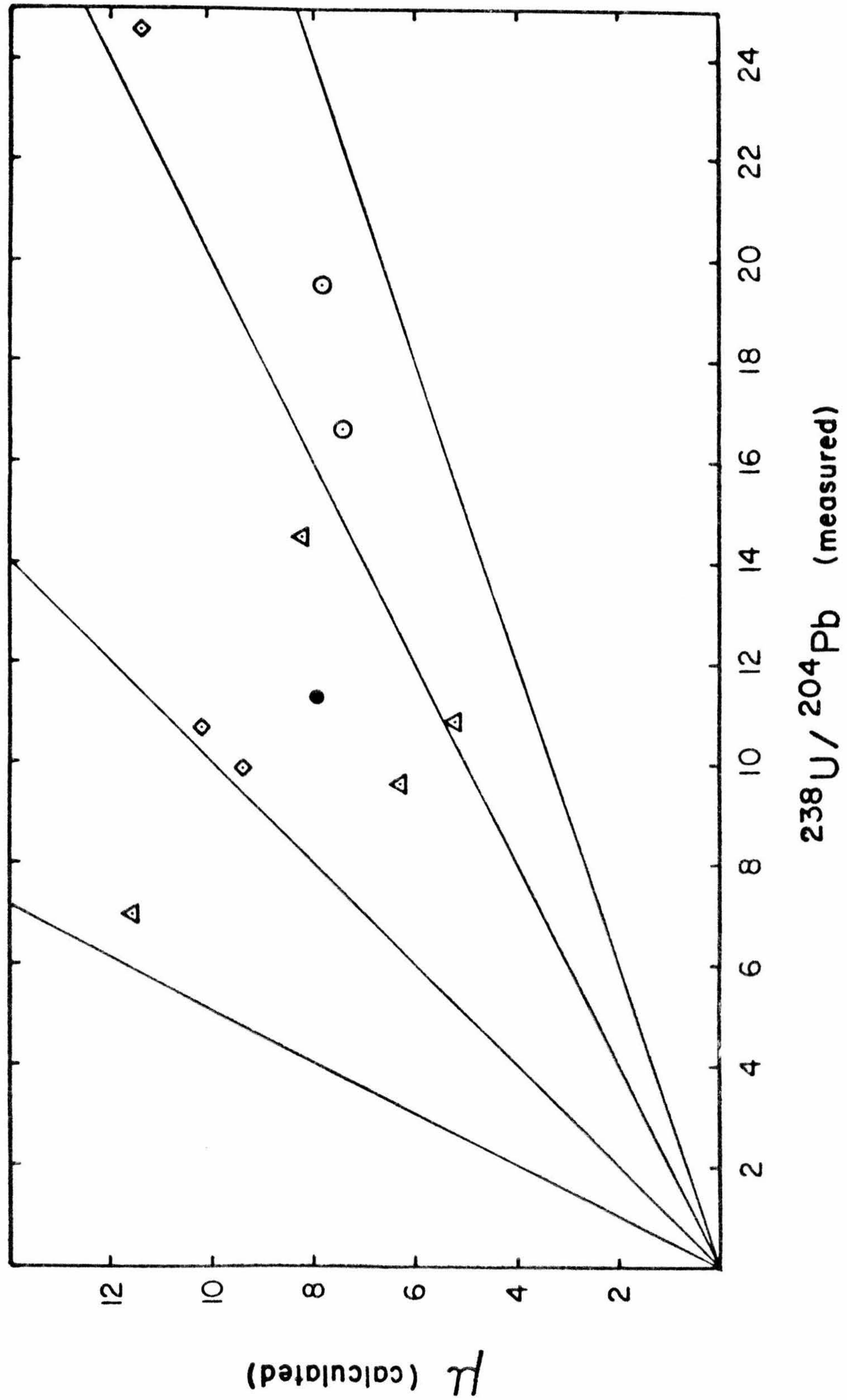

AVERAGE TERRESTRIAL MU
Data from the St. George area
Data from the Flagstaff and Prescott areas
3
4
5
6
7
8
9
10
11
12
13
MU
AVERAGE TERRESTRIAL KAPPA
Data from the St. George area
Data from the Flagstaff and Prescott areas
3.0
4.0
5.0
6.0
KAPPA

Figure 5.11

Figure 5.12: A comparison of calculated source region μ values and measured whole rock $^{238}U/^{204}Pb$ values for volcanics of the southwestern Colorado Plateau. Diamonds are olivine-augite basalts; open circles are basaltic andesites. Triangles are feldspathic basalts, and the filled circle is an andesite. Lines indicate constant ratio values between μ and measured $^{238}U/^{204}Pb$.

Figure 5.12


μ (calculated)
12
10
8
6
4
2
$^{238}U/^{204}Pb$ (measured)
2
4
6
8
10
12
14
16
18
20
22
24

concentrations for source region uranium and lead concentrations. The enrichment of U/Pb in the rock relative to the source region would tend to shift isochron ages to values lower than the true ages. By analogy these considerations suggest that the apparent ages implied by Rb/Sr pseudo-isochrons on Cenozoic basalts of the western United States are too young. According to Brooks et al. (1976) Rb-Sr data from the western Grand Canyon (St. George area) give a pseudo-isochron age of 1100 my while those from the Colorado Plateau (San Francisco volcanic field) suggest a 960 my age. In addition, data from the Snake River Plain suggest pseudo-isochron ages of 940 my and 620 my. In contrast, Pb data on Colorado Plateau volcanic rocks indicate 1500-1600 my ages, while lead data on the Snake River Plain (Leeman, 1975) indicate a 2500 my source region age.

5.10 Different Domains within the Colorado Plateau Isotopic Province

Data from different regions of the Colorado Plateau appear to exhibit similar but apparently distinguishable patterns of isotopic behavior. It has already been mentioned that data from the San Francisco volcanic field (Flagstaff-Prescott area) seem to describe a linear array on an α-β diagram different from that defined by data from the western margin of the Colorado Plateau in northern Arizona and Utah (St. George area) (see Figures 4.8a and 4.8b). The St. George isochron has a slightly greater slope than the Flagstaff-Prescott isochron and is displaced toward slightly higher $^{207}Pb/^{204}Pb$ values. The magnitude of this displacement is not great; the difference in

$^{207}Pb/^{204}Pb$ between the two isochrons varies from about .02 to .04. Nonetheless, the distinction between the two populations of data is clearcut. Nine of the ten data points from the St. George area belong to the St. George isochron, and eleven of the fourteen samples from the Flagstaff-Prescott area give leads unambiguously belonging to the Flagstaff-Prescott isochron. A Student t-test (Table 5.10) indicates that the two data sets are different beyond the 0.1% significance level.

It can also be noted that the St. George and Flagstaff-Prescott data groups seem to display a somewhat different range in their absolute isotope ratios. For example, St. George $^{206}Pb/^{204}Pb$ ratios range from 17.0 to 18.5 with an average value of 17.95. The Flagstaff-Prescott $^{206}Pb/^{204}Pb$ lead data range from 17.5 to 19.0 with an average value of 18.2. This different range of $^{206}Pb/^{204}Pb$ ratios suggests that the St. George area volcanic source regions have been generally somewhat more depleted in uranium relative to lead than the Flagstaff-Prescott area volcanic source regions.

The distinction between Flagstaff-Prescott area and St. George area data can also be seen on a ^{206}Pb-^{207}Pb-^{208}Pb triangular diagram. Figure 4.12a shows that St. George data and Flagstaff-Prescott data seem to describe completely distinct fields on the triangular diagram. The St. George data field appears to have a different orientation, or direction of elongation, from the Flagstaff-Prescott field, and is displaced toward the more thorogenic side of the diagram.

Table 5.10.

Flagstaff-Prescott Area Data		St. George Area Data	
No.	Δ	No.	Δ
A4027	-.101	U5016	.260
A4028	-.036	U5017	.106
A4029	-.918	A5019	1.44
A4080	-1.16	U5020	.002
A4031	-.736	U5022	1.22
A5014	-1.19	A6003	.861
A6014	.618	A6009	.895
A6015	.079	A6011	1.13
A6018	-.582	A6027	2.52
A6021	.342	A6028	.107
A6022	-1.88	A6030	1.57
A6023	-.330	A6031	-.178
A6053	.318	U6032	.182
A6054	-.955		
A6058	-1.12		

$N_2 = 15$

$\overline{X}_2 = -.5101$

$S_2 = .7076$

$N_1 = 13$

$\overline{X}_1 = .7781$

$S_1 = .7896$

Δ = the standardized deviation from the α-β regression defined from all Colorado Plateau data. Numerically,

$\Delta = \beta -[(13.961 + \alpha \cdot .084828)]/(.0162)$.

$$t = \frac{\overline{X}_1 - \overline{X}_2}{Sp(\frac{1}{N_1} + \frac{1}{N_2})^{1/2}} = 4.55$$

The appropriate critical value of t at the 0.1% significance level is 3.467.

Data from other Colorado Plateau regions describe data fields on the triangular diagram which are similar to but apparently different from either the St. George or Flagstaff-Prescott data fields. Data from a Colorado Plateau area along the Arizona-New Mexico border (Area H in Figure 4.7) define a data field which overlaps the St. George area field, but appears to have a different direction of elongation (see Figure 4.14). While the St. George field appears to parallel the terrestrial lead growth curve, the Area H data describe a field at an acute angle to the growth curve. Furthermore, data from central New Mexico (Area J in Figure 4.7) describe a field on the triangular diagram which overlaps parts of both the St. George and Flagstaff-Prescott data fields, but which is identical to neither of them. The orientation, or elongation, of the central New Mexico field is different from the St. George data field, and its position is somewhat displaced to the thorogenic side of the Flagstaff-Prescott data field. Indeed, the central New Mexico data field appears similar in position and orientation to the Area H data of Figure 4.14, although perhaps a bit richer in the ^{206}Pb component.

Data from northern-most New Mexico (Doe et al., 1969 and this work) and the San Juan volcanic field of southern Colorado (Lipman et al., 1978) describe a data field on the triangular diagram (see Figure 4.12e) different from that defined by central New Mexico data, but rather similar to that of the Flagstaff-Prescott area. It is interesting to note that late Pliocene basalts from northern New Mexico fall into the same field as the 30+ my old intermediate volcanic rocks from southern Colorado. Similarly, a 28 my andesite from Area H in Figure 4.7 occupies the same part of the triangular diagram as younger basalts from the same area. In addition, a 17 my andesite from the St. George area plots in the same field described by that area's young basalts. These observations would suggest that rock age and composition are not factors critically important in determining the location of a data point on the triangular diagram.

Instead one would suspect that a Colorado Plateau data field's position and orientation are dependent on long-term characteristics of the source regions from which that area's volcanics are derived. Probably the most important factors determining the position of a data field on the triangular diagram are the source region Th/U ratios and its initial lead isotopic composition at the time of differentiation. Different source regions may have different κ values, or different initial leads, or both. For example, the St. George and Flagstaff data fields point back to similar initial lead values near the terrestrial growth curve. However, the St. George data are somewhat displaced to the thorogenic side of the diagram. This would appear to be explainable by the different Th/U ratios which seem to characterize the source regions for the two areas. (According to Section 5.9, the St. George data imply a source κ of approximately 4.6, while the Flagstaff-Prescott κ is approximately 3.4.) On the other hand, it seems difficult to explain the difference between the Flagstaff-Prescott data and data from central New Mexico without assuming the two areas had source regions with different initial leads. Volcanics from both areas seem to derive from source regions having approximately similar ages. Consequently, one would normally expect both data fields on the triangular diagram to point toward the same point on the terrestrial lead growth curve, a point having an age similar to the calculated secondary isochron age. This does seem to be the case for the Flagstaff-Prescott data. However, the central New Mexico data field points to a point on the terrestrial lead growth curve whose age is much older than the data's secondary isochron age, and much older than any Precambrian crustal rocks in the region. This discrepancy would seem to indicate the central New Mexico source region did not have an initial lead on the terrestrial lead growth curve, that its initial lead composition was different from that characterizing source regions for volcanics of the southwestern Colorado Plateau.

There may also be real differences in the secondary isochron ages calculated for different areas of the Colorado Plateau. The Flagstaff-Prescott secondary isochron age is 1.50 ± 0.13 by, while the St. George isochron age is 1.60 ± 0.13 by. Lipman et al. (1978) calculated an age of 1.86 ± 0.11 by for leads from the San Juan volcanic field. These age differences might conceivably relate to different ages of Precambrian igneous activity in each area. Silver et al. (1967) has indeed noted regional differences in the ages of Precambrian igneous rocks from the southwestern United States. Plutons to the north and west of a line running diagonally across Arizona into New Mexico have been found to be older (1720-1760 my) than those south and east of the boundary (1650-1700 my). However, all three Cenozoic volcanic fields mentioned above lie in the region of older Precambrian magmatism. It is difficult, therefore, to relate differences in secondary isochron ages directly to the regional differences in the ages of the earliest Precambrian magmatism. It is possible to speculate, however, that the different isochron ages relate to the degree that the later 1400 my old episode of Precambrian igneous activity affected or reset the isotopic characteristics of Cenozoic volcanic source regions in different areas. Unfortunately, it does not seem possible at this time even to attempt to correlate the different isochron ages with the intensity of 1400 my magmatism in different areas.

It is rather more difficult to draw geographic boundaries between the different isotopic domains on the Colorado Plateau than to merely demonstrate that areal isotopic differences do exist. A much larger body of data than is currently available would be required to confirm that the areal groupings used here are not somewhat arbitrary. For example, data from near the margin of the Colorado Plateau in central Arizona (Area F in Figure 4.7) seem to define a field on a triangular diagram rather unusual for a Colorado Plateau area (see Figure 4.14). Perhaps more data would indicate that two or more types of data are being grouped together, and that this is the reason for the unusual spread of data on the triangular diagram.

5.11 Correlation between Chemical and Isotopic Composition: Implications for Source Region Heterogeneity

The wide range in lead isotopic composition found in Colorado Plateau volcanic rocks suggests that there is considerable isotopic heterogeneity in the volcanic source regions beneath the Colorado Plateau. The rough but apparently significant correlation between the isotopic and chemical compositions of Colorado Plateau volcanic rocks suggests that some of the volcanic rocks (e.g., the OA basalts) are being derived from somewhat different sources than others (e.g., the feldspathic basalts). The next few pages explore what kinds of heterogeneity in the (mantle?) source regions are more likely to produce a correlation between chemical and isotopic properties of the derivative volcanics.

Source region heterogeneity could conceivably be microscopic, vertical, lateral, or chemical in nature. Lateral differences in source region properties seem able to explain why samples from the St. George area describe one secondary isochron while samples from the Flagstaff-Prescott area define another similar but distinct isochron. However, it is difficult to see how lateral differences in source region characteristics can explain the correspondence between petrologic and isotopic properties of samples within the same local area.

Perhaps microscopic heterogeneity can explain this correspondence if the chemically uniform source rock is made of unequilibrated, isotopically distinct phases. Differing degrees of partial melting would then mix different proportions of these isotopically different minerals, giving rise to melts having different lead isotopic compositions. The feasibility of this hypothesis receives some support from the work of Zartman and Tera (1973), who recorded isotopic heterogeneities within individual peridotite xenoliths. However, high pressure experimental studies on pyrolite do not seem to support the idea that the OA basalts and the feldspathic basalts are consistently derived by different degrees of partial melting. The "petrogenetic grid" proposed by Green (1971) (Figure 5.13) indicates that high alumina basalt, alkaline olivine basalt, and olivine rich basanite can be derived from equivalent degrees (∿10-15%) of partial melting of pyrolite containing 0.1% H_2O at different pressures. The microscopic heterogeneity model would seem to predict that these rocks would be isotopically similar. But for the Colorado Plateau, basanites and alkali olivine basalts appear to display a range of lead isotopic composition somewhat different from that exhibited by the hawaiites and high alumina basalts. Moreover, in Green's petrogenetic grid alkaline olivine basalt, olivine basalts, and olivine tholeiites would be generated by increasing degrees of partial melting at approximately the same pressure. No correlation has been noted in this work between silica saturation, or alkalinity, and lead isotopic composition. Sample A4029, an olivine tholeiite, has lead ratios similar to those of A6021, a basanite. Thus microscopic or mineralogic heterogeneity in the mantle does not seem to be an obviously attractive way to explain why olivine augite basalts appear to be isotopically different from the more "differentiated" volcanics of the Colorado Plateau.

A vertical zonation of the mantle in lead isotopic composition may come closer to explaining the isotopic distinction between the two rock types. Green's petrogenetic grid suggests that hawaiites and high alumina basalts are derived from relatively shallow depths of

Figure 5.13: After Green (1971). A petrogenetic grid in which basalts are regarded as the partial melting products of pyrolite containing 0.1% H_2O. The numbers found with each basalt type indicate the normative olivine content of the basaltic melt at its depth of origin. The dashed lines indicate the conditions under which various minerals will be present in the residual phase. Note that trachybasalt, hawaiite, high alumina basalt, and olivine tholeiite can be derived by different amounts of partial melting at the same pressure. Hawaiite, alkaline olivine basalt, and basanite can be derived by similar degrees of partial melting at different pressures.

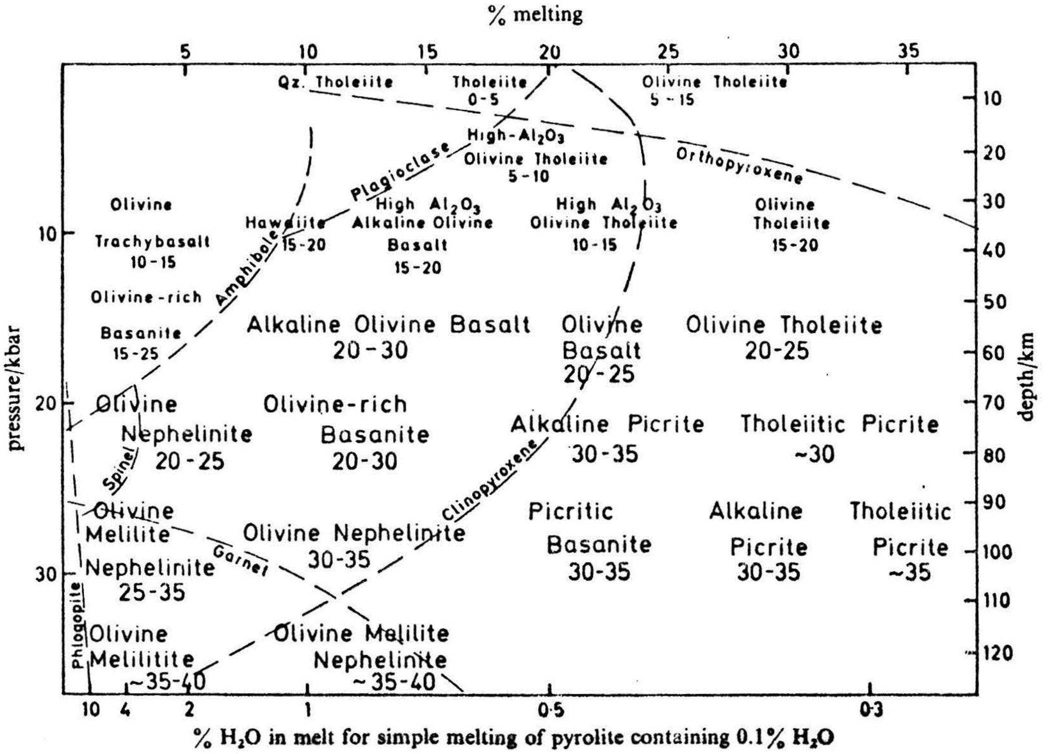

% melting
5
10
15
20
25
30
35
Qz. Tholeiite
Tholeiite 0-5
Olivine Tholeiite 5-15
High-Al2O3 Olivine Tholeiite 5-10
Orthopyroxene
Plagioclase
Olivine Trachybasalt 10-15
Hawaiite 15-20
High Al2O3 Alkaline Olivine Basalt 15-20
High Al2O3 Olivine Tholeiite 10-15
Olivine Tholeiite 15-20
Amphibole
Olivine-rich Basanite 15-25
Alkaline Olivine Basalt 20-30
Olivine Basalt 20-25
Olivine Tholeiite 20-25
Olivine Nephelinite 20-25
Olivine-rich Basanite 20-30
Alkaline Picrite 30-35
Tholeiitic Picrite ~30
Spinel
Clinopyroxene
Olivine Melilite Nephelinite 25-35
Garnet
Olivine Nephelinite 30-35
Picritic Basanite 30-35
Alkaline Picrite 30-35
Tholeiitic Picrite ~35
Phlogopite
Olivine Melilitite ~35-40
Olivine Melilite Nephelinite ~35-40
pressure/kbar
10
20
30
depth/km
10
20
30
40
50
60
70
80
90
100
110
120
10
4
2
1
0·5
0·3
% H₂O in melt for simple melting of pyrolite containing 0.1% H₂O

Figure 5.13

30-40 km. The seismic study of Warren (1969) places the base of the crust under the Colorado Plateau at similar depths - 30 km near the Basin and Range - Colorado Plateau margin and 40 km farther within the Plateau. This suggests that the feldspathic basalts can be derived from the uppermost mantle just beneath the crust. In contrast, the more mafic and alkaline basaltic rocks of the Colorado Plateau would seem to be derived from greater depths of 50-80 km, according to Figure 5.12. The sources of these mafic magmas might be near the roof of the LVZ, which Archambeau _et al_. (1969) place somewhere about 80-100 km in depth on the basis of their seismic refraction study. Thus, the isotopic difference between OA basalts and "differentiated" Colorado Plateau volcanics might be explainable in terms of an isotopic stratification of the mantle. The shallow mantle would seem to be more depleted in uranium relative to lead and to have less radiogenic leads than the deeper mantle. This seems like a reasonable conclusion. Intuitively one might expect that the mantle closer to the earth's surface would have been more subject to previous episodes of magma extraction during the formation of the crust, 1400-1800 my ago, than the material at greater depths.

In order to explain the overlap in isotopic ratio between different volcanic rock groups, it may be necessary to hypothesize that the mantle is only crudely stratified in isotopic composition. However, segregation of crystal and melt at depths less than the original source region depth would also tend to obscure the petrology/isotope ratio/source region depth correlation. The petrologic properties of a magma would reflect the depth at which residual crystals last equilibrated with melt during the ascension of a body of partially molten mantle. The isotopic properties of a magma would, on the other hand, reflect the original depth of source region from which the body was derived. Thus, a mantle diapir originating in the LVZ and having an appropriately radiogenic lead might give rise to a magma whose petrologic characteristics are indicative of a shallow deviation. Another process which might complicate the picture is wall rock interaction (e.g., zone refining) of material in the mantle during its ascent to the surface.

The mantle beneath the Colorado Plateau, besides being laterally heterogeneous and vertically zoned in its isotopic properties, may also be chemically nonuniform. Most Colorado Plateau basalts might be presumed to be derived from a peridotitic, or rather pyrolitic mantle. However, the quartz xenocrysts of the Colorado Plateau basaltic andesites cannot have formed in equilibrium with olivine. Basaltic andesite sources cannot, therefore, be peridotitic; they might possibly be quartz eclogites.

5.12 Petrogenesis of the Basaltic Andesites

The occurrence of reacting quartz and alkali-rich plagioclase crystals in basaltic andesite samples requires special consideration. As mentioned previously, some authors, notably Doe *et al*. (1969) view these crystals as xenocrysts derived from lower crustal rocks of granitic composition. This report has tended not to favor this hypothesis, one reason being that the lead and strontium isotopic compositions of the Colorado Plateau basaltic andesites do not seem especially different from those of non-"xenocrystic" volcanic rocks. Thus there does not appear to be compelling isotopic evidence that the basaltic andesites have been specially contaminated with crustal material. In addition, feldspar "xenocrysts" are commonly zoned and twinned, even in their cores. It would seem unlikely that such features could survive for any length of time under the high grade metamorphic conditions present in the lower crust. It is also curious that quartz and feldspar crystals never seem to be found together in xenoliths. If solid rock were the contaminating material, one might expect to find lithic fragments as well as isolated crystals in the basaltic andesites.

One alternative hypothesis for the origin of quartz and sodic feldspar "xenocrysts" is that these crystals are high pressure cognate phenocrysts. This interpretation is not without its difficulties, however. Quartz does not seem to be a liquidus phase, or even a near liquidus phase, for the partial melting of source regions having compositions appropriate for making basaltic andesites. High pressure experimental melting studies on basalts (e.g., Cohen et al., 1967; Green and Ringwood, 1968) indicate that clinopyroxene (or at higher pressures, garnet) is the liquidus mineral. Studies on basaltic andesites and andesites (Green and Ringwood, 1968; Green, 1972) give similar results. Thus the occurrence of quartz and feldspar crystals without accompanying phenocrysts of high pressure, aluminous clinopyroxene or garnet is somewhat puzzling.

A second difficulty lies in finding a source region depth which is compatible with both plagioclase and quartz stability fields. Quartz becomes increasingly stable at higher pressures while plagioclase becomes unstable at high pressures. Wyllie (1971) has indicated that crystalline quartz is in equilibrium with partially hydrated quartz eclogite melts only at pressures above 17-20 kb, although the dry andesite melts studied by Green (1972) had stable quartz at somewhat lower pressures (≥10 kb). On the other hand, experimental studies on basaltic systems (see Ringwood, 1975) indicate that plagioclase becomes progressively more sodic at higher pressures and finally disappears at pressures between 15 and 25 kb, depending on the chemical composition of the system. Green (1972) showed an upper limit of approximately 20 kb for plagioclase stability in his experiments on anhydrous andesites. He also found that increasing the water content of the system depressed the plagioclase stability field to even lower pressures. Water has a similar effect in basaltic systems, according to the diagrams published by Wyllie (1971). These experimental studies suggest, therefore, that the source of basaltic andesite magmas is nearly anhydrous. Otherwise, the high pressures required for quartz stability become incompatible with the low pressures needed for plagioclase stability. Even in dry systems it seems that quartz and plagioclase can coexist only within a narrow range of pressures around 20 kb (∿65 km depth).

Although they may indeed be derived from anhydrous quartz eclogites 65 km within the earth, there may be a simpler way for getting the basaltic andesites and their "xenocrysts." As recently discussed by Eichelberger (1974), these xenocrystic crystals could be interpreted as phenocrysts inherited from a rhyolitic magma during mixing with a basaltic melt. This hypothesis seems to be compatible with the isotopic similarity of basalts, basaltic andesites, and more silicic volcanic rocks from the southwestern Colorado Plateau. Mixing of a basalt with a consanguineous rhyolite, perhaps one derived by fractional crystallization of the same basaltic magma, would not be expected to result in a distinctive isotopic composition for the basaltic andesite mixture. The zoning and twinning of the feldspar xenocrysts would also be compatible with their origin as phenocrysts in a rhyolite lava. Furthermore, the presence of isolated crystals without associated lithic fragments seems consistent with the rhyolite existing as a magma rather than as a solid rock. The silica variation diagrams of Moore et al. (1976) may also have a bearing on the problem. In plots of SiO_2 versus CaO and MgO (Figure 5.14) the basaltic andesites describe a linear trend somewhat displaced from the curved trend defined by the other volcanic rocks. This basaltic andesite trend appears to cross the main variation curve both at high silica ($\sim$68%) and low silica ($\leq$50%) values. This is precisely the behavior that would be expected if rhyolites were mixing with basalts to produce the basaltic andesites.

There is one consideration, however, which does not lend support to the idea that basaltic andesites are made by magma mixing. Basaltic andesites are very common on the Colorado Plateau; they are found in abundance in every Colorado Plateau volcanic field. This is not true for rhyolites. The area around St. George, for example, does not seem to have any young silicic rocks whatsoever. It would be difficult to explain the basaltic andesites if no rhyolitic magmas were available to participate in the mixing process.

CHAPTER 6: BASALTIC VOLCANISM IN THE BASIN AND RANGE PROVINCE

6.1 Petrographic Descriptions of Basin and Range Basalts

Leeman and Rodgers (1970) petrographically examined and chemically analyzed approximately one hundred Plio-Pleistocene basalts from the western United States. They concluded that late Cenozoic basalts in the Basin and Range province are predominantly of the alkaline olivine type, while basalts from adjacent regions (including the Snake River Plain, the Cascades, and the Sierra Nevada) are predominantly tholeiitic.

The petrographic characteristics of this study's Quaternary BR basalt samples appear to be uniformly alkaline in character. The mafic rocks contain abundant, non-reacting olivine phenocrysts and groundmass grains.* In addition, the pyroxene most commonly found in these rocks is a distinctive brown-purple, slightly pleochroic clinopyroxene (titanaugite), a mineral which seems to be characteristic of alkaline basalts from a number of localities. This titaniferous clinopyroxene is rare as a phenocryst but usually quite abundant in the groundmass. It might also be noted that small, interstitial patches of brown to oxide-charged, black glass are also common in these alkaline basalts, even coarse grained samples. Plagioclase occurs as microphenocryst and groundmass laths; it is seldom found as a phenocryst phase. Although plagioclase crystals show extensive zoning, optical methods

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*Olivine crystals are, however, commonly altered in part to iddingsite.

usually indicate anorthite contents around An_{50}-An_{65} (labradorite). Ultramafic inclusions have been noted in a number of these Quaternary basalt samples, but they are by no means ubiquitous.

The petrographic uniformity of BR Quaternary basalts is remarkable. Samples from the Mohave desert (C4022 and C4025) in California, the Lunar Crater area (N5024) in Nevada, the San Bernardino volcanic field (A4003 and A4005) of Arizona, the Potrillo volcanic field (NM4010, NM4015, and NM4016), and the Jornada del Muerto field (NM7009 and NM7010) of New Mexico are virtually indistinguishable in thin section. In contrast, very few of the older basalts from the Basin and Range province or the Pliocene, Pleistocene, and Recent basalts from the Colorado Plateau would be easily mistaken for these distinctive alkaline volcanics.

Petrographically, the Pliocene and older basalts of the Basin and Range province constitute a heterogeneous group. They are variously intergranular and intersertal. Some are cryptocrystalline; others are coarse grained. Mafic (olivine-augite) basalts are not difficult to find although feldspar-rich "trachybasalts" (feldspathic basalts) are perhaps more common.

In most cases it is difficult to judge on petrographic grounds whether a particular sample is alkalic or subalkalic in character. Olivine is nearly ubiquitous in these Tertiary rocks, and although iddingsite alteration is common, reaction rims have yet to be observed. This lack of reaction might suggest alkaline tendencies, but it should be remembered that very few of the subalkaline, high alumina basalts from the Colorado Plateau display obvious olivine reaction relationships. Clinopyroxene is present in most of the Pliocene and older Basin and Range basalts, but it is very seldom the distinctive, purple titanaugite which characterizes the alkaline Quaternary basalts. Orthopyroxene is rare - it occurs in only four Basin and Range samples (N5023, A6005, N6028, and N6034). All four of these basalt samples were found in areas somewhat marginal to the Colorado Plateau isotopic province and possess leads which might conceivably be considered to be of the CP type.

Basaltic andesites containing wormy plagioclase and quartz "xenocrysts" are present in the Basin and Range, but they may not, perhaps, occur as commonly as in the Colorado Plateau volcanic suite. Three samples from one area in Arizona (A3008, A3009, and A6004), two from California (C6002 and C4025), and another from New Mexico (NM4010) have trace amounts of sieve-textured plagioclases. One rock from Nevada (N3015), a second from New Mexico (NM7009), and a third from California (C4025) have rare, partially resorbed quartz crystals. Two of these quartz bearing rocks appear to be basanitoids, and all of them display lead isotopic ratios similar to those of nearby, non-xenocrystic, isotopically typical BR basalts. N5023, a sample from southeast Nevada near the BR-CP boundary, has lead isotopic characteristics somewhat intermediate between BR type or CP type, together with wormy plagioclase grains.

6.2 Chemical Description of Basin and Range Basalts

Appendix E tabulates the chemical analyses of a number of Basin and Range basalts. The majority of these analyses were performed by A.R. McBirney of the University of Oregon on the identical samples used for this study's lead isotopic work. In several cases where it seemed reasonable to correlate the samples of this study with samples on which major element analyses had been published, chemical data were taken from the literature. Table 6.1 tabulates the petrologic classification of the chemical analyses listed in Appendix E according to the procedures proposed by Irvine and Baragar (1971).

Several inferences can be gleaned from this appendix and this table. (1) First, there are suggestions that not all of the chemical data used in this report are of the highest quality. For example, two chemical analyses of Potrillo basalts taken from Renault (1970) add up to rather low sums (94% and 96% instead of 100%). In addition, Table 6.1 shows differences between the chemical and petrographic descriptions of two Quaternary basalt samples. Petrographically, NM7005 and NM7010 are alkali-olivine basalts, a characterization consistent with literature discussion of volcanism in each locality. However, the chemical analyses of these rocks indicate that they are subalkaline - that they are high alumina basalts or tholeiites rather than alkaline basalts. Although they are not easily resolved, these differences suggest that some specific chemical analyses used in this report might be slightly inaccurate.

Table 6.1a: Chemical and petrographic characterization of Quaternary basalts from Basin and Range areas (excluding Southern Nevada)

No.	Volcanic Field	Suite	Chemical Characterization Series	Name	Petrographic Name
NM4015	Potrillo, NM	alkaline	potassic	alkaline picrite basalt	basanitoid
NM4016	Potrillo, NM	alkaline	potassic	alkaline picrite basalt	basanitoid
N5014	Lunar Crater, NV	alkaline	potassic	alkaline olivine basalt	basanitoid
A4005	San Bernardino, AZ	alkaline	potassic	alkaline olivine basalt	basanitoid
A4003	San Bernardino, AZ	alkaline	potassic	trachybasalt	alkaline olivine basalt
NM4044	Jornada del Muerta, NM	alkaline	sodic	hawaiite	alkaline olivine basalt
C4022	Mohave Desert, CA	alkaline	potassic	alkaline olivine basalt	alkaline olivine basalt
C4025	Mohave Desert, CA	alkaline	potassic	alkaline olivine basalt	alkaline olivine basalt
A3008	Sentinel, AZ	alkaline	sodic	hawaiite	basaltic andesite
A3038	Florence, AZ	alkaline	sodic	hawaiite	feldspathic basalt
C5011	Coso Mtns, CA	alkaline	sodic	hawaiite	feldspathic basalt
NM7008	Rio Grande Rift, NM	alkaline	sodic	hawaiite	olivine basalt

Table 6.1a (continued)

No.	Volcanic Field	Suite	Chemical Characterization Series	 Name	Petrographic Name
NM4010	Potrillo, NM	alkaline	potassic	alkaline olivine basalt	alkaline olivine basalt
N3029	Virginia City, NV	alkaline	potassic	alkaline olivine basalt	olivine basalt
NM4007	Animas, NM	alkaline	sodic	hawaiite	alkaline olivine basalt
NM7009	Jornada del Muerto, NM	alkaline	potassic	alkaline olivine basalt	basanitoid
NM7010	Jornada del Muerto, NM	subalkaline	calc-alkaline	high alumina basalt	basanitoid
C5010	Coso Mtns, CA	alkaline	sodic	hawaiite	feldspathic basalt
NM7005	Hachita, NM	subalkaline	tholeiite	olivine tholeiite	alkaline olivine basalt
C5001	Mohave Desert, CA	subalkaline	calc-alkaline	high alumina basalt	alkaline(?) olivine basalt

Table 6.1b: Chemical and petrographic characterization of Pliocene and older volcanic rocks from Basin and Range areas (excluding Southern Nevada)

		Chemical Characterization			
No.	Locality	Suite	Series	Name	Petrographic Name
N3027	Battle Mtn. NV	subalkaline	tholeiite	olivine tholeiite	tholeiite
C7001	Yucca Valley, CA	alkaline	sodic	hawaiite	olivine basalt
N3016	Stillwater, NV	subalkaline	calc-alkaline	high alumina basalt	feldspathic basalt
C6002	Turtle Mtns, CA	subalkaline	calc-alkaline	high alumina basalt	basaltic andesite
A6004	Quartzsite, AZ	subalkaline	calc-alkaline	high alumina basalt	basaltic andesite
N5026	Tonopah, NV	subalkaline	calc-alkaline	mafic andesite	feldspathic basalt
C4020	Jacumba, CA	subalkaline	calc-alkaline	mafic andesite	feldspathic basalt
A3041	Tucson, CA	subalkaline	calc-alkaline	high alumina basalt	feldspathic basalt
A3009	Ajo, AZ	subalkaline	calc-alkaline	andesite	basaltic andesite
N3023	Cortez, NV	subalkaline	tholeiite	quartz tholeiite	tholeiite
A6005	Tonopah, AZ	subalkaline	calc-alkaline	andesite	tholeiite(?)

Table 6.1c: Chemical and petrographic characterization of basaltic rocks from Southern Nevada and neighboring areas in California

No.	Locality	Pb Isotopic Province	Chemical Characterization			Petrographic Name
			Suite	Series	Name	
N5024	Lunar Crater, NV	BR	alkaline	potassic	alkaline picrite	basanitoid
C4025	Baker, CA	BR	alkaline	potassic	alkaline olivine basalt	alkaline olivine basalt
C5009	Death Valley, CA	SN	alkaline	potassic	alkaline olivine basalt	feldspathic basalt
C3013	Deep Springs, CA	BR	alkaline*	potassic	alkaline olivine basalt	olivine-augite basalt
N6040	Lathrop Wells, CA	SN	alkaline*	potassic	alkaline olivine basalt	feldspathic basalt
C3014	Owens Gorge, CA	SN	alkaline*	potassic	trachybasalt	olivine basalt
N5023	Leith, NV	SN	subalkaline	calc-alkaline	high alumina basalt	basaltic andesite
N6036	Volcanic Hills, NV	BR	alkaline*	potassic	trachybasalt	feldspathic basalt
N6034	White River, NV	SN	subalkaline	calc-alkaline	high alumina basalt	feldspathic tholeiite

*These rocks have some characteristics diagnostic of an alkaline suite and others diagnostic of a subalkaline suite. They contain normative hypersthene, together with normative diopside and olivine. They tend to be somewhat high in total alkali, and $K_2O/Na_2O > 1$ in two cases and $K_2O/Na_2O > 0.5$ for the other two rocks. It would appear that these particular samples display some affinity to the shoshonitic suite.

(2) Neglecting the two samples mentioned above, Table 6.1 indicates that most of the Quaternary basalts from the Southwest have an alkaline character. This is in agreement with Leeman and Rodgers' (1970) conclusion that late Cenozoic Basin and Range basalts are predominantly alkaline.

(3) However, the data in Table 6.1 seem to confirm the petrographic conclusion that Tertiary basalts in the Basin and Range province are chemically quite different from the Quaternary basalts of the same region. The older rocks appear to be predominantly subalkaline and calc-alkalic in nature, rather than alkaline like the Quaternary basalts. This might suggest that the nature of volcanism in the southwest changed sometime during the late Tertiary. Perhaps this hypothesized shift from calc-alkalic to alkalic basalt volcanism may relate to the Lipman et al. (1972) conclusion that volcanism in the western United States has changed from a fundamentally andesitic to a fundamentally bimodal basalt-rhyolite character during late Cenozoic times. However, the timing of these two volcanic transitions may be different. Christiansen and Lipman (1972) have indicated that in most areas the transition from andesitic to basalt-rhyolite volcanism occurred approximately 10-30 my ago, following a pattern in time and space which they related to Cenozoic plate tectonic interactions. The transition from calc-alkalic to alkalic basalt volcanism may have occurred more recently, perhaps 5-10 my ago. Unfortunately, the lack of precise dates on most of the Tertiary samples of this study makes it difficult to examine the timing of this transition from calc-alkalic to alkalic basalt volcanism in more detail.

(4) There are only two Tertiary samples that were found to have a tholeiitic rather than a calc-alkalic character. Both are from northern Nevada, and therefore appear relevant to a hypothesis put forward by McKee and Mark (1971). McKee and Mark (1971) argued that the "Snake River volcanic province extends about 100 miles, in a southerly direction, from Idaho into [the Basin and Range province] of Nevada." They base this conclusion on the similarities in chemical and Sr isotopic properties between Snake River Plain basalts and the basalts capping the Sheep Creek Range near Battle Mountain, Nevada. Both areas are characterized by tholeiitic basalts with Sr isotopic ratios somewhat enriched ($^{87}Sr/^{86}Sr \sim .706$) relative to normal, oceanic tholeiites ($^{87}Sr/^{86}Sr \sim .704$). Sample N3027 was collected some 40 miles south of the Sheep Creek Range and is also tholeiitic; it could be interpreted to extend the Snake River Plain volcanic province even farther south in the Basin and Range province. However, two bits of evidence which tend to conflict with the McKee and Mark interpretation must be considered. First, both tholeiitic samples examined in this report as well as the rocks studied by McKee and Mark are mid-Miocene in age, much older than most of the volcanics in the Snake River Plain. Second, the Pb isotope ratios of this work's two tholeiites are typical of BR type data, and considerably different from the type of lead data reported for the volcanics of the Snake River Plain (Leeman, 1970). The Basin and Range tholeiites have lead ratios which fall considerably off the secondary isochrons defined by Leeman's Snake River Plain volcanic rocks. In addition, the Basin and Range tholeiites tend to

have $^{206}Pb/^{204}Pb$ ratios ($\sim$19.0) considerably more radiogenic than the Snake River Plain tholeiites ($\sim$18.1). These data would not seem to support the hypothesis that some of the volcanics in northern Nevada belong to the Snake River Plain volcanic province - that is, unless Pb provincialism and chemical and Sr isotopic regionalism are independent of one another.

(5) It can be seen in Tables 6.1a and 6.1c that a number of alkaline basalts from the Basin and Range province have potassic chemistries. In comparison, the alkaline volcanics from the Colorado Plateau consistently seem to have sodic chemistries. It also appears that the potassic BR rocks may be localized to a few areas. All three of the Potrillo basalts and both basalts from the San Bernadino volcanic field seem to be potassic while volcanic rocks from neighboring areas display sodic or subalkaline chemistries. An impressive concentration of potassic volcanism occurs in a belt along the southern portion of the California-Nevada border running, at the very least, between Baker, California on the south and Tonopah, Nevada on the north. All seven of the basalt samples from this area are potassic; analyses from surrounding areas tend to be alkaline-sodic or subalkaline. This potassic character appears to be independent of sample age, since these potassic rocks range from 11 my to Holocene in age. It is also striking that potassic chemical characteristics appear to occur independently of lead isotopic properties. Many of the potassic volcanics along the California-Nevada border are characterized by anomalous, SN type Pb systematics, but there are also potassic volcanics with typical BR type

leads. Moreover, volcanic rocks from the eastern portion of the SN lead province are subalkaline rather than alkaline-potassic like the rocks found to the west. Thus chemical provincialism observed in the southern Nevada area appears to be independent of the lead isotopic provincialism observed in the same region.

6.3 Isotopic Uniformity and Diversity in the Basin and Range Province

Volcanic rocks from local areas of the Basin and Range province do not exhibit the isotopic variability found in individual Colorado Plateau volcanic fields. BR volcanic rocks from specific areas tend to be isotopically homogeneous, especially if they are of the same age and chemical composition. However, rocks from different areas display distinguishable ranges in $^{206}Pb/^{204}Pb$. Furthermore, $^{207}Pb/^{204}Pb$ values, and to some degree $^{208}Pb/^{204}Pb$ values, vary within local areas of the Basin and Range province in accordance with variations of sample age and/or chemistry.

Figure 6.1 illustrates some of these points. Note, for example, that lead data on Quaternary basalts from the Mohave desert (data field #8) seem to group together in one part of the α-β diagram shown in Figure 6.1a. Analyses on Quaternary basalts from southern Arizona (data field #9), southern New Mexico (#10), and one portion of the Rio Grande rift (#7) all appear to define distinct fields on the diagram.

Figure 6.1a also shows that the data field characterized by the highest $^{207}Pb/^{204}Pb$ ratios (data field #1) is defined by two Oligocene andesite and dacite samples. The data fields displaying relatively low

Figure 6.1a: Data on volcanic rocks from a number of individual Basin and Range areas plotted on a $^{206}Pb/^{204}Pb$-$^{207}Pb/^{204}Pb$ diagram. Open circles represent alkaline basalts, those without a black dot indicate basanitic and alkali olivine basalt samples. Open circles containing a black dot are hawaiites and trachybasalts. Crosses indicate calc-alkaline samples, including high alumina basalts, andesites, and dacites. Small filled circles represent tholeiitic samples. Data fields have been numbered as follows: 1 = Oligocene andesite and dacite samples from north-central Nevada; 2 = Pliocene and Pleistocene basalts and andesites from northern California; 3 = Pliocene and Miocene, generally calc-alkaline basalts and andesites from northern and central Nevada; 4 = Late Miocene andesitic rocks from southern California; 5 = Pliocene and Pleistocene basalts from along the California-Nevada border; 6 = Miocene and Pliocene(?) basaltic andesites and andesites from southwestern Arizona; 7 = Quaternary alkaline basalts from the Rio Grande rift between Socorro and Las Cruces, New Mexico; 8 = Quaternary, generally alkaline basalts from the Mohave desert of southern California; 9 = Quaternary alkaline basalts from southern Arizona; 10 = Quaternary, generally alkaline basalts from southwestern New Mexico; 11 = Pliocene and Quaternary potassium rich basalts from southern Nevada. Note that two areas which do not exhibit "normal" Basin and Range lead isotopic behavior (#10 and #11) have been included in the diagram. The label "N5024" indicates a sample mentioned in the text.

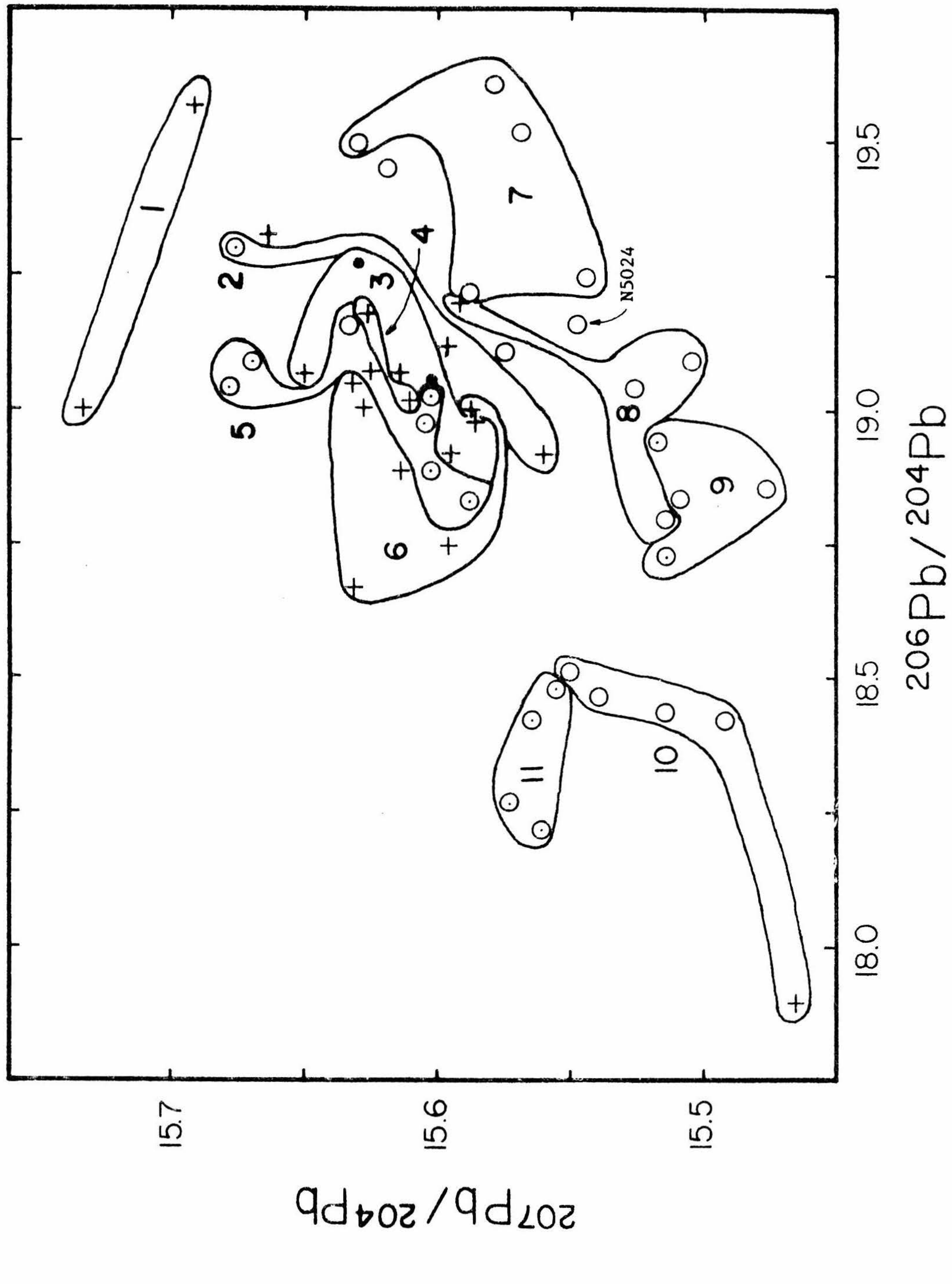

15.7
15.6
15.5
18.0
18.5
19.0
19.5
206Pb/204Pb
207Pb/204Pb
1
2
3
4
5
6
7
8
9
10
11
N5024

Figure 6.1a

Figure 6.1b: Data on volcanic samples from individual Basin and Range areas plotted on a $^{206}Pb/^{204}Pb$ - $^{208}Pb/^{204}Pb$ diagram. Symbols are the same as those in Figure 6.1a, with the following exceptions. Data on the Quaternary basalts of the Mohave desert (data field #8 in Figure 6.1a) are shown as solid diamonds. In addition data fields #3, #4, and #5 from Figure 5.1a have been grouped together in Figure 6.1b.

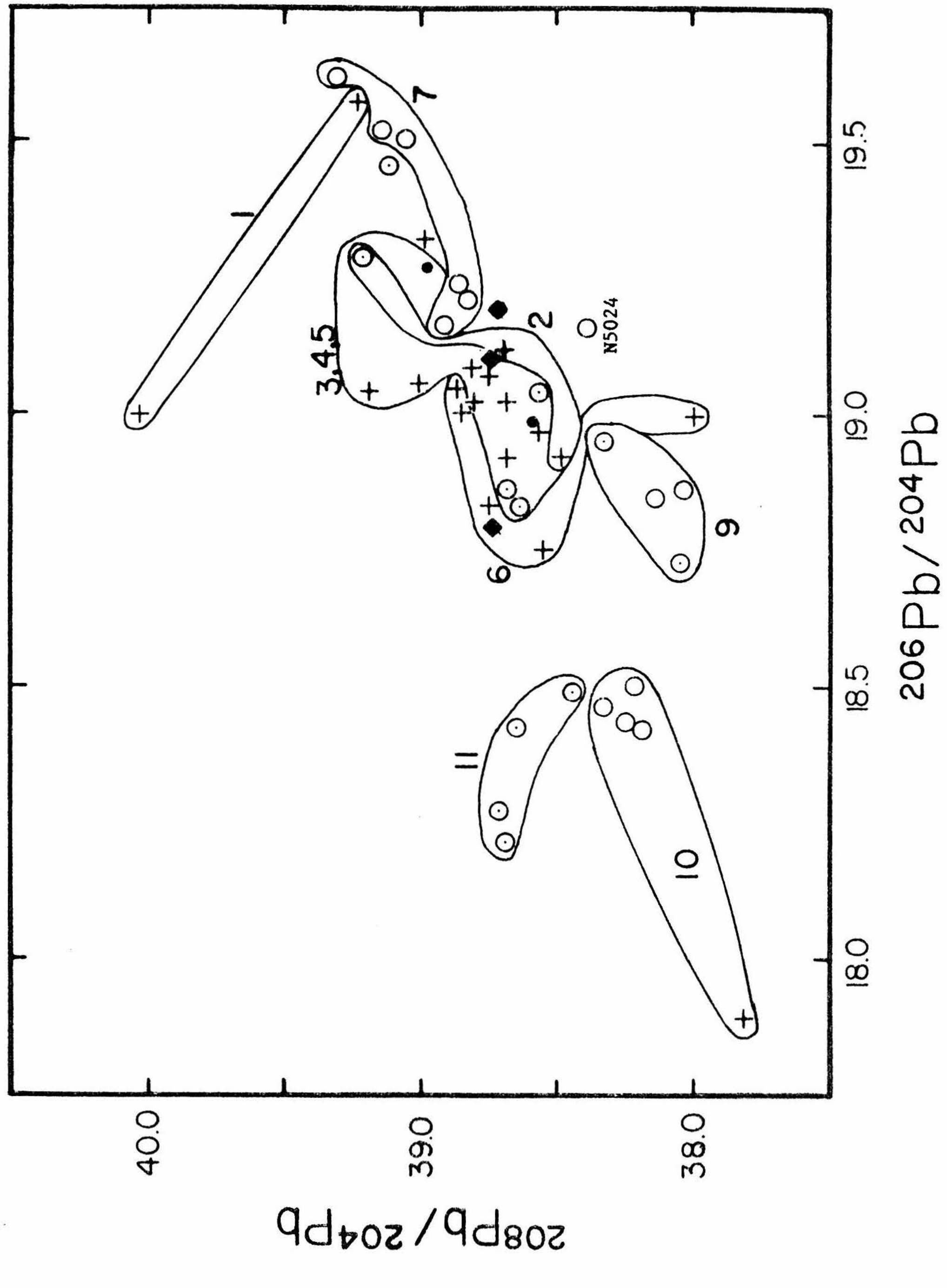

1
7
2
3,4,5
N5024
6
9
11
10
18.0
18.5
19.0
19.5
$^{206}Pb/^{204}Pb$
38.0
39.0
40.0
$^{208}Pb/^{204}Pb$

Figure 6.1b

$^{207}Pb/^{204}Pb$ ratios (#8, #9, and #10) belong to Quaternary alkaline basalts. Rocks with ages (Pliocene or Miocene) or chemical compositions (high alumina basalts, hawaiites, trachybasalts, basaltic andesites, and mafic andesites) intermediate between these extremes also tend to have intermediate $^{207}Pb/^{204}Pb$ ratios. For example, in Nevada a Quaternary basanite (N5024) has a relatively low $^{207}Pb/^{204}Pb$ ratio, Pliocene and Miocene, generally calc-alkaline basalts and andesites have distinctly higher $^{207}Pb/^{204}Pb$ ratios, and Oligocene andesite and dacite samples have still higher $^{207}Pb/^{204}Pb$ ratios. Similarly Pliocene and Miocene basaltic andesites and andesites from southern Arizona (#6) seem to have higher $^{207}Pb/^{204}Pb$ values than young basalts (#9) from the same area. It is significant, however, that young alkaline basalts and the older, commonly calc-alkaline volcanic rocks in each area have comparable ranges in $^{206}Pb/^{204}Pb$. Data points on all Arizona samples (data fields #6 and #9) have relatively unradiogenic $^{206}Pb/^{204}Pb$ values, while data from central and northern Nevada (#1, #3, and N5024) seem to display a more radiogenic range of $^{206}Pb/^{204}Pb$.

Figure 6.1b, a diagram that displays $^{208}Pb/^{204}Pb$ data in place of $^{207}Pb/^{204}Pb$ data, appears grossly similar to Figure 6.1a. The data groups in both diagrams display similar positions relative to one another. However, there appears to be somewhat less discrimination between young basalts and older, calc-alkaline volcanic rocks if one compares $^{208}Pb/^{204}Pb$ ratios rather than $^{207}Pb/^{204}Pb$ ratios. For example, the Quaternary alkaline basalts from the Mohave desert (black diamonds in Figure 6.1b) have $^{208}Pb/^{204}Pb$ ratios similar to many of the older calc-alkaline samples. And one old subalkaline sample from southern Arizona has a $^{208}Pb/^{204}Pb$ ratio as low as any of the young basalts from that region.

6.4 Basin and Range Basalts and Sialic Contamination

Although it is difficult to preclude crustal contamination in individual cases, sialic contamination does not seem consistent with either the uniformity or diversity of isotopic behavior seen in the Basin and Range province. For example, the alkali basalts and basanites of the Mohave desert have major element chemical compositions and low $^{87}Sr/^{86}Sr$ ratios (Peterman et al., 1970) which would seem to preclude sialic contamination. Quaternary basalts from southern New Mexico also have very mafic chemistries and apparently display low $^{87}Sr/^{86}Sr$ ratios (Leeman, 1970). The rocks of both areas are characterized by ultramafic xenoliths of possible mantle origin. One is drawn to the conclusion that the consistent $^{206}Pb/^{204}Pb$ differences between the rocks of the two areas are not the result of crustal contamination, but rather reflect primary heterogeneity in the mantle source regions of these rocks.

One might, however, hypothesize that the higher $^{207}Pb/^{204}Pb$ ratios exhibited by the older and relatively more "differentiated" rocks of the Basin and Range province reflect wall rock interaction on mantle derived magmas during their ascent through the crust. This proposition is difficult to defend on several grounds. In southern Arizona, southern California, and northern and central Nevada calc-alkaline rocks display $^{206}Pb/^{204}Pb$ ratios comparable to and $^{207}Pb/^{204}Pb$ ratios higher than alkaline basalts quite possibly of mantle origin. This suggests that the "contaminant" in each of these areas is similar, high in $^{207}Pb/^{204}Pb$ but comparable in $^{206}Pb/^{204}Pb$ to the mantle derived magmas. However, the crust in these different areas is very different in character. Southern Arizona and southeastern California have a Precambrian basement, the crust in north and central Nevada would seem to consist almost entirely of Cordilleran, generally Paleozoic sediments, and some samples from southern California come from areas where crust older than the Mesozoic is not known. It is hard to reconcile the diversity of crust in these different areas with the isotopic consistency apparently indicated for the "contaminating" crustal material.

The isotopic homogeneity seen in similar volcanic rocks from the same area is also difficult to understand in terms of magma interaction with crustal wall rocks. One would expect this type of contamination to be essentially random; some magmas would be quite contaminated while others would arrive at the surface essentially uncontaminated. Consequently, one would normally expect a fairly wide range in chemical and isotopic composition for the volcanics of every period in the Cenozoic. However, very few obviously uncontaminated basanites are observed earlier than the Quaternary, and few "contaminated" intermediate rocks are found later than the Tertiary in the Basin and Range province. Furthermore, rocks of similar ages from the same area display a fairly restricted range of isotopic composition. This would seem to imply that relatively constant amounts of isotopically uniform contaminating material were involved in the contamination process, or, more probably, that volcanic magmas have not incorporated significant amounts of crustal contaminant. It is also noteworthy that there does not appear to be an obvious correlation between $^{207}Pb/^{204}Pb$ and chemical composition. Both basalts and andesitic volcanic rocks can be seen to have similar $^{207}Pb/^{204}Pb$ ratios. Alkaline basalts from the Nevada-California border (data field #5 in Figure 6.1) display a range in $^{207}Pb/^{204}Pb$ similar to the subalkaline basalts and andesites of northern and central Nevada. Furthermore, petrologic evidence supporting crustal contamination (e.g., crustal xenoliths or peraluminous chemical compositions) appear rare or absent in the Basin and Range volcanics studied in this report.

It would thus appear that crustal contamination plays a relatively minor role in the petrogenesis of Basin and Range volcanic rocks. Instead, the chemical and isotopic characteristics of these rocks would appear to primarily reflect the nature of their source regions. Given the heterogeneity of the crust in different Basin and Range areas and the consistency of isotopic properties within and even between different BR areas, it is probably not likely that BR volcanics are derived from crustal sources. It is more likely that essentially all the volcanic rocks studied here were derived within the mantle.

6.5 BR Type and Oceanic/Arc Leads

Volcanics with BR type systematics have lead ratios comparable to similar volcanic rocks from oceanic and volcanic arc settings. Figure 6.2 shows the range of data exhibited by oceanic and volcanic (including

Figure 6.2a: The range of ^{206}Pb/^{204}Pb and ^{207}Pb/^{204}Pb ratios in volcanic samples from oceanic and volcanic arc settings (including continental magmatic arcs). Black dots represent abyssal basalts, which are characteristically tholeiitic, from mid-ocean ridge (M.O.R.) localities, and tholeiitic samples from the Hawaiian Islands. Crosses denote data from volcanic arc environments; these samples are generally calc-alkalic in their chemistries. Open circles indicate alkalic volcanics from oceanic islands. Data were obtained from Sun (1973), Oversby (1972), Church and Tatsumoto (1975), Sun, Tatsumoto, and Schilling (1975), Sun and Hanson (1975), Oversby and Ewart (1972), Church and Tilton (1973), Church (1976), and Armstrong and Cooper (1971).

Figure 6.2a

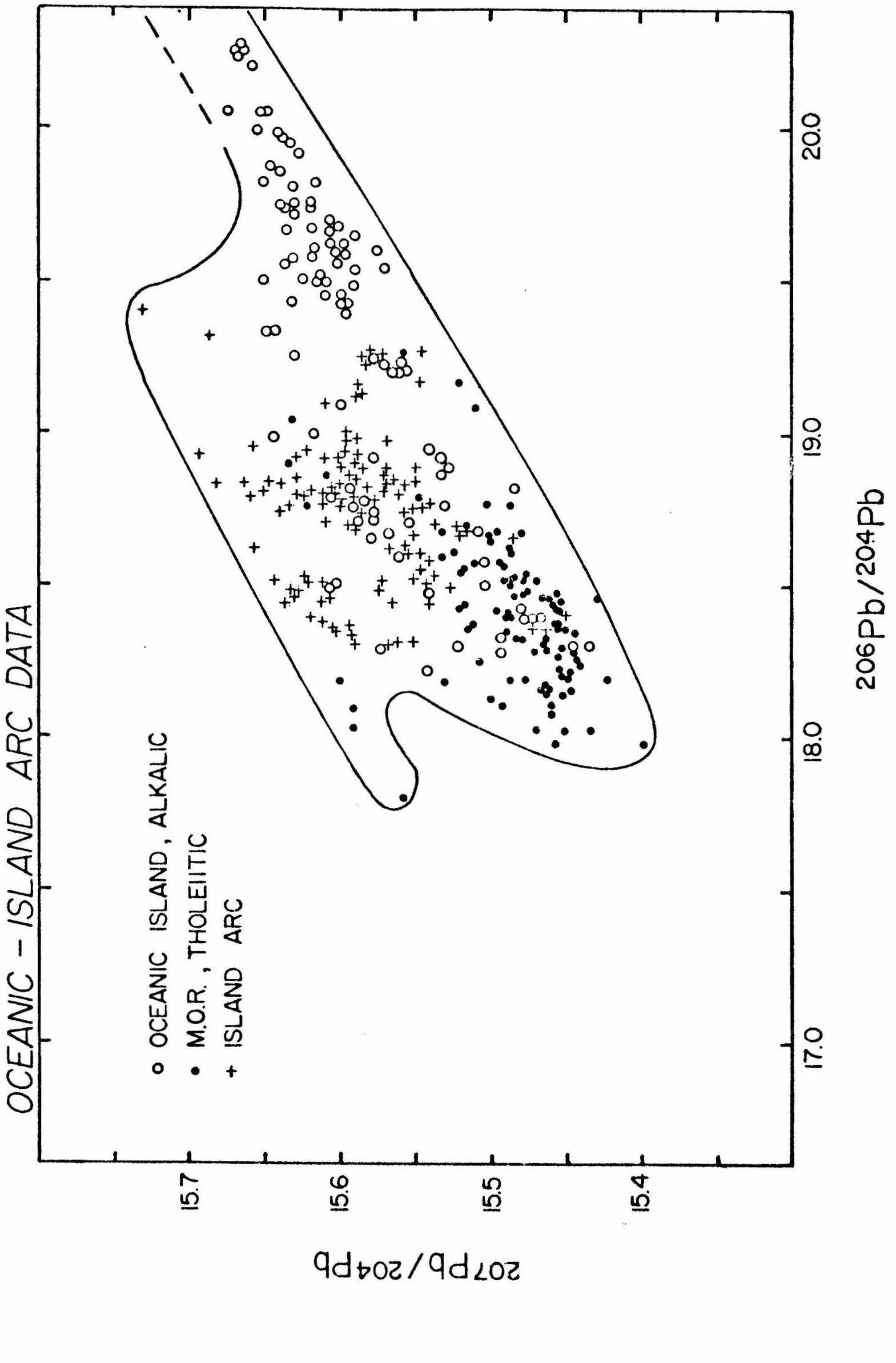

OCEANIC - ISLAND ARC DATA
o OCEANIC ISLAND, ALKALIC
• M.O.R., THOLEIITIC
+ ISLAND ARC
17.0
18.0
19.0
20.0
206Pb/204Pb
15.4
15.5
15.6
15.7
207Pb/204Pb

Figure 6.2b: $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios on volcanic rocks from oceanic and volcanic arc settings. Symbols and data sources are the same as Figure 6.2a.

Figure 6.2b

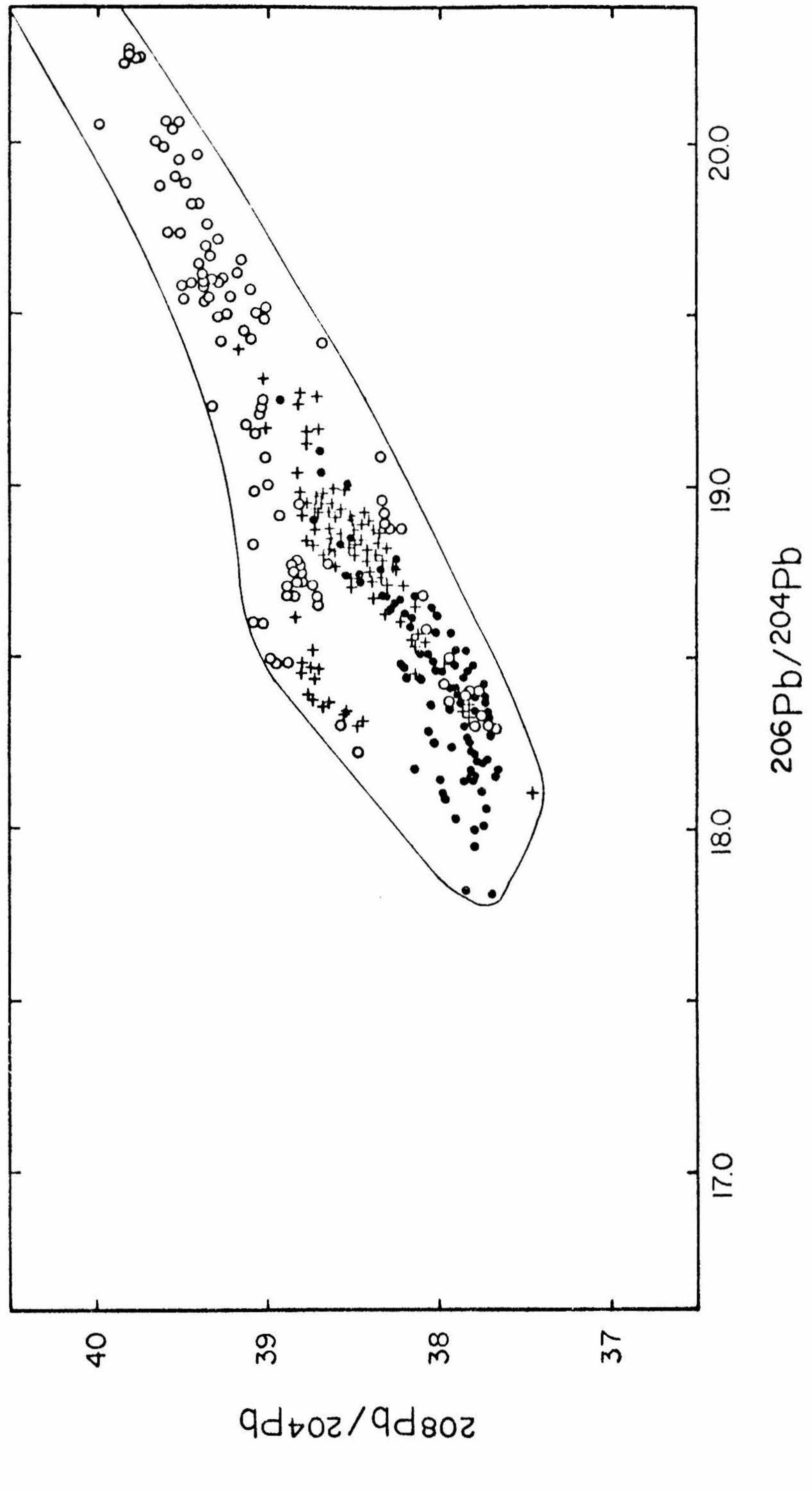


Figure 6.3a: $^{206}Pb/^{204}Pb$ data on volcanic rocks from the Basin and Range province. The data field described by the oceanic and volcanic arc data of Figure 6.2a is shown for comparison. Open circles indicate alkaline volcanic rocks, filled circles indicate tholeiitic basalts, and crosses indicate rocks with calc-alkaline affinities. Open circles containing a black dot are data from southern Nevada, and open circles with a horizontal bar are data from the Mexican Highlands of southwestern New Mexico. Volcanics from both areas are not considered to have typical BR type leads. The two crosses lying outside the oceanic-arc data field belong to Oligocene intermediate rocks from north-central Nevada.

Figure 6.3a

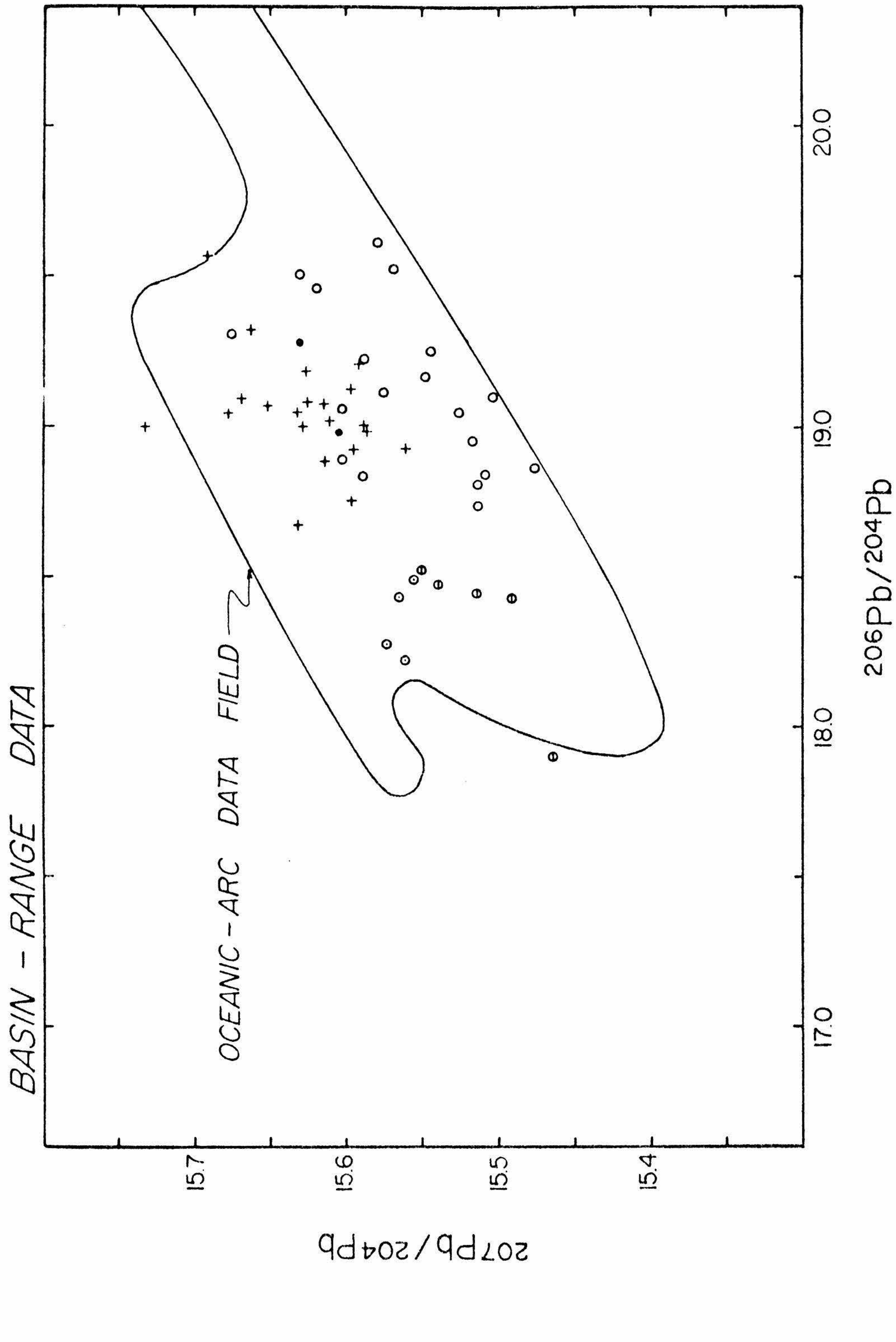
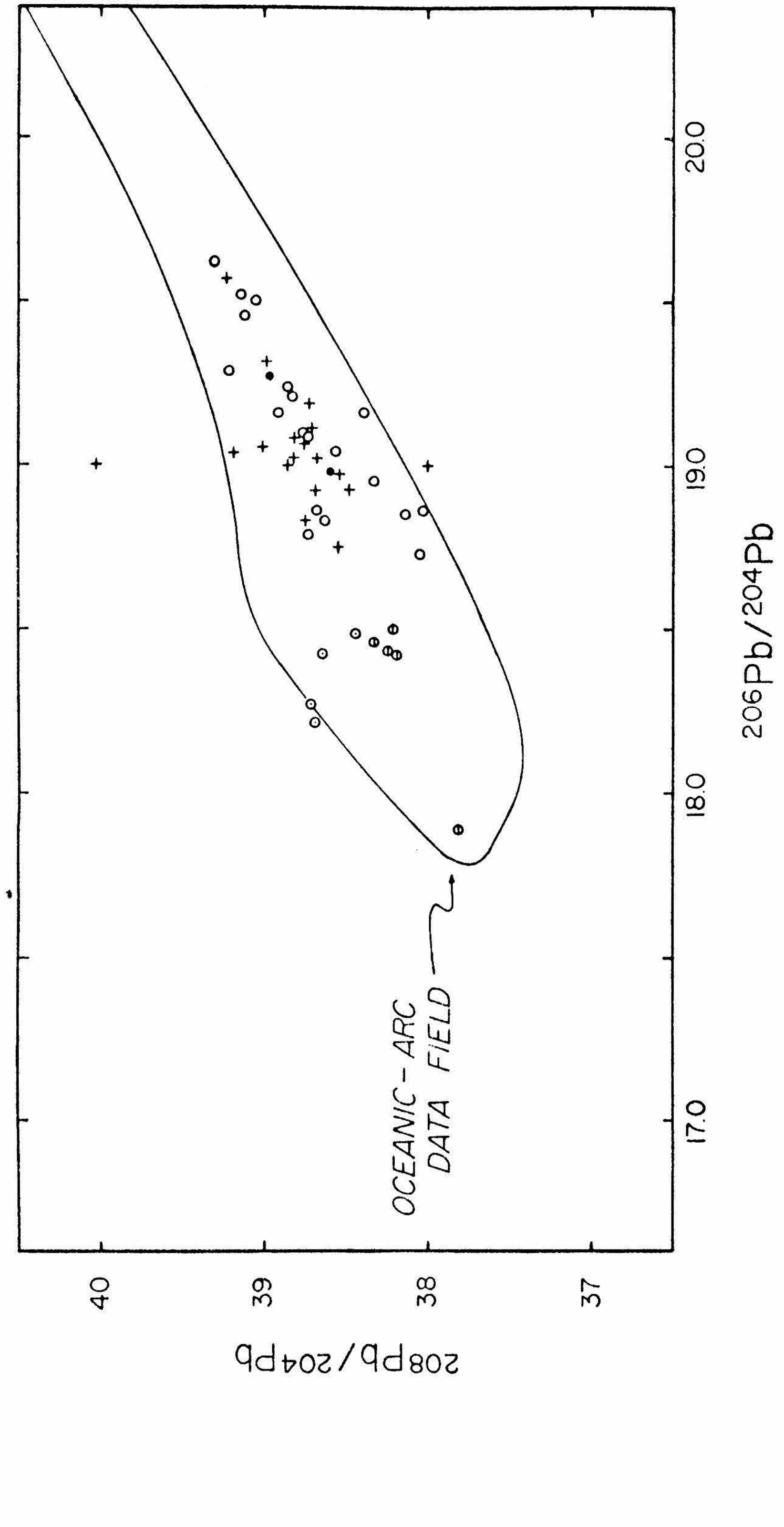

BASIN - RANGE DATA
OCEANIC - ARC DATA FIELD
17.0
18.0
19.0
20.0
$^{206}Pb/^{204}Pb$
15.7
15.6
15.5
15.4
$^{207}Pb/^{204}Pb$

Figure 6.3b: $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ data on volcanic rocks from the Basin and Range province compared to the oceanic-volcanic arc data envelope of Figure 6.2b. Symbols are the same as those used in Figure 6.3a. The cross lying above the oceanic-arc data field belongs to an Olgiocene dacite from Nevada; the cross lying below the oceanic-arc data field belongs to a Miocene(?) andesite from southern Arizona.

Figure 6.3b

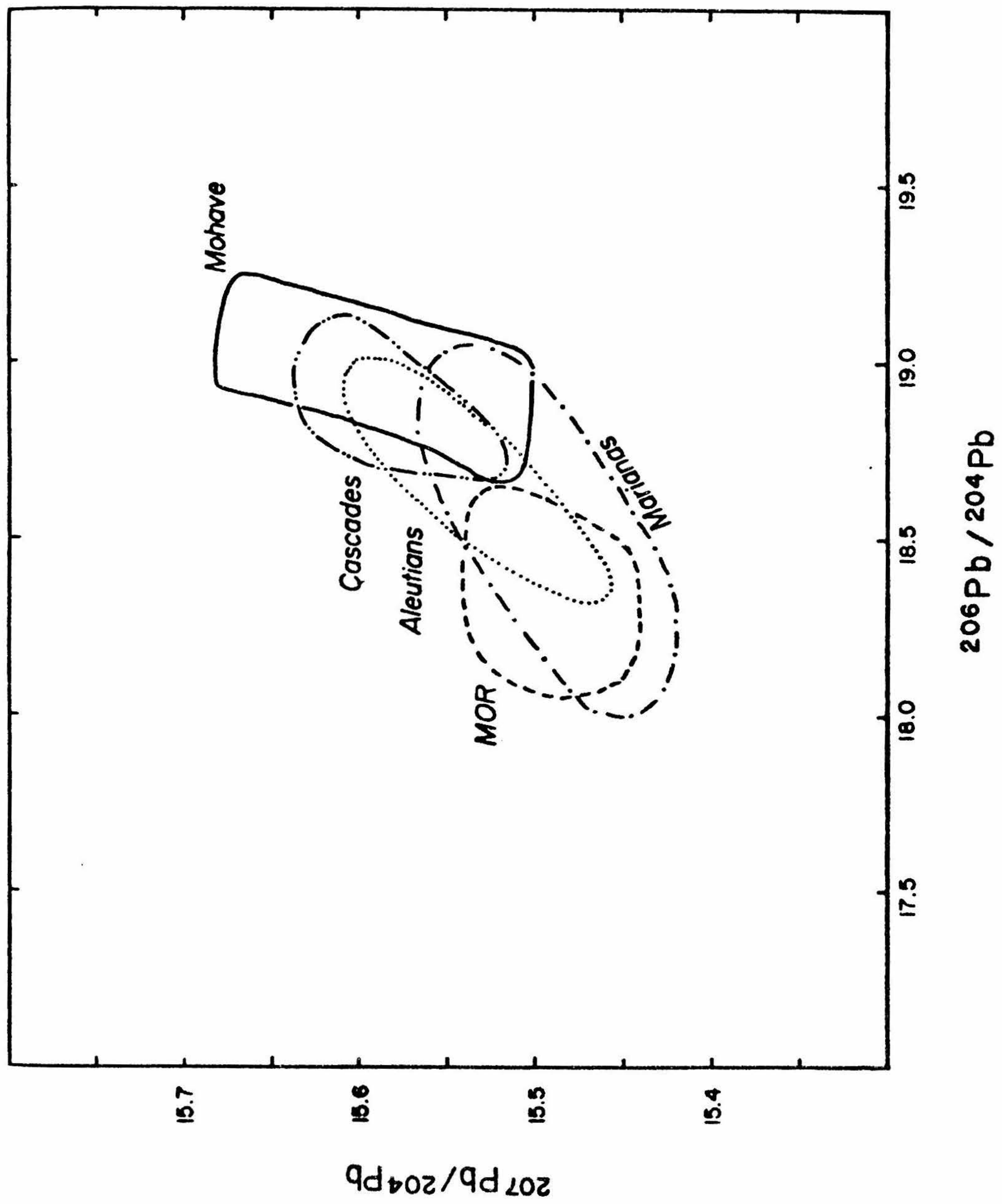

OCEANIC - ARC DATA FIELD
17.0
18.0
19.0
20.0
$^{206}Pb/^{204}Pb$
40
39
38
37
$^{208}Pb/^{204}Pb$

island and continental) arc rocks. $^{206}Pb/^{204}Pb$ ratios in this diagram run from approximately 18.0 to well above 20.0; $^{207}Pb/^{204}Pb$ ratios vary from 15.4 to at least 15.7. Oceanic tholeiites tend to occupy the unradiogenic portion of the data field while leads from alkaline island volcanics and calc-alkaline arc rocks tend to have more radiogenic $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ ratios. Arc data, in particular, exhibit an inclination towards higher $^{207}Pb/^{204}Pb$ ratios. Figure 6.3 shows that BR type leads, with only a few exceptions, fall with the range of data defined by oceanic and volcanic arc leads. Basin and Range basalts, which are predominantly of the alkaline olivine type, have leads comparable with leads from alkaline oceanic island volcanic rocks. The often older, andesitic to rhyolitic Basin and Range volcanics appear to possess relatively high $^{207}Pb/^{204}Pb$ ratios analogous to the calc-alkaline rocks from island arcs.

BR type leads share another attribute with leads from oceanic islands and volcanic arc environments. Taken as a whole, both BR and oceanic/arc leads display a fairly wide range in isotopic composition. However, data from individual localities appear much more homogeneous in their isotopic characteristics. Leads from individual oceanic islands or mid-ocean ridges (MOR) tend to form restricted clusters on a α-β diagram (see Figure 6.4). Island arc data define somewhat more extended clusters of data, perhaps because these samples come from larger areas and have a greater range in age. Similarly, samples from local Basin and Range areas, like the Mohave desert or the Potrillo volcanic field, exhibit a limited range in their lead isotope ratios,

Figure 6.4: Pb isotopic data from several oceanic and volcanic arc settings compared to data from the Mohave desert. Isotopic ratios from each area show a fairly limited range in isotopic composition. Each locality defines a data field which overlaps but which is not identical to the data fields defined by samples from other areas. Although their data fields are commonly elongate, oceanic and BR data do not generally show the well-defined covariance between $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ which characterizes data from the Colorado Plateau and other continental settings. The mid-ocean ridge (M.O.R.) data were from Sun (1973), as is the data from the Aleutians. The Marianas data are from Meijer (1976), and those from the Cascades were obtained from Church and Tilton (1973) and Church (1976).

Figure 6.4


Mohave
Cascades
Aleutians
MOR
Marianas
^{206}Pb/^{204}Pb
17.5
18.0
18.5
19.0
19.5
^{207}Pb/^{204}Pb
15.4
15.5
15.6
15.7

while data from larger areas show increased scatter in isotopic composition (see also Figure 6.1). This homogeneity suggests that the mantle sources for both BR and oceanic/arc volcanics are locally well stirred. In contrast, volcanic source regions in the continental lithosphere underlying the Colorado Plateau seem to have retained a local geochemical heterogeneity since Precambrian times (see Chapter 5).

Another consideration may bear on the interpretation of Basin and Range leads. A number of the California samples studied in this report come from near-coast areas, have calc-alkaline affinities, and ages indicating they were generated during a period of active subduction. Data on basalts and andesites from the Cascades (Church and Tilton, 1973), northern California obsidians of recent age, and a southern California Oligocene rhyodacite (Doe and Delevaux, 1973) fall into this category. Sample C3035, a 12 my old andesite from the San Francisco area, and C3006, a 25 my old andesite from southern California, might also be included. These subduction-related rocks have isotopic compositions indistinguishable from other BR type samples. The isotopic similarity of coastal and Basin and Range volcanic rocks suggest a corresponding similarity in source region characteristics.

Other geochemical data on BR type basalts also appear to be consistent with their derivation from "oceanic" mantle. Strontium ratios on basalts from areas characterized by BR leads are generally unradiogenic, with $^{87}Sr/^{86}Sr$ usually around .704 and almost always below .706. Data from the southern Cascades (Peterman et al., 1970a), the Mohave desert (Peterman et al., 1970b), the Basin and Range province of northern and central Nevada (Leeman, 1970; McKee and Mark, 1971), Arizona and New Mexico (Leeman, 1970) support this claim.

A few currently available Nd analyses on basalts from BR type areas also appear to be consistent with an "oceanic" mantle derivation for these volcanic rocks. DePaolo (1978) has reported ε_{Nd} values on three pertinent basalts. These include a sample from the southern Cascades (Mt. Shasta), the Mohave desert (Pisgah Crater), and Baja California (San Quintin). ε_{Nd} values on these basalts range from 4.6 to 6.7. These values are similar to those of oceanic island basalts, but lower than many MOR basalts.

The correspondence between Pb, Sr, and Nd isotopic data on oceanic island, volcanic arc, and Basin and Range basalts suggests that the source regions for these three groups of volcanic rocks are likewise similar. Oceanic island basalts are almost surely derived from the oceanic mantle. Arc volcanics are probably derived from sources within the mantle, although it has been argued that the calc-alkaline volcanic rocks from some arcs contain a component that was originally obtained from the oceanic crust (see, for example, Sun, 1973). It would also appear that the young basalts with Basin and Range type leads are also derived uncontaminated from the mantle (see Section 6.5). Consequently, it seems reasonable to propose that an "oceanic" or "island arc" mantle lies beneath the Basin and Range province in the southwestern United States.

6.6 Anomalous Isotopic Characteristics of Southern Nevada Samples

Chapter 4 suggested that samples from an area in southern Nevada and eastern California have anomalous isotopic characteristics. $^{206}Pb/^{204}Pb$ ratios on this area's volcanic rocks are anomalously low for normal BR type data. Southern Nevada (SN) basalts have $^{206}Pb/^{204}Pb$ ratios typically ranging between 18.2 and 18.5. Most BR type samples have $^{206}Pb/^{204}Pb \geq 18.7$. On the other hand, southern Nevada data points do not lie on the Colorado Plateau reference isochrons, do not define a linear array themselves on an α-β diagram, and appear to exhibit little local variation in isotope ratio (see Figure 4.15). They cannot, therefore, alternatively be considered CP type data. Figure 4.15 also indicates $^{208}Pb/^{204}Pb$ ratios on volcanics from this anomalous area are comparable, even perhaps somewhat higher than those of basalts from surrounding areas - in spite of their lower $^{206}Pb/^{204}Pb$ ratios.

In addition to their unusual lead characteristics, southern Nevada basalts appear to have especially radiogenic strontium isotope ratios. Leeman (1970) and Hedge and Noble (1971) reported $^{87}Sr/^{86}Sr$ ratios as high as .708 on basaltic rocks from near the California-Nevada border. A few additional data points (Hedge and Noble, 1971; Scott <u>et al</u>., 1969) indicate that radiogenic strontium ratios are to be found in the eastern part of Nevada too (see Figure 6.5).

Figure 6.5 and Figure 6.6 suggest a strong geographic correlation between $^{206}Pb/^{204}Pb$ and $^{87}Sr/^{86}Sr$ data. The degree of correlation suggested by Figure 6.6 is remarkable because in most cases lead and

Figure 6.5: A map showing lead and strontium isotopic data from southern Nevada and nearby regions in California. Open circles indicate leads with $^{206}Pb/^{204}Pb \geq 18.90$, half-filled circles indicate data points with $18.75 < {}^{206}Pb/^{204}Pb < 18.90$, and filled circles represent leads with $18.75 > {}^{206}Pb/^{204}Pb$. Open diamonds indicate data points with $^{87}Sr/^{86}Sr \leq .7055$, half-filled diamonds indicate data points with $.7055 < {}^{87}Sr/^{86}Sr < .7060$, and filled diamonds indicate data points with $^{87}Sr/^{86}Sr > .7060$. Lead data are from this report and Doe and Delevaux (1973), and includes several data points from intermediate and silicic volcanic rocks. Strontium data are exclusively on rocks of basaltic composition. Sources of the strontium data include Peterman *et al.* (1970), Hedge and Noble (1971), Leeman (1970), Scott *et al.* (1969), and Armstrong *et al.* (1972). Pb and Sr data points correlated for use in Figure 6.6 have been joined by lines. LA = Los Angeles, CA; B = Baker, CA; LV = Las Vegas, NV; and T = Tonopah, NV.

Figure 6.5

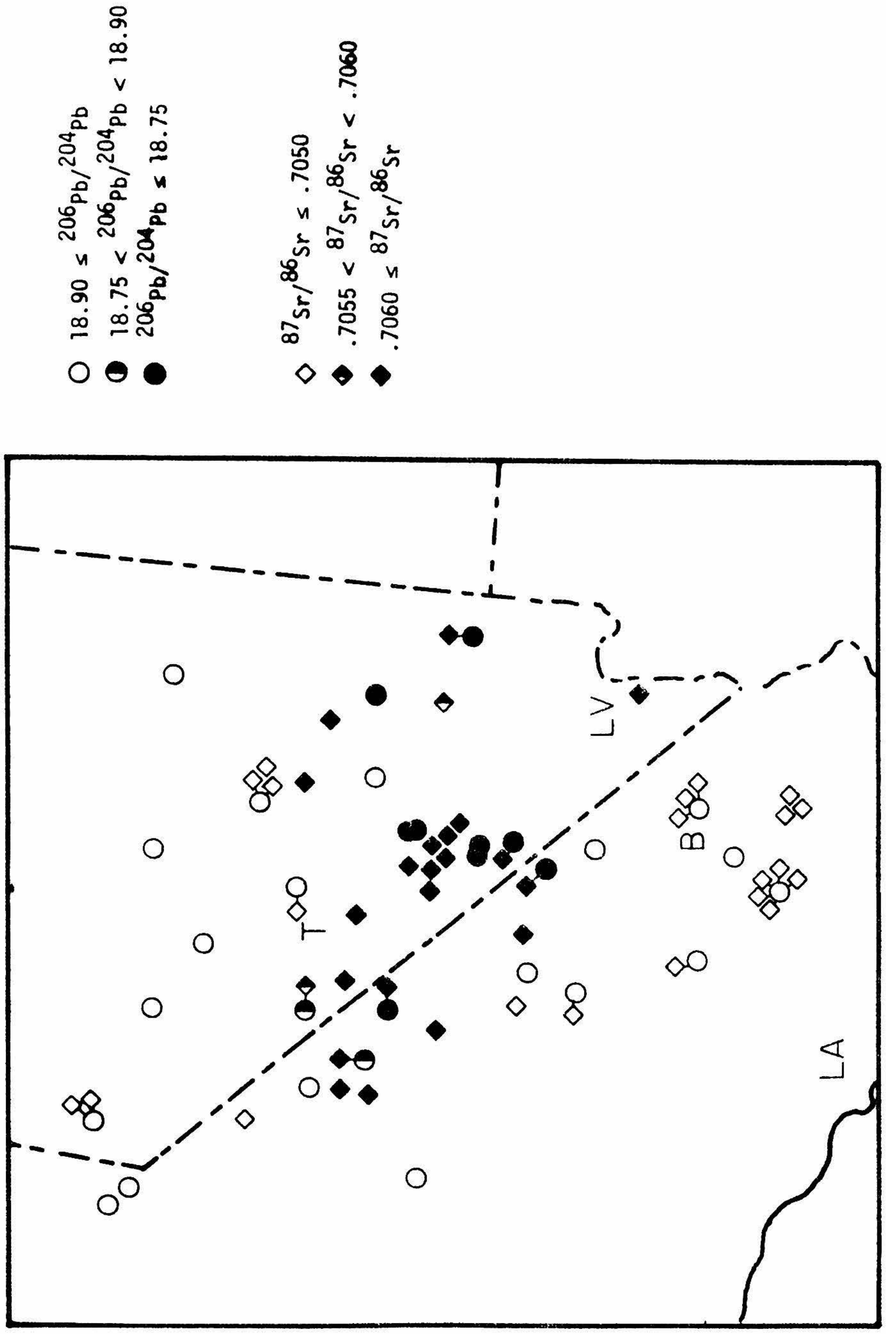
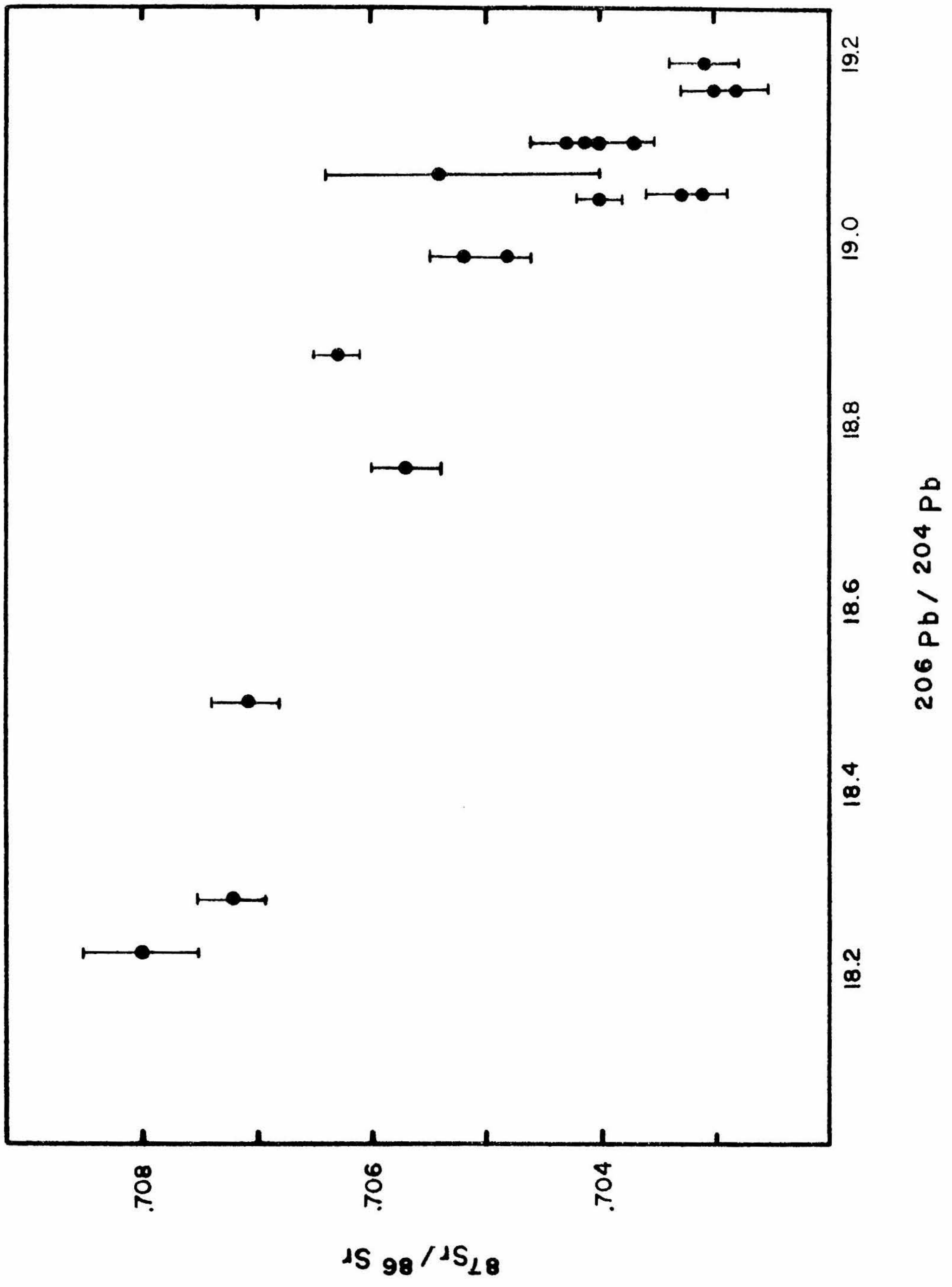

○ $18.90 \le {}^{206}\mathrm{Pb}/{}^{204}\mathrm{Pb}$
◐ $18.75 < {}^{206}\mathrm{Pb}/{}^{204}\mathrm{Pb} < 18.90$
● ${}^{206}\mathrm{Pb}/{}^{204}\mathrm{Pb} \le 18.75$
◇ ${}^{87}\mathrm{Sr}/{}^{86}\mathrm{Sr} \le .7050$
◆ $.7055 < {}^{87}\mathrm{Sr}/{}^{86}\mathrm{Sr} < .7060$
◆ $.7060 \le {}^{87}\mathrm{Sr}/{}^{86}\mathrm{Sr}$
LV
B
T
LA

Figure 6.6: Pb isotopic data and Sr isotopic data on geographically related basalt samples from southern California and southern Nevada. Locations of Pb and Sr samples used in this figure are shown in Figure 6.5, where each lead data point used in this figure is joined to the corresponding Sr data point(s) by a line. Pb data are from this report. Sr data are from Peterman *et al*. (1970), Hedge and Noble (1971), Leeman (1970), Scott *et al*. (1969), and Armstrong *et al*. (1972).

Figure 6.6



strontium samples were not from the same outcrops, and often not even from the same flow, but only from the same general area. This would suggest that there is not much isotopic variability in local SN areas, and that isotopic properties are strongly characteristic of each local area. It is interesting that the area defined by high strontium ratios appears to coincide rather well with the area exhibiting low $^{206}Pb/^{204}Pb$ values.

This SN area with "anomalous" lead and strontium characteristics also appears to have a number of distinctive geological and geophysical attributes. Eaton (1975) suggested that a fundamental, west-trending crustal boundary traverses southern Nevada. He has written that this boundary "is characterized by a steep north-facing gravity gradient of 70-100 mgals, a coherent zone of moderate seismicity...a west trending trough in the M-discontinuity, with relatively low crustal P velocities, and suggestive variation in Pn." He also indicated that this area was "the locus of abrupt northward thickening of the Phanerozoic section, and the southern limit of a dense concentration of metal mining districts."

Others have noted other differences between the southern and northern parts of the Great Basin. Wright (1976) has indicated that the tectonic style characterizing north-central Nevada is different from that found in southern Nevada. Southern Nevada, he concluded, is characterized by gently dipping normal faults and complementary strike-slip faults, while north-central Nevada features northeast trending, steeply dipping normal faults. Wright has estimated that the deformation field in northern Nevada implies up to 10% extension, while that in southern Nevada implies up to 50% extension.

It can also be noted that the area in southern Nevada having anomalous isotopic characteristics appears to coincide approximately with the northern limit of older Precambrian (Precambrian X and Y) outcrops in the Great Basin. It is also interesting that this "anomalous" area is located in the narrowest part of the Basin and Range province, and that it is physiographically distinct from the area to the north - being generally lower in elevation, and, at least in part, characterized by shorter, less well-defined mountain ranges.

6.7 Interpretation of SN Leads

The isotopic characteristics of southern Nevada (SN) basalts resist a unique or conclusive interpretation. Two previous Sr isotopic studies on these volcanics arrived at somewhat different interpretations: Hedge and Noble (1971) concluded that SN basalts were probably derived from unusual mantle material; while Leeman (1970) preferred a derivation from old, mafic lower crustal rocks. Although an unequivocal choice between these two models is not easily made, a number of constraints can be placed on the range of possible source region models.

(1) The high $^{87}Sr/^{86}Sr$ ratios of southern Nevada basalts immediately suggest crustal contamination. However, the strontium concentrations of SN basalts (up to 1600 ppm) relative to crustal rocks ($\sim$300 ppm) make sialic contamination an ineffective way of producing major changes in $^{87}Sr/^{86}Sr$ ratios. Hedge and Noble (1971) estimated that crustal material would have to make up 60% of the contaminated rock in order to change an original $^{87}Sr/^{86}Sr$ ratio of .7035 to .7070.

They conclude that "this is clearly impossible, for the resultant magma would in no way approximate a basalt in major element composition." Another consideration suggested by these authors is that the basalts with the highest strontium concentrations also tend to have the highest $^{87}Sr/^{86}Sr$ ratios. The opposite would be expected were crustal contamination occurring. Nor did Hedge and Noble (1971) find a positive correlation between $^{87}Sr/^{86}Sr$ and Rb/Sr ratios that would be indicative of mixing.

The isotopic homogeneity of SN basalt leads is also difficult to explain by wall rock assimilation. Assimilation would likely be a random process - some magmas would be heavily contaminated while others would remain essentially unaltered. In contrast, the isotopic compositions of SN basalts appear to be remarkably uniform. $^{206}Pb/^{204}Pb$ ratios vary between 18.2 and 18.5. A similarly narrow range is found in $^{87}Sr/^{86}Sr$ ratios (.7061-.7081) in the area characterized by anomalous leads. The magnitude of this scatter in isotopic ratio is comparable to that found in normal BR areas, and is difficult to reconcile with sporadic assimilation of crustal material.

The similarity of SN basalt leads to the leads of four SN rhyolitic rocks (Doe, 1970) is also difficult to reconcile with contamination models. This writer, like Hedge and Noble (1971) and Leeman (1970), is drawn to the conclusion that the isotopic peculiarities of southern Nevada volcanic rocks reflect unadulterated characteristics of a rather uniform source region which is not in the upper crust.

(2) The isotopic characteristics of SN basalts could not have developed during a short period of time; they must reflect long term geochemical properties of the volcanic source regions. Even assuming a very high source region Rb/Sr ratio of 0.24 (a typical upper crustal value), it would take 400 my to generate a $^{87}Sr/^{86}Sr$ = .707 from material that was originally isotopically similar to oceanic mantle. Furthermore, the relatively unradiogenic $^{206}Pb/^{204}Pb$ lead ratios of SN basalts imply low μ ($^{238}U/^{204}Pb$) values in the SN basalt source region. Even if a final stage $\mu = 0.0$ is assumed for the SN basalt source, it would take 600 my to develop the difference between Mohave desert and SN lead ratios. More reasonable estimates of source region μ and Rb/Sr values indicate that times greater than a billion years are necessary for SN source regions to establish their isotopic peculiarities.

(3) High $^{87}Sr/^{86}Sr$ ratios indicate that SN source regions have been enriched in Rb/Sr relative to Basin and Range, Colorado Plateau, and most oceanic volcanic source regions. Peterman and Hedge (1971) suggest, however, that most oceanic source regions have been depleted in Rb/Sr over geologic time, and that a typical, undepleted oceanic basalt would have an $^{87}Sr/^{86}Sr$ ratio of at least .7060. This might imply that the SN source regions may not have undergone much Rb enrichment, but that they have been protected from the Rb depletion affecting oceanic basalt source regions for a considerable length of time.

The lower $^{206}Pb/^{204}Pb$ ratios of southern Nevada basalts imply a depletion of uranium relative to lead in comparison to normal Basin and Range basalts. However, most BR basalt leads have large future model ages, indicating that sometime in their history their source region μ's were increased. Model ages of SN basalt leads are considerably closer to zero. This again may hint that SN sources have not undergone an absolute depletion in μ - only that their enrichment in uranium relative to lead has been less than many Basin and Range and oceanic island source regions.

The $^{208}Pb/^{204}Pb$ ratios of SN basalts are similar to BR basalt values. Thus the Th/Pb ratios of SN sources do not appear to be fractionated much relative to BR sources. However, the inferred depletion of SN sources in U/Pb seems to imply a corresponding increase in κ in order to keep $^{232}Th/^{204}Pb = (\mu \cdot \kappa)$ values relatively constant. Thus, the isotopic ratios of SN basalts indicate relative increases in Rb/Sr and κ and a decrease in μ relative to normal Basin and Range and many oceanic source regions during the Precambrian.

(4) Hedge and Noble (1971) note that a number of SN basalt Rb/Sr-$^{87}Sr/^{86}Sr$ data points lie to the left of the 4.6 by earth isochron. These rocks do not have enough Rb in them to account for their radiogenic Sr. This suggests a late stage depletion of rubidium relative to strontium. Lead and uranium concentrations measured on only two samples may record a depletion of uranium relative to lead also. Both samples (C5009 and N6040) contain high Pb concentrations (6 and 12 ppm, respectively) and somewhat low measured $^{238}U/^{204}Pb$ ratios (7.6 and 8.9). For comparison, most Basin and Range basalts have lead concentrations between 2 and 3 ppm and their measured $^{238}U/^{204}Pb$ ratios typically range from 9 to 30.

Hedge and Noble (1971) explain their Rb-Sr data by a model involving flotation of (Sr rich) plagioclase. Since plagioclase also contains relatively high Pb and low U concentrations, this model may also be consistent with the available U-Pb data. However, alternate explanations are also possible. A relatively modern episode of magma generation prior to the one that produced the young southern Nevada basalts could deplete SN source regions in Rb/Sr and U/Pb without having much effect on the source region's $^{87}Sr/^{86}Sr$ ratios.

(5) SN data do not imply a basalt derivation from ordinary oceanic mantle. The $^{87}Sr/^{86}Sr$ ratios (.7060-.708) of SN basalts are higher than most of the more radiogenic values found in oceanic basalts ($\sim$.7060). Most of the lead data on SN basalts do fall within the data field defined by oceanic data. However, oceanic basalts with leads comparable to SN leads are predominantly tholeiitic in character, while SN basalts are commonly alkalic. It is also difficult to reconcile the differences between normal BR and SN source regions if they are both "oceanic" in character. Why should the anomalous "oceanic" sources be localized along the boundary of Precambrian basement in the Great Basin? It is perhaps easier to rationalize the long term differences between BR and SN source regions if the SN sources have been associated with the continent for a considerable length of time, and BR sources have not. On the other hand, SN basalts do not display the isotopic characteristics of Colorado Plateau volcanics, which have been interpreted to come from stable, Precambrian continental lithosphere.

(6) The geochemical characteristics of southern Nevada basalts do not compellingly lead to a unique - or even satisfying - conclusion regarding the nature and history of their source regions. The localization of anomalous basalts to southern Nevada, an area with a number of anomalous geological characteristics, favors in this writer's opinion the view that SN basalt sources have been associated with the North American continent for a considerable length of time (1.5 by?). "Ordinary" mantle protected from plate tectonic processes for 1500 my or so might conceivably have the right Rb/Sr, μ, and κ values to make SN basalts; but gabbro and mafic granulite are alternate possibilities for the source material. The isotopic homogeneity of southern Nevada basalts could reflect an original homogeneity of their source regions, but large scale mixing of the source material during any one of a number of orogenic episodes could also result in a geochemical homogenization. Considerably more information is required before it is possible to do more than speculate about the nature and history of SN basalt sources.

6.8 The Mexican Highlands Transition Zone

The Mexican Highlands area of southern New Mexico (Figure 1.2) appears to have crustal and mantle characteristics intermediate between or different from those of surrounding regions. Structurally the area is part of the Basin and Range province, with alternating uplift ranges and downdropped basins. Topographically the Highlands area is considerably higher than many Basin and Range areas, with basin elevations between 4000 and 5000 feet, and with uplifted ranges even higher. These elevations would be typical of many Colorado Plateau province areas. Fenneman (1931), in fact, states that "in New Mexico the mutual boundary of the Colorado Plateau and the Mexican Highland... is probably not clear." Furthermore, the thickness of the crust beneath the Mexican Highlands also appears to be intermediate between the crustal thicknesses of neighboring regions. According to Warren (1969) the crust's thickness in the Basin and Range province of south-central Arizona is approximately 21 km, with crustal thickness increasing to 42 km beneath the Colorado Plateau. Pakiser and Zietz (1965) show the Mexican Highlands to have crustal thicknesses between 30 and 40 km. It might also be noted that the Mexican Highlands sit near the bottom of a broad low in the gravity profile running from Texas to the Pacific coast (Ramberg et al., 1978). The gravity values of the Mexican Highlands area seem to be more like those of the Great Plains than the Basin and Range province of Arizona. In addition, Herrin and Taggart (1962) indicate that the Mexican Highlands lie over an area of exceptionally high Pn velocities in the mantle. While many areas in the Basin and Range province have Pn's of 7.8 km/sec or less, some parts of the Mexican Highlands have Pn velocities as high as 8.2 km/sec. These values would be more typical of the mantle beneath the stable, cratonic areas of the Great Plains than the active, orogenic areas of the Basin and Range province.

In analogy to the area's geophysical characteristics, the lead isotopic characteristics of basalts from the Mexican Highlands of southern New Mexico are also somewhat intermediate between those characterizing the Basin and Range province to the west and the Colorado Plateau province to the north (see Section 4.5). Southern New Mexico basalts have leads which are less radiogenic than most Basin and Range volcanics. On the other hand, data from local areas within the Mexican Highlands do not seem to display the isotopic heterogeneity characteristic of Colorado Plateau volcanic fields. Mexican Highlands data do seem, however, to fall near the CP reference isochrons. Figure 4.14 shows that if data from the New Mexico Mexican Highlands are grouped with data from the Basin and Range areas just to the west in Arizona, the resulting data field displays an elongation typical of BR type data If they are grouped with data points from the nearby Colorado Plateau, the resulting data field shows a position and an elongation characteristic of CP type data.

The discriminant function analysis of Chapter 4 suggested that leads from southwestern New Mexico are consistently of the Colorado Plateau type. Basalts from the Mexican Highlands, like other CP type volcanics, may then be derived from the continental lithosphere. Because Mexican Highlands leads do not display the isotopic heterogeneity characteristic of CP volcanic fields, one seems required to hypothesize that the mantle lithosphere beneath southern New Mexico has been extensively homogenized, perhaps by a large scale mechanical mixing process. If one were to average all the lead data from the Colorado Plateau of New Mexico, the resulting means would be rather similar to data from the Mexican Highlands. On the other hand, it is possible to speculate that the intermediate character of Mexican Highlands leads is due to extensive mixing of BR type and CP type source regions. In either case, a very efficient mixing of volcanic source regions seems to be implied.

6.9 Structural Characteristics of the Rio Grande Rift: Relationship to Isotopic and Petrologic Characteristics of Rift Basalts

The Rio Grande Rift consists of a series of fault bounded, sediment filled, northward trending basins which bisect the state of New Mexico. It is an area characterized by extensional tectonism, abundant late Cenozoic volcanism, and high heat flow. The structural similarity of the rift zone to the Basin and Range province has been noted by Hamilton and Myers (1966) (among others), who suggest that the rift zone, as part of the Basin and Range province, extends well into Colorado. However, the classic work of Fenneman (1931) on the physiographic provinces of the western United States includes the northern part of the rift zone in the Southern Rocky Mountain province, and interprets only the southern part of the rift as belonging to the Basin and Range province. Tectonic maps (e.g., Woodward *et al*., 1975) do indeed show structural differences between the northern and southern portions of the rift zone. The northern rift is a single continuous depression made up of a series of en-echelon basins, with successive basins being offset to the east as one proceeds northward. South of Socorro, New Mexico the rift zone broadens into a series of parallel basins separated by northerly trending ranges of pre-rift (mostly

Paleozoic and Mesozoic) sedimentary and (Precambrian) crystalline rocks. In southernmost New Mexico the rift zone merges indistinctly into the wider expanse of the Mexican Highlands section of the Basin and Range province.

The petrologic characteristics of rift zone volcanic rocks appear to be related to the structural characteristics of the area in which they erupt. Lipman (1969) concluded that basalts in the northern rift are, predominantly, tholeiitic in character while those in adjacent areas outside the rift have alkalic tendencies. Baldridge (1978) has suggested that basalts erupting at the "offset" between two successive en-echelon basins exhibit more chemical diversity (both alkalic and tholeiitic magmas) than basalts from other areas of the rift (tholeiitic magmas). Aoki and Kudo (1976) have also correlated the chemical properties of volcanic magmas to structural setting. They indicate that basalts from the northern Rio Grande rift, the southern Rocky Mountains, and the Great Plains have calc-alkaline differentiation trends. In contrast, the basalts of the Colorado Plateau, middle, and lower Rio Grande depression show a differentiation trend having moderate Fe enrichment. Aoki and Kudo (1976) also note that olivine tholeiites in New Mexico appear to be confined to the Colorado Plateau, the upper middle segments of the Rio Grande rift, and the margin of the Great Plains. Tholeiites appear to be completely lacking in the southern portion of the rift zone; only alkaline basalts are found south of Socorro, New Mexico.

The petrologic distinction between northern and southern rift volcanics is apparent even in the few samples collected for this study. Samples collected from the southern rift - the Potrillo volcanic field, the Jornada del Muerto volcanic field, the Elephant Butte, and Hillsboro areas - all seem to have the petrographic and chemical characteristics diagnostic of alkaline rocks. Glass poor samples from this area contain abundant olivine phenocrysts and groundmass grains, a distinctive purple-brown clinopyroxene (titanaugite), no orthopyroxene, and no plagioclase phenocrysts. In contrast, samples from the northern Rio Grande rift uniformly lack these distinctive alkaline characteristics. Many of these northern samples are similar to the feldspathic basalts of the Colorado Plateau. They commonly contain feldspar phenocrysts, abundant groundmass plagioclase, and trachytic textures. Olivine is less abundant in these feldspathic rocks, and hypersthene is occasionally observed in thin section. Rocks with quartz and alkali feldspar "xenocrysts" have also been observed in the northern rift area (Doe et al., 1969; Aoki, 1967). These "xenocrystic" rocks appear to be analagous to the basaltic andesites of the southwestern Colorado Plateau.

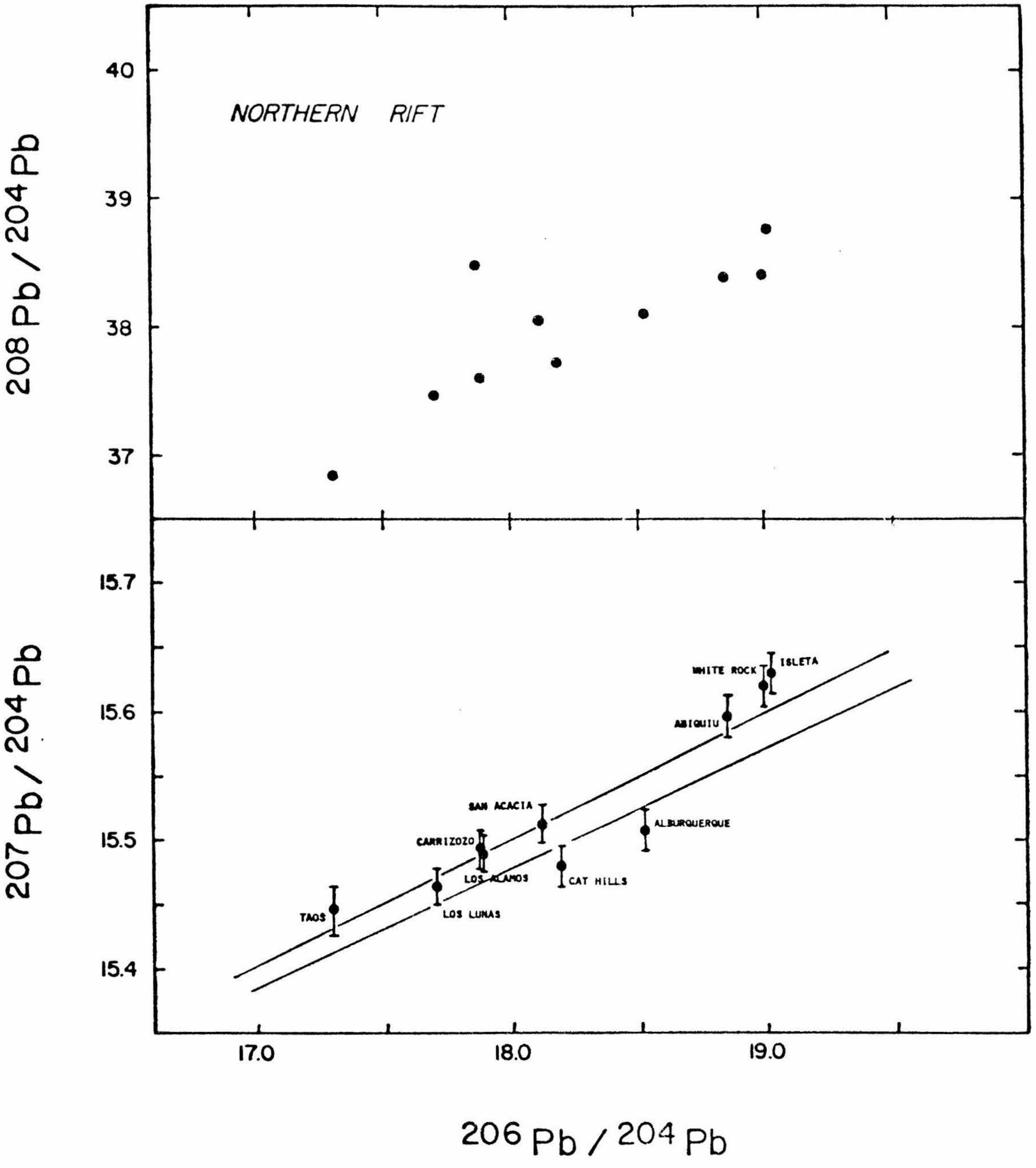
Kudo and others (1971) have related the strontium isotopic characteristics of New Mexico basalts to their major element chemical compositions. They report that $^{87}Sr/^{86}Sr$ ratios of nepheline normative basalts are uniformly low (.7028-.7044). Hypersthene basalts, on the other hand, exhibit a fairly wide range of isotopic ratios - many hypersthene basalts having $^{87}Sr/^{86}Sr \leq .7050$, but a few having ratios as high as .7078. Given the petrologic differences between southern and northern rift volcanics, these strontium isotopic differences may find an areal expression.

The lead data from this report clearly and strikingly display regional differences (see Figure 4.4). Samples from the Colorado Plateau areas of New Mexico display lead isotopic properties similar to those of the Colorado Plateau of Arizona and Utah. New Mexico CP data is generally unradiogenic but may exhibit, locally, large variations in isotopic ratio. New Mexico CP data points also seem to fall on the two isochrons defined by St. George area and Flagstaff-Prescott area data.

A number of samples located outside the boundaries of the Colorado Plateau in New Mexico also appear to exhibit CP type leads (see Figure 4.19). A basalt sample (NM7011) from the Recent Carrizozo flow, which borders on the Great Plains, has an unradiogenic lead easily interpreted to be of the CP type. Nine samples from the northern part of the Rio Grande rift (one from near San Acacia, three from near Los Lunas, one from near Albuquerque, three from the Jemez volcanic field, and one from near Taos) also appear to have leads resembling those of Colorado Plateau samples (see Figure 6.7). These include rather unradiogenic data points (e.g., with $^{206}Pb/^{204}Pb < 18.0$). Data from local areas in the northern rift also display a wide range in isotopic composition. For example, three samples collected in the Albuquerque-Belen basin within a few miles of one another - NM7013 from Cerro del Los Lunas, NM7014 from the Cat Hills flows, and 74-005

Figure 6.7: Lead isotopic data on volcanics from the Rio Grande rift north of Socorro, New Mexico. These data are similar to CP type data in several ways. First, unradiogenic ratios are commonly observed. Seven of the ten data points have $^{206}Pb/^{204}Pb$ ratios below 18.6 and four have $^{206}Pb/^{204}Pb$ values below 18.0. Second, large variations are found in samples from the same local area. For example, the Isleta, Cat Hills, and Los Lunas samples were collected within ten miles of one another, and the White Rock and Los Alamos sample localities are only a few miles distant from each other. Nonetheless, the Pb ratios from each of these local areas nearly span the entire range in isotopic composition observed in volcanics of the northern Rio Grande rift. Third, most of the samples lie on the two reference Colorado Plateau isochrons defined by data from the southwestern Colorado Plateau (Figure 3.11). However, the general dispersion of data around the CP isochrons appears to be somewhat greater than is typical for CP type samples.

Figure 6.7


NORTHERN RIFT
208 Pb / 204 Pb
40
39
38
37
207 Pb / 204 Pb
15.7
15.6
15.5
15.4
ISLETA
WHITE ROCK
ABIQUIU
SAN ACACIA
ALBURQUERQUE
CARRIZOZO
LOS ALAMOS
CAT HILLS
TAOS
LOS LUNAS
17.0
18.0
19.0
206 Pb / 204 Pb

from the Isleta volcano - range from 17.7 to 19.0 in $^{206}Pb/^{204}Pb$. In addition, most data from the northern Rio Grande rift appear to lie on or near the two southwestern Colorado Plateau reference isochrons (Figure 6.7). However, it should be noted that a few data points lie somewhat farther away from the CP reference lines than experimental error would appear to allow. Furthermore, in contrast to data from the St. George or Flagstaff areas data from individual volcanic fields in the Rio Grande rift do not seem to lie consistently on one isochron or the other. For example, the sample from Los Lunas lies between the isochrons, the one from Isleta lies above the St. George regression line, and the one from the Cat Hills lies below the Flagstaff-Prescott line. This would suggest that the volcanic source regions beneath the northern rift zone are rather more heterogeneous in their isotopic properties than the volcanic sources for the St. George or Flagstaff-Prescott areas. Perhaps the rift volcanic sources have had a more complex or longer Precambrian history than the volcanic source regions supplying the southwestern Colorado Plateau. Alternately, this heterogeneity might plausibly relate to Cenozoic tectonism in the rift zone. Clearly, more detailed lead isotopic work needs to be done to examine these problems.

The basalts from a more southern segment of the Rio Grande rift have lead isotopic characteristics very different from the rift volcanics to the north, and from the rift zone in the Mexican Highlands even farther to the south. The six basalt samples taken between Socorro and Las Cruces, New Mexico are characterized by extremely radiogenic leads. The $^{206}Pb/^{204}Pb$ ratios of these basalts range from 19.2 to 19.6, and include the most radiogenic $^{206}Pb/^{204}Pb$ ratios measured in this study. The $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios of basalts from this segment of the rift are also radiogenic. However, in proportion to the extremely high values of $^{206}Pb/^{204}Pb$, these are perhaps not quite as high as one might expect. $^{207}Pb/^{204}Pb$ ratios tend to lie somewhat to the low side of the CP reference isochrons (Figure 6.8), and $^{208}Pb/^{204}Pb$ data are not drastically higher than one would expect for a CP sample having an equivalent $^{206}Pb/^{204}Pb$ ratio.

The data from this section of the rift can easily be interpreted as Basin and Range type. The uniformly radiogenic ratios of this area's basalts seem to call for this conclusion, as does the limited scatter in data from local areas. Data from this central segment of the rift do not consistently fall on the CP reference isochrons. Nor do they appear to define an elongate data field on a α-β diagram. Thus the leads from this region seem quite typical of normal Basin and Range leads from, for instance, the northern Great Basin or southern California.

The northern extent of BR leads in the rift zone probably lies somewhere around Socorro, New Mexico. If this is true, there may be a correspondence between the isotopic properties of the rift volcanic rocks and the structural features of the rift. As mentioned previously, the rift zone seems to change in its structural character in the Socorro

Figure 6.8: Pb isotopic data on basalts from the Rio Grande rift between Socorro and Las Cruces, New Mexico. Note the radiogenic $^{206}Pb/^{204}Pb$ ratios of samples from this area as well as the lack of covariance between $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ ratios. The two southwestern Colorado Plateau isochrons (Figure 3.11) are shown for reference.

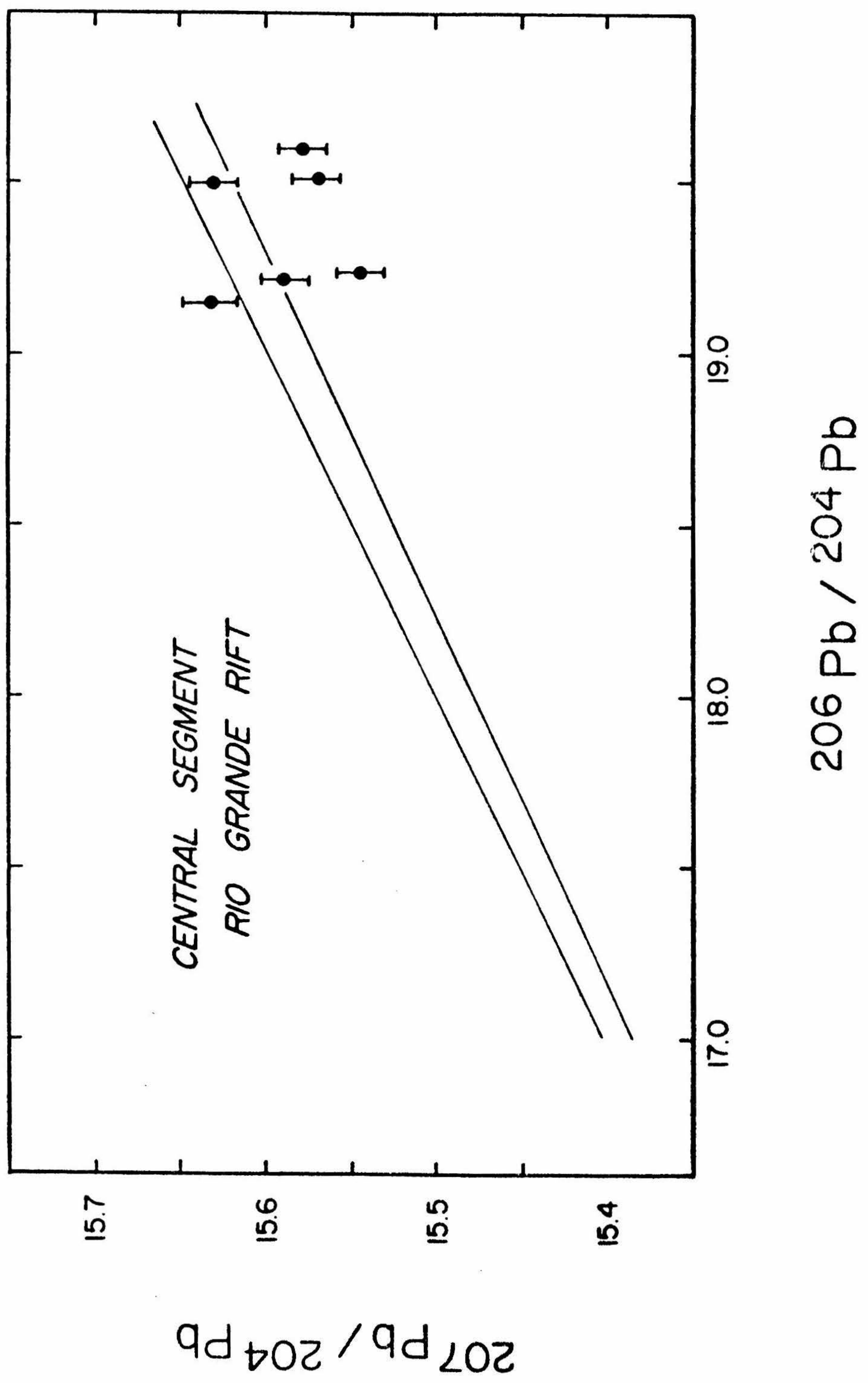

CENTRAL SEGMENT
RIO GRANDE RIFT
15.7
15.6
15.5
15.4
$^{207}Pb / ^{204}Pb$
17.0
18.0
19.0
$^{206}Pb / ^{204}Pb$

Figure 6.8

area. To the north it is a single, continuous depression; to the south the rift zone consists of a number of parallel basins separated by intrarift horsts.

The southern extent of BR leads in the rift zone might possibly be related to the boundary between the Mexican Highlands section of southern New Mexico and the more confined area of Basin and Range faulting in the rift zone to the north. However, an effective comparison between the lead isotopic data and the structural setting of the two areas is obscured by lack of lead data and the lack of a distinct structural boundary between the two regions.

6.10 Models for Rio Grande Rift Volcanic Sources

Basalts from different sections of the Rio Grande rift appear to display different types of lead systematics. This observation seems to imply that rift volcanics are derived from several different types of sources. Volcanics from the northern rift have leads similar to the volcanics of the Colorado Plateau. Extrapolating the conclusions reached in Chapter 5 into New Mexico, northern rift volcanics would be interpreted to have source regions in the mantle of the continental lithosphere. The isotopic and petrologic characteristics of basalts in the central segment of the rift zone appear analogous to volcanic rocks from oceanic islands. Like the Basin and Range type volcanics along the West Coast, these basalts might plausibly be derived from an "oceanic" mantle. The basalts from the Rio Grande rift south of Las Cruces (the Potrillo volcanic field) have leads indistinguishable from the other basalts of the Mexican Highlands. Although it is as yet difficult to interpret the leads from this area, their characteristics might indicate a derivation from homogenized continental lithosphere or perhaps a well-mixed combination of continental lithosphere and oceanic mantle.

The inferred presence of "oceanic" mantle under one section of the rift zone presents several problems. For example, one has to consider how this isolated "island" of oceanic mantle got beneath the rift zone. At one time the continental lithosphere-asthenosphere boundary must have been at considerable depth, 200-400 km beneath the surface (Jordan, 1975). Modern volcanic rocks are presumably derived from a low velocity zone which, geophysical studies seem to suggest, is at considerably shallower depths (∿90 km). The petrologic properties of rift basalts suggest that at least some of these basalts equilibrated at even shallower depths of 40-50 km. This seems to imply a penetration or upwelling of asthenospheric ("oceanic") mantle into the continental lithosphere. The consistency of isotopic properties in the rift section between Socorro and Las Cruces (∿150 km in length) suggests that this upwelling body of asthenosphere has a diameter comparable to the area characterized by oceanic leads. A greater regional diversity in isotopic properties might be expected if asthenospheric mantle was rising in volcano sized diapirs. Perhaps this large body of upwelling mantle hypothesized to exist beneath one segment of the Rio Grande rift is similar to the "plumes" called upon to explain the tectonism (e.g., doming and subsequent collapse) and volcanism found in the African rift system (Burke and Whiteman, 1973).

Geophysical studies present data which are, in several ways, consistent with mantle upwarp or upwelling. The high heat flow associated with the rift zone probably indicates the presence of hot (partially molten?) material at shallow depths beneath the rift (Reiter and others, 1975; Decker and others, 1975). Geomagnetic studies have revealed the presence of a thick layer of highly conductive material in the upper mantle (50-400 km) underlying the rift. Both the heat flow and geomagnetic data might be explained if deep, hot mantle were being transported to shallower depths. The gravity data of Ramberg and others (1978) also appear to be consistent with "a deep upwarp of the mantle that results in crustal attenuation." However, it should be noted that these geophysical studies have not singled out the rift zone between Socorro and Las Cruces as an area with special characteristics. Heat flow and geomagnetic data appear to be relatively consistent along the length of the rift. The contrast between isotopic and geophysical models for the mantle underlying the rift is puzzling.

And, although the structural distinction between the northern and southern portions of the rift zone appears to correlate well with the isotopic properties of rift basalts, there is no immediate and obvious reason for this correspondence. The structural, petrologic, and isotopic segmentation of the rift zone, and the relationship between these properties and the geophysical attributes of the mantle await further investigation.

CHAPTER 7: CONCLUSIONS

7.1 Interpretations from Previous Chapters

Three different types of regional isotopic systematics have been described in this report: one characteristic of Colorado Plateau volcanic fields, a second found in most areas of the Basin and Range province and in areas near the Pacific coast, and a third which appears to be peculiar to an area in southern Nevada.

The southern Nevada (SN) isotopic province covers a triangular area roughly 350 km on a side, and is distinguishable from neighboring Basin and Range areas by its structural, geological, and geophysical characteristics. It is characterized by volcanic rocks with relatively unradiogenic $^{206}Pb/^{204}Pb$ ratios (18.2-18.5) and relatively radiogenic $^{87}Sr/^{86}Sr$ ratios (.7060-.7080). The high strontium concentrations and the uniformity of Pb and Sr isotopic data found in the basalts of this province indicate that sialic contamination is probably not responsible for the area's isotopic characteristics. Instead, the isotopic properties of SN basalts appear to reflect the long term (≥1 by old) geochemical characteristics of their source regions in the mantle or lower crust.

Basalts from the Colorado Plateau are characterized by variable but commonly unradiogenic lead ratios ($^{206}Pb/^{204}Pb$ as low as 17.0) which define linear arrays on $^{206}Pb/^{204}Pb$-$^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$-$^{208}Pb/^{204}Pb$ diagrams. These linear arrays are best interpreted by a secondary isochron model, and suggest that CP basalts are being derived from a source region which was variably depleted in U relative to lead approximately 1.4-1.7 by ago. Most or all CP basalts are probably derived from the mantle, but it should be noted that the first continental crystalline crust in the southwestern United States also appears to have formed approximately 1.4-1.8 by ago and tends to be rich in uranium relative to lead. This suggests that the sources of CP basalts lie within the continental lithosphere, and that this continental lithosphere acquired its geochemical characteristics during the generation of the first crystalline crust in the Southwest.

There seems to be a rough but apparently significant correlation between chemical and isotopic composition in the Colorado Plateau volcanic suite. The more felsic volcanics tend to have somewhat less radiogenic leads than the more mafic basalts. Moreover, different regions (domains) in the Colorado Plateau seem to display distinguishable patterns of isotopic behavior. For example, data from one region may define an α-β regression that has a slightly greater slope than data from another region, or one area may be characterized by slightly higher $^{208}Pb/^{204}Pb$ ratios at equivalent $^{206}Pb/^{204}Pb$ values than another area.

Although these differences are real and significant, they are clearly subordinate to the general uniformity in lead systematics observed throughout the whole Colorado Plateau. As mentioned previously, all Colorado Plateau data appear to fall on one or the other of two similar secondary isochrons. Indeed, it has been noted that isotopic characteristics similar to those of the Colorado Plateau volcanic suite appear to be present in the volcanic rocks of other physiographic provinces (e.g., the Rocky Mountains, the Snake River Plain, and the Great Plains), and may extend continuously from the Mexican to the Canadian border (section 4.6).

The "Basin and Range" isotopic province is characterized by relatively radiogenic leads. $^{206}Pb/^{204}Pb$ ratios in BR basalts usually exceed 18.7. Within local areas (which may be hundreds of kilometers across) of the Basin and Range province, isotopic compositions appear to be relatively uniform, especially for samples of the same age and chemical composition. However, different areas within the BR isotopic province appear to exhibit seemingly distinct ranges in isotopic composition. In addition, there appears to be a variation in $^{207}Pb/^{204}Pb$ within local areas of the Basin and Range province which is dependent on sample age and chemical-petrologic affinity. Older (Pliocene and Miocene), calc-alkaline volcanics seem to have higher $^{207}Pb/^{204}Pb$ ratios (and to a lesser degree, higher $^{208}Pb/^{204}Pb$) than Quaternary alkaline volcanics.

BR basalts apparently have been derived uncontaminated from the mantle. The lead isotopic properties of BR basalts, as well as some Sr and Nd isotopic data, suggest mantle source regions for these rocks similar to those giving rise to oceanic island and volcanic arc basalts.

"Basin and Range" type isotopic systematics extend beyond the physiographic boundaries of the Basin and Range province, to other areas characterized by a history of extensive Phanerozoic orogenic activity.

For example, the Pacific border province, the Sierra Nevada, and the Cascades also seem to be characterized by volcanic rocks with BR type leads.

7.2 Mantle Heterogeneity in the Southwestern United States

Both BR and CP basalts are best interpreted to be derived uncontaminated from the mantle. It follows that the isotopic variability displayed within and between these two isotopic provinces reflects isotopic heterogeneity in the upper mantle.

Considerable isotopic variability is exhibited within individual Colorado Plateau volcanic fields, and a rough but apparently significant correlation appears to exist between the isotopic and chemical compositions of CP volcanic rocks. Feldspar rich basalts, whose chemical characteristics suggest a relatively shallow depth of derivation (∿40 km?), tend to have less radiogenic leads than olivine and clinopyroxene rich basalts, which seem to come from deeper in the mantle (∿60-80 km). This suggests that the continental lithosphere underlying the Colorado Plateau may be isotopically zoned or "stratified," becoming generally more radiogenic in lead (and apparently less depleted in uranium relative to lead) with depth. This might indicate that the episode of chemical fractionation which affected the Precambrian mantle was more strongly developed just beneath the crust than in the deeper parts of the lithosphere.

It is not clear, however, that this isotopic zonation can account for all the isotopic variability found in individual CP volcanic fields. It also seems feasible that the mantle underlying the Colorado Plateau is made up of isotopically distinct "nodules." These nodules might be the variously depleted source regions of Precambrian igneous rocks found in the crust, and may have dimensions measured in kilometers. Nodular heterogeneity would be able to account for the wide range in isotopic composition observed in rocks with similar chemical compositions, and with apparently similar derivation depths in the mantle.

The dimensions of the different regional isotopic domains observed on the Colorado Plateau seem to indicate that the mantle beneath this province is relatively uniform in its isotopic characteristics for areas some hundreds of kilometers across - rather more heterogeneous when considered on a larger scale (see Figure 7.1). Adjacent subprovinces or domains in the CP mantle may have slightly different differentiation ages, initial lead isotopic compositions, average μ values, or average κ values. Understanding the differences between these different isotopic domains is a fascinating but difficult problem. Further work on this topic may allow one to assess the isotopic heterogeneities already developed in the Precambrian mantle prior to formation of the lithosphere. Such studies might also allow a detailed examination of the pattern of lithosphere formation and Precambrian continental accretion in the southwest.

Different regions within the Basin and Range province also appear to exhibit distinguishable ranges in lead isotopic composition, especially if one compares rocks having similar ages and chemical compositions. This seems to imply that the mantle underlying the Basin

Figure 7.1: Map of the southwestern United States showing isotopic province boundaries as heavy black lines. BR = Basin and Range isotopic province; CP = Colorado Plateau isotopic province; and SN = Southern Nevada isotopic province. Dashed lines show the conjectural boundaries of various isotopic domains within the several isotopic provinces. These subprovince boundaries are only intended to display the approximate dimensions and plausible locations of areas displaying homologous isotopic characteristics within each isotopic province. These dashed boundaries should be regarded as extremely tentative.

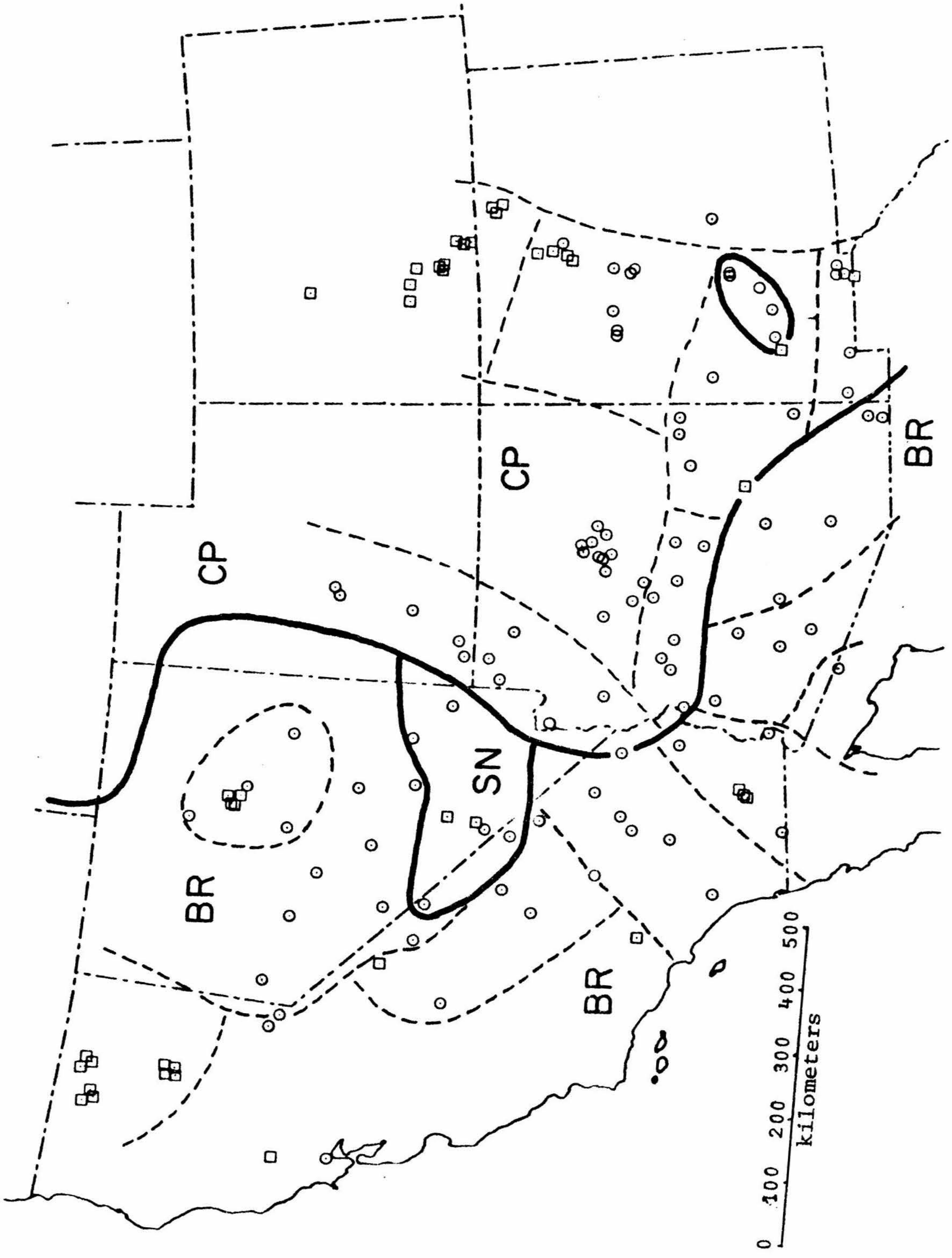


Figure 7.1

and Ranges may be laterally homogeneous for distances measuring up to several hundred kilometers, but somewhat more heterogeneous when considered at a larger scale (see Figure 7.1). In some cases lateral changes in isotopic properties appear sharp. For instance, the Quaternary alkaline basalts from the southernmost Rio Grande rift (south of Las Cruces, New Mexico) are dramatically different from those from the Rio Grande rift just to the north of Las Cruces. It might also be noted that the isotopic differences between basalts in southern Nevada and neighboring, typical BR type areas are also dramatic and geographically sharp. In other cases the isotopic differences between different, neighboring areas seem to be gradational in character. For example, the isotopic compositions of Quaternary basalts from southern California are similar to but slightly more radiogenic in $^{206}Pb/^{204}Pb$ than the Quaternary basalts of southern Arizona.

It has also been noted that within the same local area in the Basin and Range province, the Quaternary alkaline basalts tend to have lower $^{207}Pb/^{204}Pb$ ratios than older, Pliocene and Miocene, generally calc-alkaline volcanic rocks. This would suggest that the calc-alkaline volcanic rocks in the Basin and Range province are being generated from sources different from those giving rise to the Quaternary alkaline basalts. These differences might conceivably relate to differences in source region depth or chemical composition. It is alternatively possible that the character of the mantle underlying BR type areas has changed during the late Cenozoic, perhaps due to tectonic processes related to Basin and Range development.

Both BR and CP isotopic provinces have dimensions measured in thousands of kilometers. It is difficult to interpret these large scale regional differences in terms of small scale mantle heterogeneities. For example, it is possible to hypothesize that the mantle beneath the southwestern United States is macroscopically homogeneous but heterogeneous on a microscopic or mineralogic scale, and that different conditions of partial melting in different areas, in conjunction with isotopic disequilibrium during melting, might be responsible for generating both BR and CP isotopic systematics. However, the chemical compositions of many BR volcanic rocks are similar to those of many CP volcanic rocks. This similarity would seem to imply that similar conditions of partial melting are found in both CP and BR type areas, so that isotopic differences between the two areas do not consistently appear to reflect different conditions of petrogenesis. It can also be noted that BR type isotopic compositions are not easily interpreted to be the radiogenic endmember in the CP population of isotopic compositions. CP type leads appear to be characterized by a very limited range in $^{207}Pb/^{204}Pb$ at a given $^{206}Pb/^{204}Pb$ value. BR leads show a much greater range in $^{207}Pb/^{204}Pb$ at a given $^{206}Pb/^{204}Pb$ value. Consequently, mixing radiogenic, BR type leads with unradiogenic, CP leads would give rise to mixing "triangles" rather than the linear arrays characteristics of CP volcanic fields. Similar "mixing" arguments might also be employed to show that it is unlikely that mantle heterogeneities meters or even kilometers in size can account for the differences between CP and BR type leads. Instead, these arguments suggest that BR and CP type leads are coming from distinctly different kinds of mantle. The general consistency of isotopic properties within an isotopic province suggests that basically the same type of mantle can be found over areas measuring up to thousands of kilometers in size.

It is pertinent to inquire about the spatial or topological relationship between CP and BR type mantle. If CP basalts are indeed being derived from ancient, Precambrian continental lithosphere, it is reasonable to expect that this continental lithosphere is normally continuous with the continental crust above. If BR basalts are being derived from an "oceanic" mantle, it is likely that this oceanic mantle is present as asthenosphere, presumably beneath the continental lithosphere. This reasoning might be taken to suggest that the southwestern United States is everywhere underlain by two layers in the mantle, continental lithosphere above and oceanic asthenosphere below. However, there is both geophysical and petrologic evidence that BR basalts are not consistently derived from greater depths than CP basalts, and that continental lithosphere may be missing in some areas of the southwestern United States. For example, Archambeau _et al_. (1969) indicated that the low velocity zone, a region in the mantle usually interpreted to be partially molten, is present at very shallow depths (30-40 km) beneath the Basin and Range province - that is, just below the crust. It is petrologically reasonable for at least some BR basalts to come from sources this shallow. Consequently, the lack of CP type leads in the Basin and Range province seems to indicate that CP type mantle (continental lithosphere) is missing in these areas. Furthermore, Archambeau _et al_. (1969) also indicate that the low velocity zone (LVZ) beneath the Colorado Plateau has its roof at somewhat greater depths, 70-100 km. Petrologic evidence also suggests that some CP magmas may come from depths as great as 80 km. Thus it would appear that BR basalts need not consistently come from greater depths than CP basalts. These considerations suggest that BR type ("oceanic") mantle may sit side by side with CP type mantle (continental lithosphere).

Figure 7.2 is a schematic east-west cross section which interprets the nature of the mantle beneath the southwestern United States in a way consistent with the geochemical results reported in this study. "Oceanic" mantle is presumed to lie beneath the coastal regions and much of the Basin and Range province. Continental lithosphere is interpreted to lie beneath the Colorado Plateau and the Great Plains. It might also be noted that in the Figure 7.2 model continental lithosphere is shown to extend some distance out into the Basin and Range province. This interpretation is required to accommodate the presence of CP leads in areas displaying a Basin and Range structural style. Figure 7.2 also suggests that there is an upwelling of "oceanic" type mantle beneath the Rio Grande rift. At the latitude of this cross section the zone of magma generation in the mantle does not appear to intersect this body of oceanic mantle. Farther to the south in the Rio Grande rift, there is an area whose volcanics are believed to derive exclusively from this upwelling asthenosphere.

Figure 7.2: A schematic east-west cross section across the southwestern United States at a latitude of approximately 35°N which interprets the nature of mantle under different areas according to the isotopic properties observed in each area's basalts. BR type, or "oceanic," mantle is shown as left slanting dashes. Dashes slanting to the right indicate CP type mantle, continental lithosphere. Fine variously orientated dashes show the presence of crystalline Precambrian basement in the crust. Black dots show conjectural depths of volcanic source regions based on the petrogenetic grid of Green (1971).

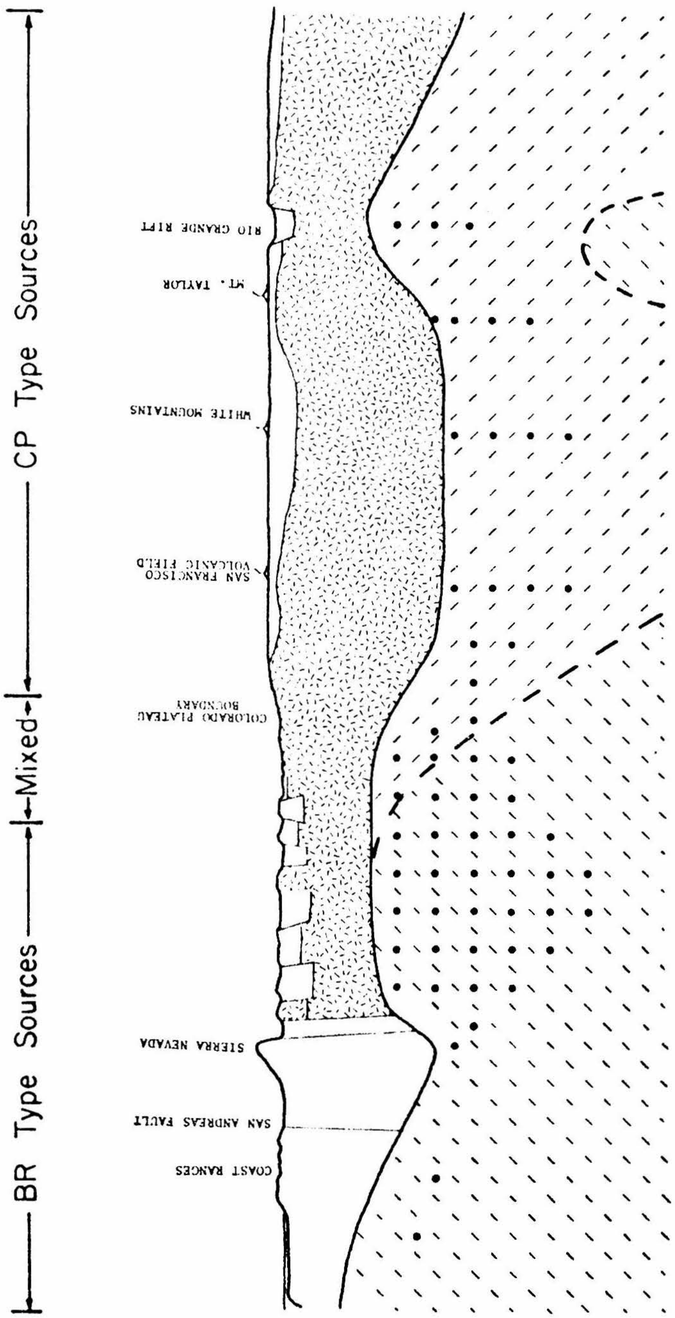

BR Type Sources
Mixed
CP Type Sources
COAST RANGES
SAN ANDREAS FAULT
SIERRA NEVADA
COLORADO PLATEAU BOUNDARY
SAN FRANCISCO VOLCANIC FIELD
WHITE MOUNTAINS
MT. TAYLOR
RIO GRANDE RIFT

Figure 7.2

The depth of magma generation shown in Figure 7.1 is somewhat conjectural. These depths were obtained by comparing the variety of basalt rock types to the petrogenetic grid of Green (1971). This procedure assumes that each magma equilibrated with its source rock at the original source depth, and that there has been no significant upward movement of crystals and melt phases together. The inferred zone of magma generation for the Colorado Plateau appears to lie almost completely above the LVZ roof given by Archambeau _et al_. (1969) for the Colorado Plateau.

It can also be seen in the diagram that the zone of magma generation is believed to include both BR and CP mantle for some areas near the boundary of the Basin and Range province and the Colorado Plateau. This detail attempts to explain the occasional presence of what may be a BR lead in an otherwise CP type area (see Figure 4.19). Mixing of CP and BR mantle in these marginal areas or zone refining of BR magmas by overlying CP mantle may also explain the transitional isotopic characteristics found in some regions (e.g., the Mexican Highlands).

In this cross section "oceanic" mantle is inferred to exist beneath some areas known to have a Precambrian crystalline basement. Such areas might normally be presumed to be underlain by thick, old continental lithosphere in the mantle. The absence today of continental lithosphere beneath areas with a Precambrian basement is extremely significant, and apparently requires removal or disruption of a pre-existing lithosphere by some fundamental tectonic mechanism.

7.3 A Relationship between Mantle and Crustal Tectonism

The southwestern United States can be broadly divided into two structural provinces: one lying to the west along the Pacific Coast, and a second farther inland. The western regime would include the Basin and Range, Sierra-Cascade, and Pacific border provinces, and has been characterized by an extensive history of tectonism and magmatism. The Devonian Antler orogeny, the Permo-Triassic Sonoma orogeny, the Triassic mythical megashearing of the western continental edge, the Mesozoic episode of plutonism that formed the Sierra Nevada and southern California batholiths, the Mesozoic-Early Teritary thrusting episodes of the Nevadan-Sevier-Laramide orogenies, as well as the late Cenozoic extensional tectonism of the Basin and Range province and strike slip faulting of the Pacific border area have all been confined to this active, "orogenic" region along the Pacific coast. In contrast, the structural province to the east, which includes the Colorado Plateau, Rocky Mountains, and Great Plains, has had a relatively stable history. In recognition of this, Hamilton and Myers (1966) referred to this eastern province as "platform."*

The boundary between basically stable and fundamentally disturbed regions can be drawn according to a number of criteria. These might include the eastern extent of late Cretaceous-early Tertiary thrusting,

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*Hamilton and Myers (1966) differentiated two types of platforms - stable platform like the Great Plains, and unstable platform, like the Rocky Mountains and Colorado Plateau.

Figure 7.3: Map of the southwestern United States showing comparatively stable, "platform" areas in striped patterns. The boundary of the patterned region follows the physiographic province boundary of Fenneman (1931). In Arizona the dashed line indicates the Colorado Plateau boundary proposed by Heindl and Lance (1960). The dot-dash line shows the Colorado Plateau boundary of Hayes (1969). The two dot-dash line is the Colorado Plateau tectonic boundary suggested by L.T. Silver (personal communication). The hachured line represents the extent of late Mesozoic-early Tertiary thrusting in the southwestern United States as delimited by the maps of Burchfiel and Davis (1977), Burchfiel and Davis (1972), and Drewes (1978). The heavy line on which black dots are superimposed represents the BR-CP isotopic province boundary.

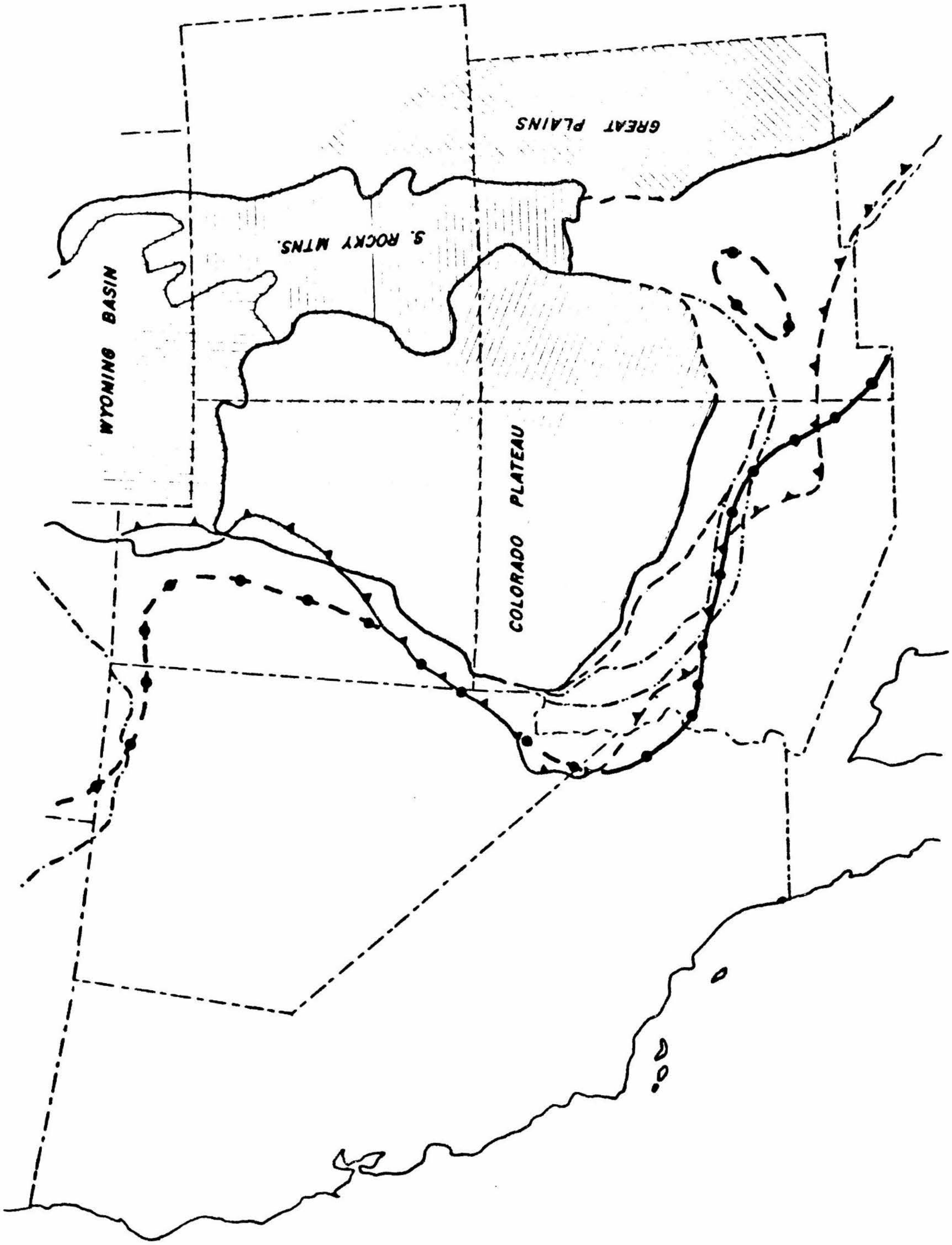

Figure 7.3

the extent that Mesozoic and Laramide intrusives have penetrated the Colorado Plateau, the presence or absence of deformation in the Precambrian basement, and the limit of Basin and Range type normal faulting. None of these structural boundaries coincide along their whole length (as Figure 7.3 shows), but they all seem to have similar trends in the southwestern United States. In Utah they trend SSW along the physiographic boundary of the Colorado Plateau. In Arizona they also seem to parallel the physiographic boundary of the Colorado Plateau, trending due S to SE in different areas.

It is significant that the boundary between CP and BR type lead systematics, which has been interpreted to reflect a fundamental boundary in the mantle, follows the same trends as the crustal structural boundaries shown in Figure 7.3. It is also significant that CP type mantle, which preserves an ancient, 1.6 by old time signature (suggesting that it has been stable since the Precambrian), lies beneath crust that has also been characterized by a relatively stable Phanerozoic history. On the other hand, BR type ("oceanic") mantle has had an apparently complex, multi-stage history, and lies beneath a region of the crust characterized by a succession of orogenic (both magmatic and tectonic) episodes. It is furthermore interesting that the BR-CP mantle boundary can be interpreted as a "tectonic" contact - that this contact reflects the extent that previously stable continental lithosphere has been disrupted and removed in conjunction with the emplacement of new "oceanic"asthenosphere. These considerations strongly suggest a genetic relationship between tectonism in the crust and disruption of the underlying lithospheric mantle.

7.4 Timing of Lithospheric Disruption

It is not really clear when the mantle achieved the characteristics which have been recorded as regional isotopic patterns in the late Cenozoic volcanics of the southwestern United States. If new "oceanic" mantle has in fact disrupted ancient continental lithosphere, the maximum age for this disruption is approximately 1.4-1.8 by, the age of the Southwest's continental lithosphere. A minimum age for this disruption is suggested by the ages of the volcanics analyzed in this report. No dramatic correlation between a sample's age and its isotopic affinity has been observed. The older samples from each Basin and Range area display BR type leads, as do the younger samples. Both old and young samples from the Colorado Plateau exhibit CP type lead systematics. This might indicate that the mantle achieved its geochemical properties sometime before the age of the oldest lead isotope sample in each area of the southwest. The oldest rock analyzed in this report is a 35 my old andesite from central Nevada. Thus, the mantle beneath the Great Basin may have obtained its "oceanic" character sometime prior to the Oligocene. Samples with 20-25 my ages from other areas suggest a pre-Miocene emplacement of "oceanic" mantle under the southern Basin and Range province in Arizona and southeastern California.

The emplacement age of oceanic mantle between these broad upper and lower limits cannot be uniquely determined. However, it has been noted that a number of late Cretaceous to late Cenozoic boundaries in the crust correspond rather well with the trace of the BR-CP isotopic boundary (section 7.2 and Figure 7.3). This geographic correspondence suggests that the breakup of continental lithosphere could be related either to the compressional deformation of Mesozoic to early Tertiary time or to the extensional tectonism of late Cenozoic times.

It does not seem feasible to limit the age of lithospheric disruption more precisely at this time, since much potentially pertinent evidence appears to be ambiguous or lacking. For example, information on the geographical association of isotopic and structural features does not seem to be especially definitive. In some places (e.g., northern Nevada) the BR-CP isotopic boundary appears to follow the physiographic boundary of the Basin and Range province more closely than the Cordilleran foreland thrust belt. In other areas (e.g., southern New Mexico) the opposite appears to be true.

On one hand $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ differences between calc-alkaline volcanic rocks of Pliocene and Miocene age and alkaline basalts of Quaternary age could suggest that alterations in Basin and Range volcanic source regions continued very late in the Cenozoic era. This might tend to favor a fairly recent (post mid-Tertiary?) development of BR type sources in the mantle. On the other hand, Zartman's (1974) data suggested to him that regional isotopic patterns in the western United States have been relatively persistent for up to 200 my. The data of Doe and Delevaux (1973) on Mesozoic granites from the Sierra Nevada do appear compatible with BR type data on nearby Miocene and Pliocene calc-alkaline volcanic rocks. However, this type of evidence should be treated with some caution. It is not clear that granitic rocks are always derived from the same, mantle sources as basalts. Doe and Delevaux (1973) favored a derivation of their granitic rocks from the lower crust on isotopic grounds, as did Presnall and Bateman (1973) on chemical grounds. In addition, most Mesozoic igneous rocks isotopically analyzed for lead come from areas lacking known Precambrian crystalline basement - from areas probably never underlain by a Precambrian mantle lithosphere. It is not really appropriate to use data on such rocks to suggest an age for disruption of continental lithosphere. Unfortunately, lead data on Mesozoic igneous samples from southeastern California and southern Arizona (areas with known Precambrian basement) are not yet available.

7.5 Mechanisms for Lithospheric Disruption

It is not possible to specify the physical conditions responsible for disruption of continental lithosphere and the emplacement of oceanic mantle beneath the Basin and Range province. However, the literature offers several models possibly pertinent to speculations on this topic. Burchfiel and Davis (1975), interpreting the inferred relationship and migration of plutonism and thrust faulting in the Cordillera, argued that the North American continent has progressively overriden a zone of hot, magma generating ("oceanic"?) mantle originally occurring along the western edge of the continent. From spatial, temporal, and chemical data on igneous rocks, Coney and Reynolds (1977) and Keith (1978) suggested that the dip angle of the Pacific coast subduction zone shallowed from approximately 50° in Cretaceous time to approximately 10° during the mid-Tertiary. If correct, this shallowing of dip angle might plausibly relate to disruption (beveling?) of continental lithosphere. The double subduction zone geometry inferred by Lipman *et al*. (1972) from chemical data on Tertiary volcanics might also provide another plausible mechanism for lithospheric disruption and introduction of new "oceanic" mantle beneath the western United States. Large scale mantle upwelling, as hypothesized by Scholz *et al*. (1971) to explain geophysical properties and time-space patterns of volcanism in the Great Basin, could provide still another mechanism for introducing asthenosphere to shallow levels beneath the Basin and Range province.

Although none of these particular models may be the ultimate answer, they all suggest the feasibility of finding a mechanism appropriate for relating crustal tectonism and mantle evolution in the Mesozoic and Cenozoic history of the Southwest.

7.6 Overview

The lead isotopic data presented in this report argue for an intimate involvement of mantle twice in the history of the continental crust. These data suggest a temporal correspondence between magma extraction from (oceanic?) mantle previously rather uniform in its isotopic properties and the plutonism (and tectonism) involved in the creation of continental crust during the Precambrian. In this case the orogenic interaction of mantle and crust was constructive; both mantle and crust were transformed and developed into an association (the continental lithosphere) that proved stable for well over a billion years. In contrast, the second involvement of mantle in crustal orogeny would seem to be disruptive in nature, involving modifications in both the crust and the underlying mantle. In this case the evidence for the association of crustal and mantle activity is largely geographic in character - an approximate spatial correspondence between lead isotopic boundaries (interpretable in terms of a contact between different types of mantle) and fundamental structural boundaries in the crust.

This study would seem to illustrate the particular usefulness of lead isotopic studies in investigating the complicated interactive history of crust and mantle in mobile belts. This potency is in part derived from the ability of lead isotopes to establish the time constants of a system with a complex history - a power lacking in geophysical studies which are constrained to examine present day systems, and not found in other isotopic systems which lack the capability to deconvolute a two-stage history. The lead system also appears to be especially apt in distinguishing and characterizing various types of heterogeneity in the mantle. Using lead isotopes to map mantle heterogeneity may allow an intricate examination of patterns of continental accretion and lithosphere formation in stable areas, as well as help delimit the geographic extent, timing, and mechanism of lithospheric disruption in orogenic belts - not only in the southwestern United States but throughout the world.

REFERENCES

Ackers, J.P., 1964, Geology and ground water in the central part of Apache County, Arizona: U.S. Geol. Survey Water Supply Paper 1771, 107 p.

Albers, J.P., and Stewart, J.H., 1972, Geology and mineral deposits of Esmeralda County, Nevada: Nevada Bur. Mines and Geol. Bull., v. 78, 80 p.

Anderson, C.A., and Creasey, S.C., 1971, Geology and ore deposits of the Jerome area, Yavapai County, Arizona: U.S. Geol. Survey Prof. Paper 308, 185 p.

Anderson, C.A., and Blacet, P.M., 1972, Geologic map of the Mount Union quadrangle, Yavapai County, Arizona: U.S. Geol. Survey Map, GQ-997.

Anderson, R.E., Longwell, C.R., Armstrong, R.E., and Marvin, R.F., 1972, Significance of K-Ar ages of Tertiary rocks from the Lake Mead region, Nevada-Arizona: Geol. Soc. Amer. Bull., v. 83, p. 273-288.

Anderson, T.W., 1958, An introduction to multivariate statistical analysis, New York, J. Wiley and Sons, Inc., 374 p.

Aoki, K., 1967, Petrography and petrochemistry of latest Pliocene olivine-tholeiites of Taos area, northern New Mexico, U.S.A.: Contr. Mineral. and Petrol., v. 14, no. 3, p. 190-203.

Aoki, K.I., and Kudo, A.M., 1976, Major-element variations of late Cenozoic basalts of New Mexico: New Mexico Geol. Soc. Spec. Publ. No. 5, p. 82-88.

Archambeau, C.B., Flinn, E.A., and Lambert, D.G., 1969, Fine structure of the upper mantle: J. Geophys. Res., v. 74, no. 25, p. 5825-5865.

Armstrong, R.L., Erken, E.B., McKee, E.H., and Noble, D.S., 1969, Space-time relations of Cenozoic silicic volcanism in the Great Basin of the western United States: Amer. J. Sci., v. 267, p. 478-490.

Armstrong, R.L., 1970, Geochronology of Tertiary igneous rocks, eastern Basin and Range province, western Utah, eastern Nevada, and vicinity, U.S.A.: Geochim. et Cosmochim. Acta, v. 34, p. 203-232.

Armstrong, R.L., and Cooper, J.A., 1971, Lead isotopes in island arcs: Bull. Volcan., v. 35, p. 27-63.

Armstrong, R.L., Dick, H., and Vitaliano, C.H., 1972, K-Ar dates and strontium isotope initial ratios of some Cenozoic volcanic rocks from west central Nevada: Isochron/West, no. 3, p 23-28.

Armstrong, R.L., and Higgins, R.E., 1973, K-Ar dating of the beginning of Tertiary volcanism in the Mojave Desert, California: Geol. Soc. Amer. Bull., v. 84, p. 1095-1100.

Armstrong, R.L., Speed, R.C., Graustein, W.C., and Young, A.Y., 1976, K-Ar dates from Arizona, Montana, Nevada, Utah, and Wyoming: Isochron/West no. 16, p. 1-6.

Atwater, T., 1970, Implications of plate tectonics for the Cenozoic evolution of western North America: Geol. Soc. Amer. Bull., v. 81, p. 3513-3536.

Babcock, J.W., 1975, Volcanic rocks in the Coso Mountains, California: Geol. Soc. Amer. Abstracts with Programs, v. 7, no. 3, p. 291-292.

Bachman, G.O., Marvin, R.F., Mehnert, H.H., and Merritt, V., 1975, K-Ar ages of basalt flows at Los Lunas and Albuquerque, central New Mexico: Isochron/West, no. 13, p. 3-4.

Baldridge, W.S., 1978, Petrology of Plio-Pleistocene basaltic rocks from the central Rio Grande rift (New Mexico, USA) and their relation to rift structure, in Neumann, E.R., and Ramberg, I.B., eds., Petrology and geochemistry of continental rifts, Boston, D. Reidel Co., p. 71-78.

Best, M.G., 1970, Kaersutite-peridotite inclusions and kindred megacrysts in basanitic lavas, Grand Canyon, Arizona: Contr. Mineral. Petrol., v. 27, p. 25-44.

Best, M.G., and Brimhall, W.H., 1974, Late Cenozoic alkalic basalt magmas in the western Colorado Plateaus and the Basin and Range transition zone, U.S.A., and their bearing on mantle dynamics: Geol. Soc. Amer. Bull., v. 85, p. 1677-1690.

Bikerman, M., 1972, New K-Ar ages on volcanic rocks from Catron and Grant Counties, N.M.: Isochron/West, no. 3, p. 9-12.

Bikerman, M., 1976, Initial Sr^{87}/Sr^{86} ratios and K-Ar dates of some volcanic rocks from Catron County, New Mexico: Geol. Soc. Amer. Abstracts with Programs, v. 8, no. 5, p. 569.

Bikerman, M., and Damon, P.E., 1966, K/Ar chronology of the Tuscon Mountains, Pima County, Arizona: Geol. Soc. Amer. Bull., v. 77, p. 1225-1234.

Bishop, C.C. (compiler), 1964, Geologic map of California, Needles sheet: Calif. Bur. Mines and Geol.

Black, L.P., Gale, N.H., Moorbath, S., and Panlehurst, R.J., 1971, Isotopic dating of very early Precambrian amphibolite facies gneisses from the Godthaab district, West Greenland: Earth Planet. Sci. Lett., v. 12, p. 245-259.

Bonham, H.F., and Garside, L.J., 1974, Road log and trip guide, Carver Station-Tonopah: Nevada Bur. Mines and Geol. Rept. 19, p. 42-48.

Brookins, D.H., and Moore, R.B., 1975, Strontium isotope initial ratios from the San Francisco volcanic field, Arizona: Isochron/West, No. 12, p. 1-2.

Brooks, C., James, D.E., and Hart, S.R., 1976, Ancient lithosphere: its role in young continental volcanism: Science, v. 193, p. 1086-1093.

Burchfiel, B.C., and Davis, G.A., 1972, Structural framework and evolution of the southern part of the Cordilleran orogen, western United States: Amer. J. Sci., v. 272, p. 91-118.

Burchfiel, B.C., and Davis, G.A., 1975, Nature and controls of Cordilleran orogenesis, western United States: extensions of an earlier synthesis: Amer. J. Sci., v. 275-A, p. 363-396.

Burchfiel, B.C., and Davis, G.A., 1977, Geology of the Sagamore Canyon-Slaughterhouse Spring area, New York Mountains, California: Geol. Soc. Amer. Bull., v. 88, p. 1623-1640.

Burke, K., and Whiteman, A.J., 1973, Uplift, rifting, and break-up of Africa, _in_ Tarling, D., and Runcorn, S., eds., Implications of continental drift to the earth sciences, Vol. 2, New York, Academic Press, p. 735-755.

Burnett, J.L., and Jennings, C.W. (compilers), 1962, Geologic map of California, Chico sheet: Calif. Div. of Mines and Geol.

Cannon, R.S., Pierce, A.P., Antweiler, J.C., and Buck, K.L., 1961, The data of lead isotope geology related to problems of ore genesis: Econ. Geol., v. 56, no. 1, p. 1-38.

Carden, J.R., and Laughlin, A.W., 1974, Petrochemical variations within the McCarthys basalt flow, Valencia County, New Mexico: Geol. Soc. Amer. Bull., v. 85, p. 1479-1484.

Catanzaro, E.J., 1967, Absolute isotopic abundance ratios of three common lead reference samples: Earth Planet. Sci. Lett., v. 3, p. 343-346.

Christiansen, R.L., and Lipman, P.W., 1972, Cenozoic volcanism and plate-tectonic evolution of the western United States. II Late Cenozoic: Phil. Trans. Roy. Soc. Lond., v. A 271, p. 249-284.

Church, S.E., 1976, The Cascade Mountains revisited: a re-evaluation in light of new lead isotopic data: Earth Planet. Sci. Lett., v. 29, p. 175-188.

Church, S.E., and Tatsumoto, M., 1975, Pb isotope relations in oceanic basalts from the Juan de Fuca-Gorda Ridge area, N.E. Pacific Ocean.: Contrib. Mineral. Petrol., v. 53, p. 253-279.

Church, S.E. and Tilton, G.R., 1973, Lead and strontium isotopic studies in the Cascade Mountains: bearing on andesite genesis: Geol. Soc. Amer. Bull., v. 84, p. 431-454.

Cohen, L.H., Ito, K., and Kennedy, G.C., 1967, Melting and phase relations in an anhydrous basalt to 40 kilobars: Amer. J. Sci., v. 265, p. 475-518.

Compston, W., and Oversby, V.M., 1969, Lead isotopic analysis using a double spike: J. Geophys. Res., v. 74, no. 17, p. 4338-4348.

Condie, K.C., and Barsky, C.K., 1972, Origin of Quaternary basalts from the Black Rock Desert region, Utah: Geol. Soc. Amer. Bull., v. 83, p. 333-352.

Coney, P.J., and Reynolds, S.J., 1977, Cordilleran Benioff zones: Nature, v. 270, p. 403-405.

Cooper, J.R., 1960, Reconnaissance map of the Wilcox, Fisher Hills, Cochise, and Dos Cabezas quadrangles, Chochise and Graham Counties, Arizona: U.S. Geol. Survey Map MF-231.

Cornwall, H.R., 1972, Geology and mineral deposits of southern Nye County, Nevada: Nevada Bur. Mines and Geol. Bull., v. 77, 49 p.

Crowe, B.M., 1978, Cenozoic volcanic geology and probable age of inception of basin-range faulting in the southeasternmost Chocolate Mountains, California: Geol. Soc. Amer. Bull., v. 89, p. 251-264.

Dalrymple, G.B., 1963, Potassium-argon dates of some Cenozoic volcanic rocks of the Sierra Nevada, California: Geol. Soc. Amer. Bull., v. 74, p. 379-390.

Dalrymple, G.B., 1964, Cenozoic chronology of the Sierra Nevada, California: Univ. Calif. Publ. in Geol. Sci., v. 47, 41 p.

Damon, P.E. (senior investigator), 1966, Correlation and chronology of ore deposits and volcanic rocks: Atomic Energy Comm. Annual Progress Report No. COO-689-60, p. 26.

Damon, P.E. (senior investigator), 1968, Correlation and chronology of ore deposits and volcanic rocks: U.S. Atomic Energy Comm. Progress Report No. COO-689-100, p. 44.

Damon, P.E. (senior investigator), 1970, Correlation and chronology of ore deposits and volcanic rocks: U.S. Atomic Energy Comm. Progress Report No. COO-689-130, p. 41.

Damon, P.E., Shafigullah, M., and Leventhal, J.S., 1974, K-Ar chronology for the San Francisco volcanic field and rate of erosion of the Little Colorado River, in Geology of northern Arizona, Part I - regional studies, for Geol. Soc. Amer. Rocky Mountain Sect. Mtg., Flagstaff, Arizona, 1974, p. 221-256.

Dane, C.H., and Bachman, G.O., 1965, Geologic map of New Mexico, U.S. Geol. Survey.

Davis, G.L., Tilton, G.R., Aldrich, L.T., Hart, S.R., and Steiger, R.H., 1964, Isotopic composition of lead and strontium in crystalline rocks from the northern Cascade Range, United States: Carnegie Inst. Washington Yearbook 64, p. 171-174.

Davis, J.C., 1973, Statistics and data analysis in geology, New York, J. Wiley and Sons, Inc., 550 p.

Decker, E.R., Cook, F.A., Ramberg, I.B., and Smithson, S.B., 1975, Significance of geothermal and gravity studies in the Las Cruces area: New Mexico Geol. Soc. Guidebook, 26th Field Conf., p. 251-260.

DePaolo, D.J., 1978, Study of magma sources, mantle structure and the differentiation of the earth from variations of $^{143}Nd/^{144}Nd$ in igneous rocks: Ph.D. Thesis, California Institute of Technology, 359 p.

Dibblee, T.W., 1966, Geologic map of the Lavic quadrangle, San Bernardino County, California: U.S. Geol. Survey Map I-472.

Dibblee, T.W., Jr., 1967, Geologic map of the Joshua Tree quadrangle, San Bernardino and Riverside Counties, California: U.S. Geol. Survey Map I-516.

Dibblee, T.W., 1968, Geology of the Fremont Peak and Opal Mountain quadrangles, California: Calif. Div. Mines and Geol. Bull. No. 188, 64 p.

Doe, B.R., 1967, The bearing of lead isotopes on the source of granitic magma: J. Petrol., v. 81, p. 51-83.

Doe, B.R., 1968, Lead and strontium isotopic studies of Cenozoic volcanic rocks in the Rocky Mountain region - a summary: Colorado School of Mines Quarterly, v. 63, p. 149-174.

Doe, B.R., 1970, Lead isotopes, New York, Springer-Verlag, 137 p.

Doe, B.R., Lipman, P.W., and Hedge, C.E., 1969, Primitive and contaminated basalts from the southern Rocky Mountains, U.S.A.: Contr. Mineral. Petrol., v. 21, p. 142-156.

Doe, B.R., and Delevaux, M.H., 1973, Variations in lead-isotopic compositions in Mesozoic granitic rocks of California: a preliminary investigation: Geol. Soc. Amer. Bull., v. 84, p. 3513-3526.

Drewes, H., 1963, Geology of the Funeral Peak quadrangle, on the east flank of Death Valley: U.S. Geol. Surv. Prof. Paper 413, 78 p.

Drewes, H., 1978, The Cordilleran orogenic belt between Nevada and Chihuahua: Geol. Soc. Amer. Bull., v. 89, p. 641-657.

Eaton, G.P., 1975, Characteristics of a transverse crustal boundary in the Basin and Range province of southern Nevada: Geol. Soc. Amer. Abstracts with Programs, v. 7, no. 7, p. 1062-1063.

Eberly, L.D., and Stanley, T.B., 1978, Cenozoic stratigraphy and geologic history of southwestern Arizona: Geol. Soc. Amer. Bull., v. 89, p. 921-940.

Eichelberger, J.C., 1974, Magma contamination within the volcanic pile: origin of andesite and dacite: Geology, v. 2, no. 1, p. 29-33.

Elston, W.E., Damon, P.E., Coney, P.J., Rhodes, R.C., Smith, E.I., and Bikerman, M., 1973, Tertiary volcanic rocks, Mogollon-Datil province, New Mexico, and surrounding region, K-Ar dates, patterns of eruption, and periods of mineralizations: Geol. Soc. Amer. Bull., v. 84, p. 2259-2274.

Elston, W.E., 1976, Tectonic significance of mid-Tertiary volcanism in the Basin and Range province: a critical review with special reference to New Mexico: New Mexico Geol. Soc. Special Publ. No. 5, p. 93-102.

Elston, W.E., Rhodes, R.C., Coney, P.J., and Deal, E.G., 1976, Progress report on the Mogollon Plateau volcanic field, southwestern New Mexico, No. 3 - surface expression of a pluton: New Mexico Geol. Soc. Special Publ. No. 5, p. 3-28.

Everson, J.E., and Silver, L.T., 1976, Contrasting lead isotopic characteristics of late Cenozoic basalts from the southwestern Colorado Plateau and the nearby Basin and Range province: Geol. Soc. Amer. Abstracts with Programs, v. 8, no. 6, p. 857.

Faure, G., 1977, Principles of isotope geology, New York, J. Wiley and Sons, 476 p.

Fenneman, N.M., 1931, Physiography of western United States, New York, McGraw-Hill, 534 p.

Fleck, R.J., 1970, Age and tectonic significance of volcanic rocks, Death Valley area, California: Geol. Soc. Amer. Bull., v. 81, p. 2807-2816.

Fleck, R.J., Anderson, J.J., Rowley, P.D., 1975, Chronology of mid-Tertiary volcanism in the High Plateaus region of Utah: Geol. Soc. Amer. Special Paper 160, p. 53-61.

Fodor, R.V., 1978, Ultramafic and mafic inclusions and megacrysts in Pliocene basalt, Black Range, New Mexico: Geol. Soc. Amer. Bull., v. 89, p. 451-459.

Gale, N.H., and Mussett, A.E., 1973, Episodic uranium-lead models and the interpretation of variations in the isotopic composition of lead in rocks: Rev. Geophys. Space Phys., v. 11, no. 1, p. 37-86.

Gancarz, A.J., 1976, I: Isotopic systematics in Archean rocks, west Greenland. II: Mineralogic and petrologic investigations of lunar rock samples, Ph.D. Thesis, California Institute of Technology, 349 p.

Gilluly, J., 1946, The Ajo mining district, Arizona: U.S. Geol. Survey Prof. Paper 209, 112 p.

Gray, C.M., and Oversby, V.M., 1972, The behaviour of lead isotopes during granulite facies metamorphism: Geochim. Cosmochim. Acta, v. 36, p. 939-952.

Green, D.H., 1971, Composition of basaltic magmas as indicators of conditions of origin: application to oceanic volcanism: Phil. Trans. Roy. Soc. Lond., v. A 268, p. 707-725.

Green, T.H., 1972, Crystallization of calc-alkaline andesite under controlled high pressure hydrous conditions: Contr. Mineral. Petrol., v. 34, p. 150-166.

Green, T.H., and Ringwood, A.E., 1968, Genesis of the calc-alkaline igneous rock suite: Contr. Minerol. Petrol., v. 18, p. 105-162.

Griggs, R.Y., 1964, Geology and groundwater resources of the Los Alamos area, New Mexico: U.S. Geol. Survey Water-Supply Paper 1753, 106 p.

Hall, W.E., and MacKevett, E.M., 1962, Geology and ore deposits of the Darwin quadrangle, Inyo County, California: U.S. Geol. Survey Prof. Paper 368, 87 p.

Hamblin, W.K., 1963, Late Cenozoic basalts of the St. George basin, Utah: Intermountain Asso. of Petroleum Geol. 12th Annual Field Conf. Guidebook, p. 85-89.

Hamblin, W.K., 1974, Late Cenozoic volcanism in the western Grand Canyon, _in_ Breed, W.J., and Roat, E.C., eds., Geology of the Grand Canyon, Flagstaff, Arizona, Museum of Northern Arizona, p 142-169.

Hamblin, W.K., and Best, M.G., 1975, The geologic boundary between the Colorado Plateau and Basin and Range province: Geol. Soc. Amer. Abstracts with Programs, v. 7, no. 7, p. 1097.

Hamilton, W., and Myers, W.B., 1966, Cenozoic tectonics of the western United States: Rev. of Geophys., v. 4, p. 509-549.

Harper, C.T. (ed.), 1973, Geochronology: radiometric dating of rocks and minerals, Stroudsburg, Pennsylvania, Dowden, Hutchinson, and Ross, 469 p.

Hausel, W.D., and Nash, W.P., 1977, Petrology of Tertiary and Quaternary volcanic rocks, Washington County, southwestern Utah: Geol. Soc. Amer. Bull., v. 88, p. 1831-1842.

Hawkins, J.W., 1970, Petrology and possible tectonic significance of late Cenozoic volcanic rocks, Southern California and Baja California: Geol. Soc. Amer. Bull., v. 81, p. 3323-3338.

Hayes, P.T., 1969, Geology and topography, in Mineral and water resources of Arizona, Ariz. Bur. of Mines Bull. v. 180, p. 35-58.

Hedge, C.E., and Noble, D.C., 1969, Upper Cenozoic basalts with high Sr^{87}/Sr^{86} and Sr/Rb ratios, southern Great Basin, western United States: Geol. Soc. Amer. Bull., v. 82, p. 3503-3510.

Heier, K.S., and Thoresen, K., 1971, Geochemistry of high grade metamorphic rocks, Lofoten-Verstalen, north Norway: Geochim. Cosmochim. Acta, v. 35, p. 89-99.

Heindl, L.A., and Lance, J.F., 1960, Topographic, physiographic, and structural subdivisions of Arizona: Ariz. Geol. Soc. Digest, v. 3, p. 12-18.

Herrin, E., and Taggart, J., 1962, Regional variations in Pn velocity and their effect on the localization of epicenters: Bull. Seismol. Soc. Amer., v. 52, no. 5, p. 1047-1056.

Hintz, L.F., 1963, Geologic map of southwestern Utah, special guidebook edition: Intermountain Asso. of Petroleum Geol. 12th Annual Field Conf. Guidebook.

Hoffer, J.M., 1969, Volcanic history of the Black Mountain-Santo Tomas basalts, Potrillo volcanics, Doña Ana County, New Mexico: New Mexico Geol. Soc. 20th Field Conf. Guidebook, p. 108-114.

Holland, J.G., and Lambert, R.S.J., 1975, The chemistry and origin of the Lewisian gneisses of the Scottish mainland: the Scourie and Inver assemblages and subcrustal accretion: Precambrian Res., v. 2, p. 161-188.

Hunt, C.B., 1956, Cenozoic geology of the Colorado Plateau, U.S. Geol. Survey Prof. Paper 279, 99 p.

Irvine, T.N., and Baragar, W.R.A., 1971, A guide to the chemical classification of the common volcanic rocks: Can. J. Earth Sci., v. 8, p. 523-548.

Jaffey, A.H., Flynn, K.F., Glendenin, L.E., Bentley, W.C., and Essling, A.M., 1971, Precision measurement of half-lives and specific activities of ^{235}U and ^{238}U: Phys. Rev. C, v. 4, p. 1889.

Jennings, C.W.(compiler), 1961, Geologic map of California, Kingman sheet: Calif. Div. Mines and Geol.

Jennings, C.W., Burnett, J.L., and Troxel, B.W., 1962, Geologic map of California, Trona sheet: Calif. Div. Mines and Geol.

Jones, L.M., Walker, R.L., and Stormer, J.C., 1974, Isotope composition and origin of volcanic rocks of the Raton-Clayton district, northeast New Mexico: Geol. Soc. Amer. Bull., v. 85, p. 33-36.

Jordan, T.H., 1975, The continental tectosphere: Reviews of Geophys. and Space Phys., v. 13, no. 3, p. 1-12.

Kanasewich, E.R., 1968, The interpretation of lead isotopes and their geological significance, in Hamilton, E.L., and Farguhar, R.M., eds., Radiometric dating for geologists, New York, Interscience-J. Wiley and Sons, 506 p.

Keith, S.B., 1978, Paleosubduction geometries inferred from Cretaceous and Tertiary magmatic patterns in southwestern North America: Geology, v. 6, p. 516-521.

King, P.B., 1977, The evolution of North America, Princeton, NJ, Princeton Univ. Press, 189 p.

Koenig, J.B. (compiler), 1963, Geologic map of California, Santa Rosa sheet: Calif. Div. of Mines and Geol.

Krieger, M.H., 1965, Geology of the Prescott and Paulden quadrangles, Arizona: U.S. Geol. Survey Prof. Paper 467, 127 p.

Kudo, A.M., Aoki, K.I., and Brookins, D.C., 1971, The origin of Pliocene-Holocene basalts of New Mexico in the light of strontium isotopic and major element abundances: Earth Planet. Sci. Lett., v. 13, p. 200-204.

Kuno, H., 1960, High alumina basalt: J. Petrol., v. 1, p. 121-145.

Lasky, S.G., and Webber, B.N., 1949, Manganese resources of the Artillery Mountains region, Mohave County, Arizona: U.S. Geol. Survey Bull. 961, 86 p.

Laughlin, A.W., Manser, G.K., and Carden, J.R., 1974, Feldspar megacrysts in alkali basalts: Geol. Soc. Amer. Bull. v. 85, p. 413-416.

Leeman, W.P., 1970, The isotopic composition of strontium in late-Cenozoic basalts from the Basin-Range province, western United States: Geochim. Cosmochim. Acta, v. 34, p. 857-872.

Leeman, W.P., 1974, Late Cenozoic alkali-rich basalt from the western Grand Canyon area, Utah and Arizona: isotopic composition of strontium: Geol. Soc. Amer. Bull., v. 85, p. 1691-1696.

Leeman, W.P., and Rodgers, J.J.W., 1970, Late Cenozoic alkali-olivine basalts of the Basin-Range province, U.S.A.: Contr. Mineral. Petrol. v. 25, p. 1-24.

Leeman, W.P., 1975, Radiogenic tracers applied to basalt genesis in the Snake River Plain-Yellowstone National Park region - evidence for a 2.7 by old upper mantle keel: Geol. Soc. Amer. Abstracts with Programs, v. 7, no. 7, p. 1165.

LeRoux, L.J., and Glendenin, L.E., 1963, Half-life of thorium-232: Proc. Natl. Conf. on Nuclear Energy, Pretoria, April.

Lipman, P.W., 1969, Alkalic and tholeiitic basaltic volcanism related to the Rio Grande depression, southern Colorado and northern New Mexico: Geol. Soc. Amer. Bull., v. 80, p. 1343-1354.

Lipman, P.W., Prostka, H.J., and Christiansen, R.L., 1972, Cenozoic volcanism and plate tectonic evolution of the western United States. I. Early and middle Cenozoic: Phil. Trans. Roy. Soc. Lond., A 271, p. 217-248.

Lipman, P.W., Doe, B.R., Hedge, C.E., and Steven, T.A., 1978, Petrologic evolution of the San Juan volcanic field, southwestern Colorado: Pb and Sr evidence: Geol. Soc. Amer. Bull., v. 89, p. 59-82.

Lipman, P.W., and Moench, R.H., 1972, Basalts of the Mount Taylor volcanic field, New Mexico: Geol. Soc. Amer. Bull., v. 83, p. 1335-1344.

Longwell, C.R., 1963, Reconnaisance geology between Lake Mead and Davis Dam, Arizona-Nevada: U.S. Geol. Survey Prof. Paper 347-E 51 p.

Lowder, G.C., 1973, Late Cenozoic transitional alkali olivine-tholeiitic basalt and andesite from the margin of the Great Basin, southwest Utah: Geol. Soc. Amer. Bull., v. 84, p. 2993-3012.

Ludwig, K.R., 1974, Precambrian geology of the central Mazatzal Mountains, Arizona (Part I) and lead isotopic heterogeneity in Precambrian igneous feldspars (Part II), Ph.D. Thesis, California Institute of Technology, 363 p.

Ludwig, K.R., and Silver, L.T., 1977, Lead-isotope inhomogeneity in Precambrian igneous feldspars: Geochim. Cosmochim. Acta, v. 41, p. 1457-1471.

Mack, C., 1967, Essentials of statistics for scientists and technologists, New York, Plenum Press, 174 p.

Mankinen, E.A., 1972, Paleomagnetism and potassium argon ages of the Sonoma volcanics, California: Geol. Soc. Amer. Bull., v. 83, p. 2063-2072.

Marvin, R.F., Stern, T.W., Creasey, S.C., and Mehnert, H.H., 1973, Radiometric ages of igneous rocks from Pima, Santa Cruz, and Cochise Counties, southeastern Arizona: U.S. Geol. Survey Bull. 1379, 27 p.

McGetchin, T.R., and Silver, L.T., 1972, A crustal-upper-mantle model for the Colorado Plateau based on observations of crystalline rock fragments in the Moses rock dike: J. Geophys. Res., v. 77, no. 35, p. 7022-7037.

McKay, E.J., 1972, Geologic map of the Show Low quadrangle, Navajo County, Arizona: U.S. Geol. Survey Map GQ-973.

McKee, E.D., and McKee, E.H., 1972, Pliocene uplift of the Grand Canyon region - time of drainage adjustment: Geol. Soc. Amer. Bull., v. 83, p. 1923-1932.

McKee, E.H., 1968, Geologic map of the Spencer Hot Springs quadrangle, Lander County, Nevada: U.S. Geol. Survey Map GQ-770.

McKee, E.H., and Anderson, C.A., 1971, Age and chemistry of Tertiary volcanic rocks in north-central Arizona and relation of the rocks to the Colorado Plateau: Geol. Soc. Amer. Bull., v. 82, p. 2767-2782.

McKee, E.H., and Mark, R.K., 1971, Strontium isotopic composition of two basalts representative of the southern Snake River volcanic province: U.S. Geol. Survey Prof. Paper 750-B, p. B92-B95.

McKee, E.H., and Silberman, M.L., 1970, Geochronology of Tertiary igneous rocks in central Nevada: Geol. Soc. Amer. Bull., v. 81, p. 2317-2328.

Meijer, A., 1976, Pb and Sr isotopic data bearing on the origin of volcanic rocks from the Mariana island-arc system: Geol. Soc. Amer. Bull., v, 87, p. 1358-1369.

Merrill, R.K., and Pewe, T.L., 1977, Late Cenozoic geology of the White Mountains, Arizona: Ariz. Bur. Geol. Mineral Tech. Special Paper No. 1.

Miller, D.G., Lee, G.K., Damon, P.E., and Shafigullah, M., 1977, Age of Tertiary volcanism and tilt-block faulting in west-central Arizona: Geol. Soc. Amer. Abstracts with Programs, v. 9, no. 4, p. 466.

Moench, R.H., 1963, Geologic map of the Seboyeta quadrangle, New Mexico: U.S. Geol. Survey Map GQ-207.

Moorbath, S., Welke, H., and Gale, N.H., 1969, The significance of lead isotopic studies in ancient high grade metamorphic basement complexes, as exemplified by the Lewisian rocks of northwest Scotland: Earth Planet. Sci. Lett., v. 6, p. 245-256.

Moore, R.B., Wolfe, E.W., and Ulrich, G.E., 1974, Geology of the eastern and northern parts of the San Francisco volcanic field, Arizona, in Geology of northern Arizona, Part II - Areal studies and field guides for Geol. Soc. Amer. Rocky Mountain Sect. Mtg., p. 465-520.

Moore, R.B., Wolfe, E.W., and Ulrich, G.E., 1976, Volcanic rocks of the eastern and northern parts of the San Francisco volcanic field, Arizona: U.S. Geol. Survey J. of Res., v. 4, no. 5, p. 549-560.

Morrison, R.B., 1965, Geologic map of the Duncan and Canador Peak quadrangles, Arizona and New Mexico: U.S. Geol. Survey Map I-442.

Nichols, R.L., 1946, McCartys basalt flow, Valencia County, New Mexico: Geol. Soc. Amer. Bull., v. 57, p. 1049-1086.

Nichols, J., Carmichael, I.S.E., and Stormer, J.C., Jr., 1971, Silica activity and P_{total} in igneous rocks: Contr. Mineral. Petrol., v. 33, p. 1-20.

Noble, D.C., and Hedge, C.E., 1969, Sr^{87}/Sr^{86} variations within ash flow sheets: Geol. Surv. Res. 1969, U.S. Geol. Surv. Prof. Paper 650-C, p. 133-139.

Oversby, V.M., 1972, Genetic relations among the volcanic rocks of Reunion: chemical and lead isotopic evidence: Geochim. Cosmochim. Acta, v. 36, p. 1167-1175.

Oversby, V.M., and Ewart, A., 1972, Lead isotopic compositions of Tongo-Kermandec volcanics and their petrogenetic significance: Contr. Mineral. Petrol., v. 37, p. 181-210.

Ozima, M., Kono, M., Kaneoka, I., Kinoshita, H., Kobayashi, K., Nagata, T., Larson, E.E., and Strangway, D., 1967, Paleomagnetism and potassium-argon ages of some volcanic rocks from the Rio Grande Gorge, New Mexico: J. Geophys. Res., v. 72, no. 10, p. 2615-2621.

Page, B.M., 1965, Preliminary geologic map of a part of the Stillwater Range, Churchill County, Nevada: Nevada Bur. Mines Map 28.

Pakiser, L.C., and Zietz, I., 1965, Transcontinental crustal and upper mantle structure: Rev. of Geophys., v. 3, no. 4, p. 505-520.

Patterson, C.C., 1956, Age of meteorites and the earth: Geochim. Cosmochim. Acta, v. 10, p. 230-237.

Peterman, Z.E., Doe, B.R., and Prostka, H.J., 1970, Lead and strontium isotopes in rocks of the Absoroka volcanic field, Wyoming: Contr. Mineral. Petrol., v. 27, p. 121-130.

Peterman, Z.E., Carmichael, I.S.E., and Smith, A.L., 1970, Strontium isotopes in Quaternary basalts of southeastern California: Earth Planet. Sci. Lett., v. 7, p. 381-384.

Peterman, Z.E., Carmichael, I.S.E., and Smith, A.L., 1970, Sr^{87}/Sr^{86} ratios of Quaternary lavas of the Cascade Range, northern California: Geol. Soc. Amer. Bull., v. 81, p. 311-318.

Peterman, Z.E., and Hedge, C.E., 1971, Related strontium isotopic and chemical variations in oceanic rocks: Geol. Soc. Amer. Bull., v. 82, p. 493-500.

Presnall, D.C., and Bateman, P.C., 1973, Fusion relations in the system $NaAlSi_3O_8$-$CaAl_2Si_2O_8$-$KAlSi_3O_8$-H_2O and generation of granitic magmas in the Sierra Nevada batholith: Geol. Soc. Amer. Bull., v. 84, p. 3181-3202.

Pushkar, P., and Condie, K.C., 1973, Origin of the Quaternary basalts from the Black Rock Desert region, Utah: strontium isotopic evidence: Geol. Soc. Amer. Bull., v. 84, p. 1053-1058.

Ramberg, I.B., Cook, F.A., and Smithson, S.B., 1978, Structure of the Rio Grande rift in southern New Mexico and West Texas based on gravity interpretation: Geol. Soc. Amer. Bull., v. 89, p. 107-123.

Reeves, C.C., and DeHon, R.A., 1965, Geology of Potrillo Maar, New Mexico and northern Chihuahua, Mexico: Amer. J. Sci., v. 263, p. 401-409.

Reiter, M., Edwards, C.L., Hartman, H., and Weidman, C., 1975, Terrestrial heat flow along the Rio Grande rift, New Mexico and southern Colorado: Geol. Soc. Amer. Bull., v. 86, p. 811-818.

Renault, J., 1970, Major-element variations in the Potrillo, Carrizozo, and McCartys basalt fields, New Mexico: New Mexico Bur. of Mines and Min. Res. Circular 113, 22 p.

Ringwood, A.C., 1975, Composition and petrology of the earth's mantle, New York, McGraw-Hill, 618 p.

Robinson, H.H., 1913, The San Francisco volcanic field, Arizona: U.S. Geol. Survey Prof. Paper 76, 213 p.

Robinson, P.T., 1972, Petrology of the potassic Silver Peak volcanic center, western Nevada: Geol. Soc. Amer. Bull., v. 83, p. 1693-1708.

Rodgers, T.H., 1966, Geologic map of California, Santa Ana sheet: Calif. Div. of Mines and Geol.

Russell, R.D., and Farquhar, R.M., 1960, Lead isotopes in geology, New York, Interscience, 243 p.

Rye, R.O., Doe, B.R., and Wells, J.D., 1974, Stable isotope and lead isotope study of the Cortez, Nevada gold deposit and surrounding area: U.S. Geol. Survey J. Res., v. 2, no. 1, p. 13-23.

Schilling, J.H., 1965, Isotopic age determinations of Nevada rocks: Nevada Bur. Mines Report 10, 79 p.

Scholz, C.H., Baranzangi, M., and Sbar, M.L., 1971, Late Cenozoic evolution of the Great Basin, western United States, as an ensialic interarc basin: Geol. Soc. Amer. Bull., v. 82, p. 2979-2990.

Scott, D.H., and Trask, N.J., 1971, Geology of the Lunar Crater volcanic field, Nye County, Nevada: U.S. Geol. Survey Prof. Paper 599-I, I1-I22.

Scott, R.B., Nesbitt, R.W., Dasch, E.J., and Armstrong, R.L., 1969, A strontium isotope evolution model for Cenozoic magma genesis, eastern Great Basin, U.S.A.: Bull. Volcanol., v. 35, p. 1-26.

Shakel, D.W., 1976, Pliocene uplift of the Grand Canyon region - time of drainage adjustment: discussion: Geol. Soc. Amer. Bull., v. 87, p. 1205-1207.

Silver, L.T., Anderson, C.A., Crittenden, M., and Robertson, J.M., 1977, Chronostratigraphic elements of Precambrian rocks of the southwestern and far western United States: Geol. Soc. Amer. Abstracts with Programs, v. 9, no. 7, p. 1176.

Sinha, A.K., Davis, G.L., Hart, S.R., and Krough, T., 1971, Lead isotopic analysis: Carnegie Inst. Washington Yearbook 69, p. 386-388.

Smith, A.L., and Carmichael, I.S.E., 1969, Quaternary trachybasalts from southeastern California: Amer. Mineral., v. 54, p. 909-923.

Snyder, R.P., Ekren, E.B., and Dixon, G.L., 1972, Geologic map of the Lunar Crater quadrangle, Nye County, Nevada: U.S. Geol. Survey Map I-700.

Spooner, C.M., and Fairbairn, 1970, Strontium 87/strontium 86 initial ratios in pyroxene granulite terranes: J. Geophys. Res., v. 75, no. 32, p. 6706-6713.

Stacey, J.S., Zartman, R.E., and Nkomo, I.T., 1968, A lead isotope study of galenas and selected feldspars from mining districts in Utah: Econ. Geol., v. 63, p. 796-814.

Stacey, J.S., and Kramers, 1975, Approximation of terrestrial lead isotope evolution by a two-stage model: Earth Planet. Sci. Lett., v. 26, p. 207-221.

Steiger, R.H., and Jaeger, E., 1977, Subcommission on geochronology: convention on the use of decay constants in geo- and cosmochemistry: Earth Planet. Sci. Lett., v. 36, p. 359-362.

Stewart, J.H., 1972, Initial deposits in the Cordilleran geosyncline: evidence of a late Precambrian (<850 my) continental separation: Geol. Soc. Amer. Bull., v. 83, p. 1345-1360.

Stoeser, D.B., 1974, Xenoliths of the San Francisco volcanic field, in Geology of northern Arizona, Part II - areal studies and field guides for Geol. Soc. Amer. Rocky Mountain Sect. Mtg. Flagstaff, Arizona, p. 530-545.

Strand, R.G. (compiler), 1967, Geologic map of California, Mariposa sheet: Calif. Div. of Mines and Geol.

Strand, R.G. (compiler), 1962, Geologic map of California, San Diego-El Centro sheet: Calif. Div. of Mines and Geol.

Sun, S.S., 1973, Lead isotope studies of young volcanic rocks from oceanic islands, mid-ocean ridges, and island arcs, Ph.D. Thesis, Columbia Univ., 139 p.

Sun, S.S., and Hanson, G.N., 1975, Evolution of the mantle: geochemical evidence from alkali basalt: Geology, v. 3, no. 6, p. 297-302.

Sun, S.S., Tatsumoto, M., and Schilling, J.G., 1975, Mantle plume mixing along the Reykjanes ridge axis: lead isotopic evidence: Science, v. 190, p. 143-147.

Suppe, J., Powell, C., and Berry, R., 1975, Regional topography, seismicity, and Quaternary volcanism, and the present day tectonics of the western United States: Amer. J. Sci., v. 275-A, p. 307-346.

Synder, W.S., Dickinson, W.R., and Silberman, M.L., 1976, Tectonic implications of space-time patterns of Cenozoic magmatism in the western United States: Earth Planet. Sci. Lett., v. 32, p. 91-106.

Tatsumoto, M., 1966, Isotopic composition of lead in volcanic rocks from Hawaii, Iwo Jima, and Japan: J. Geophys. Res., v. 71, no. 6, p. 1721-1733.

Tatsumoto, M., and Knight, R.J., 1969, Isotopic composition of lead in volcanic rocks from central Honshu with regard to basalt genesis: Geochem. J., v. 3, p. 53-86.

Tatsumoto, M., and Snavely, P.D., 1969, Isotopic composition of lead in rocks of the Coast Range, Oregon and Washington: J. Geophys. Res., v. 74, p. 1087-1100.

Tatsumoto, M., Knight, R.J., and Allegre, C.J., 1973, Time differences in the formation of meteorites as determined from the ratio of lead-207 to lead-206: Science, v. 180, p. 1279-1283.

Taylor, P.N., 1975, An early Precambrian age for migmatic gneisses from Vilcan I Bø, Vesteralen, north Norway: Earth Planet. Sci. Lett., v. 27, p. 35-42.

Thaden, R.E., Merrin, S., and Raup, O.B., 1967, Geologic map of the Grants SE quadrangle, Valencia County, New Mexico: U.S. Geol. Survey Map GQ-682.

Thompson, G.A., and White, D.E., 1964, Regional geology of the Steamboat Springs area, Washoe County, Nevada: U.S. Geol. Survey Prof. Paper 458-A, 52 p.

Tilton, G.R., Patterson, C., Brown, H.S., Inghram, M.C., Hayden, R.J., Hess, D.C., and Larsen, E.S., 1955, Isotopic composition and distribution of lead, uranium, and thorium in a Precambrian granite: Geol. Soc. Amer. Bull., v. 66, p. 1131-1148.

Tolman, C.F., 1909, Geology of the Tumamoc Hills, Carnegie Inst. Washington Publ. No. 113, p. 67-82.

Tschanz, C.M., and Pampeyan, E.H., 1970, Geology and mineral deposits of Lincoln County, Nevada: Nevada Bur. Mines Bull., v. 73, 187 p.

Ulrich, G.E., and Bailey, N.G., 1974, Geologic map of the SP Mountain quadrangle, Coconino County, Arizona: U.S. Geol. Survey open-file report 74-5.

Vitaliano, C.J., 1963, Cenozoic geology and sections of the Ione quadrangle, Nye County, Nevada: U.S. Geol. Survey Map MF-255.

Vitaliano, C.J., and Vitaliano, D.B., 1972, Cenozoic volcanic rocks in the southern Shoshone Mountains and Paradise Range, Nevada: Geol. Soc. Amer. Bull., v. 83, p. 3269-3280.

Vollmer, R., 1977, Terrestrial-lead isotopic evolution and formation time of the earth's core: Nature, v. 270, no. 10, p. 144-147.

Warren, D.H., 1969, A seismic-refraction survey of crustal structure in central Arizona: Geol. Soc. Amer. Bull., v. 80, p. 257-282.

Weber, R.H., 1963, Cenozoic volcanic rocks of Socorro County: New Mexico Geol. Soc. 14th Field Conf. Guidebook, p. 132-143.

Weber, R.H., 1964, Geology of the Carrizozo quadrangle, New Mexico: New Mexico Geol. Soc. 15th Field Conf. Guidebook, p. 100-109.

Wenrich-Verbeek, K., 1974, Major and trace element variation through a lava sequence and its implications on the magmatic evolution of the San Francisco peaks, Arizona: Geol. Soc. Amer. Abstracts with Programs, v. 6, no. 5, p. 482.

Wetherill, G.W., 1956, Discordant uranium-lead ages, I: Amer. Geophys. Union Transactions, v. 37, no. 3, p. 320-326.

Wilson, E.D., Moore, R.T., and Cooper, J.R., 1969, Geologic map of Arizona, Ariz. Bur. of Mines, U.S. Geol. Survey.

Wise, W.S., 1969, Origin of basaltic magmas in the Mojave Desert area, California: Contr. Mineral. Petrol., v. 23, p. 53-64.

Woodward, L.A., Callender, J.F., Gries, J., Seager, W.R., Chapin, C.E., Shaffer, W.L., and Zilinski, R.E., 1975, Tectonic map of the Rio Grande region, Colorado-New Mexico border to Presidio, Texas: New Mexico Geol. Soc. 26th Field Conf. Guidebook.

Wright, L., 1976, Late Cenozoic fault patterns and stress fields in the Great Basin and westward displacement of the Sierra Nevada block: Geology, v. 4, p. 489-494.

Wyllie, P.J., 1971, Role of water in magma generation and initiation of diapiric uprise in the mantle: J. Geophys. Res., v. 76, p. 1328-1338.

Zartman, R.E., and Tera, F., 1973, Lead concentration and isotopic composition in five peridotite inclusions of probable mantle origin: Earth Planet. Sci. Lett., v. 20, p. 54-66.

Zartman, R.E., 1974, Lead isotopic provinces in the Cordillera of the western United States and their geologic significance: Econ. Geol., v. 69, p. 792-805.

APPENDIX A: THE Pb-U-Th SYSTEM

Lead has four naturally occurring stable isotopes: ^{204}Pb, ^{206}Pb, ^{207}Pb, and ^{208}Pb. ^{206}Pb, ^{207}Pb, and ^{208}Pb are, respectively, the end-products, or daughters, of ^{238}U, ^{235}U, and ^{232}Th radioactive decay. Thus over geologic time a radioactively derived component has been added to lead of masses 206, 207, and 208. As a result the ratios of these (partially) radiogenic isotopes to parentless, nonradiogenic ^{204}Pb have changed in time. The values of ^{206}Pb/^{204}Pb, ^{207}Pb/^{204}Pb, and ^{208}Pb/^{204}Pb in any system today are functions of (1) the original lead isotopic composition of the system, (2) the amount of uranium and thorium relative to lead in the system over time, and (3) the time over which decay has taken place. In the case of a closed system, where no U, Th, or Pb has entered or left the system during the period of interest, the appropriate mathematical expressions are given by equations (1), (2), and (3) of Table A.1.

By algebraic manipulation of equation (1) and (2) it is possible to derive equation (4), sometimes called the Holmes-Hautermans equation. It is easily shown from this equation that $(^{207}\text{Pb}/^{204}\text{Pb})_f$ is linearly dependent on $(^{206}\text{Pb}/^{204}\text{Pb})_f$ (see equation (5)). The proportionality between these two variables depends only on the ages of the system and $(^{235}\text{U}/^{238}\text{U})_n$. Because the value of $(^{235}\text{U}/^{238}\text{U})_n$ is a constant in every case heretofore investigated, the Holmes-Hautermans equation allows calculation of the age of the system without any knowledge of its U or Th content. This is particularly important in studies involving young volcanic rocks. The chemical fractionation which occurs during

Table A.1: Lead equations, assuming radioactive decay in a closed system*

(1) $$({}^{206}\mathrm{Pb}/{}^{204}\mathrm{Pb})f = ({}^{206}\mathrm{Pb}/{}^{204}\mathrm{Pb})i + ({}^{238}\mathrm{U}/{}^{204}\mathrm{Pb})n[\exp(\lambda_8 T_i) - \exp(\lambda_8 T_f)]$$

(2) $$({}^{207}\mathrm{Pb}/{}^{204}\mathrm{Pb})f = ({}^{207}\mathrm{Pb}/{}^{204}\mathrm{Pb})i + ({}^{235}\mathrm{U}/{}^{204}\mathrm{Pb})n[\exp(\lambda_5 T_i) - \exp(\lambda_5 T_f)]$$

(3) $$({}^{208}\mathrm{Pb}/{}^{204}\mathrm{Pb})f = ({}^{208}\mathrm{Pb}/{}^{204}\mathrm{Pb})i + ({}^{232}\mathrm{Th}/{}^{204}\mathrm{Pb})n[\exp(\lambda_2 T_i) - \exp(\lambda_2 T_f)]$$

(4) $$\frac{\left(\frac{{}^{207}\mathrm{Pb}}{{}^{204}\mathrm{Pb}}\right)f - \left(\frac{{}^{207}\mathrm{Pb}}{{}^{204}\mathrm{Pb}}\right)i}{\left(\frac{{}^{206}\mathrm{Pb}}{{}^{204}\mathrm{Pb}}\right)f - \left(\frac{{}^{206}\mathrm{Pb}}{{}^{204}\mathrm{Pb}}\right)i} = \frac{{}^{235}\mathrm{U}}{{}^{238}\mathrm{U}}\ n \cdot \frac{[\exp(\lambda_5 T_i) - \exp(\lambda_5 T_f)]}{[\exp(\lambda_8 T_i) - \exp(\lambda_2 T_f)]}$$

(5) $$\left(\frac{{}^{207}\mathrm{Pb}}{{}^{204}\mathrm{Pb}}\right)f = \left(\frac{{}^{206}\mathrm{Pb}}{{}^{204}\mathrm{Pb}}\right)f \cdot F(t) + \left[F(t) \cdot \left(\frac{{}^{206}\mathrm{Pb}}{{}^{204}\mathrm{Pb}}\right)i + \left(\frac{{}^{207}\mathrm{Pb}}{{}^{204}\mathrm{Pb}}\right)i\right]$$

where i = initial value

f = final value

T_i = age, in years before present, of beginning of the system

T_f = age, in years ago, of end of the system

n = value if the system had been allowed to remain undisturbed until the present

λ_8 = the decay constant of $^{238}\mathrm{U}$

λ_5 = the decay constant of $^{235}\mathrm{U}$

λ_2 = the decay constant of $^{232}\mathrm{Th}$

F(t) = RHS of (4)

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*See Wetherill (1956), Russel and Farquhar (1960), or Faure (1977) for derivations of these equations.

the generation of the volcanic magma invariably changes U/Pb and Th/Pb ratios so that source region values cannot be measured directly in the volcanic derivatives.

There are two chief circumstances where equation (4) can be employed. In both the validity of the calculation requires the closed system assumption to be true. The first, termed the single stage or model age calculation, calculates T_f assuming T_i is the 4.57 by age of the earth* and the initial lead ratios are those of Canyon Diablo troillite -- the least radiogenic lead ever measured, and the one thought best to represent the primordial values of the solar system. For modern volcanics the calculated T_f should be zero. However, modern volcanics commonly give model ages hundreds of millions of years in the past or in the future. This fact is strong evidence that young volcanic leads have not evolved in a closed system since the formation of the earth. Indeed the predominance of future ages suggests that most volcanics have come from systems in which $\mu = {}^{238}U/{}^{204}Pb$ has increased in time.

Equation (4) is also used in a two stage or secondary isochron calculation. Here it is assumed that the lead evolved from T_0 (the age of the earth) to T_i in a closed system having a constant μ. At T_i the original system differentiated into a number of subsystems having different μ's. These subsystems have separately evolved as closed systems

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*More precisely T_i is presumed to be the age implied by the meteoric isochron. See Tatsumoto _et al_. (1973) and Patterson (1956).

until T_f. According to equation (5) the lead in these subsystems will lie on a straight line in a $^{206}Pb/^{204}Pb$-$^{207}Pb/^{204}Pb$ diagram, the slope of which is equal to the right hand side of equation (4). For young volcanics $T_f = 0$ so T_i is the only variable on which the slope is dependent. Thus, a number of $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ measurements determining a straight line can be used to determine T_i, the age at which the whole supersystem formed. But care must be exercised in evaluating the validity of this calculation; mixing or contamination processes can also generate straying line arrays on $^{206}Pb/^{204}Pb$-$^{207}Pb/^{204}Pb$ diagrams.

The interested reader is referred to Faure (1977), Gale and Mussett (1973), Harper (1973), Doe (1970), Kanasewich (1968), and Russell and Farquhar (1960) for more detailed discussion of Pb-U-Th systematics. The numerical values of isotopic parameters used in this work are shown in Table A.2.

Table A.2: Isotopic parameters used in this report

Parameter	Commonly used Symbol	Value	Reference
Decay Constants			
^{235}U	λ_5, λ'	.155125 by^{-1}	Jaffey *et al.* (1971)
^{238}U	λ_8, λ	.98485 by^{-1}	Jaffey *et al.* (1971)
^{232}Th	λ_2, λ''	.049475 by^{-1}	LeRoux and Glendenin (1963)
Primordial Pb Ratios (Canyon Diablo Troillite)			
$(^{206}Pb/^{204}Pb)_{To}$	Ap,Xo	9.307	Tatsumoto *et al.* (1973)
$(^{207}Pb/^{204}Pb)_{To}$	bp,Yo	10.294	Tatsumoto *et al.* (1973)
$(^{208}Pb/^{204}Pb)_{To}$	Cp,Zo	29.476	Tatsumoto *et al.* (1973)
Present Day Ratios			
$(^{238}U/^{235}U)_n$		137.88	Steiger and Jaeger (1977)
$(^{238}U/^{204}Pb)_n$	μ	variable but ∿9 for many systems	
$(^{232}Th/^{238}U)_n$	κ	variable but ∿4 for many systems	
$(^{232}Th/^{204}Pb/_n$	$\mu \cdot \kappa$	variable but ∿36 for many systems	

APPENDIX B: ANALYTICAL METHODS

Sample Preparation

Samples of basalt were cleaned of external, atmospherically contaminated surfaces in the field with a sledge hammer. Those samples shown by thin section examination to be unweathered were later crushed into pea-sized particles by a smaller hammer on an iron plate. Except for a few samples ground in an agate motar, pea-sized particles were ground into a fine powder by a Spex Industries tungsten carbide Shatterbox.

Determination of Pb Isotopic Compositions

For isotopic composition determinations lead was extracted from 2 to 4 grams of powdered rock sample using pyrochemical techniques similar to those employed by Ludwig (1974). Rock samples were heated in outgassed quartz tubes under vacuums of less than 0.1 mm Hg at temperatures of approximately 1100° C for periods of 24 hours or more, while volatilized Pb was collected on a fused silica cold finger. Volatilized lead was removed from the cold finger by dipping the tip of the finger in a dilute HCl solution. Yields for the volatilization procedure range from 71 to 87%.

Lead in the HCl dip solution was purified by conventional dithizone extraction, which has been described by Tilton *et al*. (1955). The first step of this procedure is the addition to the dip solution of potassium cyanide and ammonium citrate (1 ml of 1% KCN solution and 2 ml of 25% citrate for normal sized samples) followed by enough NH_4OH

to raise the solution pH to a value of approximately 9.3. The resulting aqueous solution is then shaken in a separatory funnel with an appropriate amount of sodium dithizone-chloroform solution (1 ml of standard dithizone solution, which is 6.0 mg of dithizone for each liter of $CHCl_3$, is adequate for complexing 2 μg of Pb). This transfers Pb into the $CHCl_3$ phase while most other, undesirable metal ions remain in the aqueous phase. After separating the two phases, the dithizone-Pb solution is shaken in a second separatory funnel with 10 ml of dilute HCl. This step causes the Pb to be extracted back into the aqueous solution, with further purification resulting. The lead bearing HCl solution is then dried in a 10 ml pyrex beaker. Once dry, small amounts of concentrated nitric and perchloric acids are added to decompose any organic matter present. The 10 ml beaker is again heated until it is dry.

For mass spectrometry Pb was loaded on high purity, outgassed Re filaments using the silical gel method. The method used is modified from that described in N.B.S. Technical Note 546, E.B. Shields, editor. The method employed in this laboratory consists of adding 0.02 ml of concentrated HNO_3 to the 10 ml beaker containing the Pb sample, heating the beaker to dryness, adding 0.02 ml 0.75 N H_3PO_4, and then reheating for 15-20 minutes. A 0.02 ml portion of silica gel in water is then used to wash the beaker bottom and to transfer the Pb in the beaker onto the Re filament. The silical gel solution is dried by passing 1.2 amps through the filament, which is also placed under a heat lamp. After drying, the filament is heated for 2 or 3 minutes at 1.5 amps, raised to

1.75 amps for a minute or two more, and finally heated at 2.0 to 2.5 amps for a second or so. The filament is then immediately introduced into the mass spectrometer.

The mass spectrometers used in this study are single focusing 30 cm radius instruments interfaced with a Digital Equipment Corporation PDP 11/40 computer. Typical signal intensities are 0.3 to 1 volt for a 10^{11} ohm resistor on the ^{206}Pb peak from the simple collector. Data are typically taken at filament temperatures between 950° and 1050° C and at filament currents of 1.4 to 1.7 amps. Besides Pb at masses of 204, 206, 207, and 208, the mass spectra commonly exhibited peaks at mass 209(Bi). Less common were peaks at masses 205 and 203 (Tl), 202 and 204(Hg), and broad asymmetric peaks at 203 and 201 (ReO); no Pb data were taken while any of these peaks were present.

Pb, U, and Th Concentrations

Pb, U, and Th concentrations were determined by isotopic dilution. In the procedure used here spikes of essentially pure ^{208}Pb, ^{235}U, and ^{230}Th in solutions of known concentrations were added by calibrated pipettes to a weighed quantity of powdered rock. Typical sample weights were 2 to 4 grams. Approximately 3 grams of heated concentrated HNO_3, 12 grams of 50% HF solution, and 3 grams of concentrated $HClO_4$ were used to dissolve spiked rock samples during a two-step attack lasting more than 24 hours. Pb, U, and Th were extracted from dissolved samples by heating rock residues with concentrated HNO_3 for a minimum of 6 hours. After centrifuging for an hour, this nitric acid solution was decanted from the rock residue and subjected to Tatsumoto's barium coprecipitation procedure (Tatsumoto, 1966). The lead-bearing barium precipitate was dissolved in distilled water and processed through a dithizone extraction identical to that done in Pb isotopic composition determinations. Mass spectrometry procedures for Pb in spiked, concentration samples were also identical to those used in Pb isotopic composition analyses.

The U and Th extracted from the rock sample are found in the supernate from the barium coprecipitation. To this nitric acid solution, 3 or 4 drops of $Al(NO_3)_3$ were added, followed by 25% NH_4OH until a stable brown hydroxide precipitate formed. After centrifuging for an hour the supernate was decanted and discarded, and the precipitate dissolved in 35 ml 7 N nitric acid. Following the Tatsumoto (1966) resin column procedure, this 7 N HNO_3 solution was loaded onto a nitrate Dowex 1-X8 anion resin column 15 ml in volume. The column was washed with 30 ml of 7 N HNO_3. The U and Th on the column were then eluted by rinsing the column with 20 ml H_2O followed by 20 ml 6 N HCl. The elutant was collected and dried. Uranium and thorium in the dried beaker were once again dissolved, this time in 6 ml 7 N HNO_3. This solution was loaded onto a 3 mil anion exchange column, and the column rinsed with 20 ml of 7 N HNO_3. Finally U and Th were eluted by 10 ml of a 0.5 N HCl wash. This was collected and dried in a 10 ml pyrex beaker. A small amount of concentrated HNO_3 and $HClO_4$ was added to the beaker, and the beaker was again dried. The chemical procedures now completed, U and Th were loaded on the side filaments of a Re triple filament using approximately 0.04 ml of concentrated nitric acid. The side filament was dried at 1.2 amps filament current, and then baked at 1.4 amps. Once in the mass spectrometer sizeable signals of U were encountered at side filament currents of approximately 1.8 A and center filament currents of 4.0 A. Th signals tended to come in at hotter filament temperatures associated with 2.5 amps of side filament current and 4-5 amps of center filament current. Depending on the sample, U metal or UO, and Th metal or ThO, signals could be encountered.

APPENDIX C: DESCRIPTIVE DATA

Introductory Notes

Some of the rock names used in the following pages are not in common usuage. Because many basalts from the southwestern United States cannot be unambiguously assigned to traditional petrologic categories on petrographic grounds, descriptive, if untraditional, names have been employed. To briefly reiterate discussions in the text, olivine-augite basalts are mafic basalts rich in olivine and augite usually with more than 35% of these minerals). They usually contain large, abundant olivine phenocrysts, very rarely contain plagioclase phenocrysts. Feldspathic basalts contain a higher percentage of plagioclase (40-60%), and commonly plagioclase phenocrysts. While olivine-augite basalts tend to have ophitic or subophitic textures, many feldspathic basalts have trachytic textures. Feldspathic basalts compositionally grade into andesites, with SiO_2 concentrations usally between 50 and 54%. Olivine-augite basalts usually have SiO_2 contents less than 50%. The term "basaltic andesite" has been reserved for those mafic volcanic rocks containing sieve-textured plagioclase and/or quartz "xenocrysts." In the cases where it was possible to establish whether a sample was alkaline or subalkaline from its petrographic characteristics, the descriptive labels discussed above were replaced by more traditional names.

The numbers quoted in the following petrographic descriptions should be regarded as semiquantitative. The minerals percentages given here were subjectively estimated, and consequently imprecise.

Plagioclase compositions were determined by relatively inaccurate, optical methods on crystals which were commonly zoned. The 2V data given are also approximate.

Abbreviations

anh	anhedral
B+(-)	biaxial positive (negative)
euh	euhedral
grdmass	groundmass
lt	light
med	medium
pheno	phenocryst
quad	quadrangle
sec	section
subh	subhedral
v	very
xeno	xenocryst
U+(-)	uniaxial positive (negative)
μpheno	microphenocryst

C3006

Name: Hornblende andesite

Megascopic description: Lt to med gray, fine grained, unvesicular, unaltered, with orientated hornblende phencrysts

Coordinates: 114°33'12"W - 32°56'55"N

Township: 300'S, 500'E of SE corner sec 16, T14S, R23E, Little Picacho Peak 7.5' quad, Imperial Co., CA

Locality: Near headwaters of Ferguson Wash, ∿2 mi E of Senator Wash Recreation Area, Chocolate Mtns.

Field relations: Capping flow on a faulted cuesta, overlies tuffaceous unit

Age: K/Ar, 24.7 ± 1.2 my (Damon, 1968)

Reference: Crowe (1978)

Minerals:

15%	Hornblende, phenos, equant to elongate, often rounded at corners, 0.4-4 mm in length, pleochroic tan to deep brown, oxidized along outer edges
30%	Plagioclase, phenos, short laths, 0.2-1 mm in size, some grains have partially reacted (wormy) cores, zoned, ∿An35
40%	Plagioclase, grdmass, acicular microlites, 50 μ in size, ∿An25?
10%	Oxides, grdmass, equant, 50-150 μ size
5%	Glass, grdmass, interstitial to plagioclase microlites

Texture: Hornblende and plagioclase phenocrysts show a preferred orientation, but the texture is really not trachytic. Groundmass minerals are unoriented. This lack of orientation as well as their very fine sizes suggest that groundmass crystals formed by devitrification of an originally glassy matrix.

Comment: A rock that is remarkably free of alteration.

A3008

Name: Basaltic andesite

Megascopic description: Medium gray, basically unvesicular, aphanatic volcanic rock; contains mm sized plagioclase phenocrysts, and an occasional red-brown iddingsite pseudomorph of olivine

Coordinates: 113°08'29"W - 32°52'59"N

Township: 800'W, 100'S, NW corner sec 25, R1W, T6S, Sentinel 15' quad, Maricopa Co., AZ

Locality: Flow, south side Sentinel Peak cinder cone

Field relations: From a morphologically youthful but probably not recent flow

Age: Quaternary, according to the Arizona state geologic map (Wilson *et al*., 1969)

Reference: Wilson *et al*. (1969)

Minerals:

7%	Plagioclase, phenos, stubby, 1-2 mm in diameter, rounded, sometimes embayed, cores and annuluses of partially reacted (wormy) material, poorly twinned, zoned, sometimes exist in multi-grain aggregates
Tr	Quartz, phenos, equant, ∿1 mm, surrounded by fine grained clinopyroxene (?) reaction rim
15%	Olivine, micropheno and grdmass grains, eu-an, 50-400 μ in size, larger grains in large part altered to iddingsite
5%	Clinopyroxene, grdmass, anh, 40 μ in size
40%	Plagioclase, microphenocrysts and grdmass grains, euh-subh laths, 40-400 μ in length, clean and unreacting, ∿An30-An50 in composition
10%	Oxides, equant, 50-100 μ in size
20%	Glass, interstitial material, usually ≤20 μ across, brown color, mostly devitrified
Tr	Serricite alteration along vesicle borders

Texture: Feldspar laths show a consistent orientation, but there is too much mesostasis to label this a pilotaxitic texture

Comment: The presence of wormy plagioclase and quartz "xenocrysts" in this rock is remininscent of basaltic andesite from the Colorado Plateau. These features have been only infrequently observed in the mafic, generally alkaline volcanics of the Basin and Range province. However, two nearby samples (A3009 and A6005) show similar, unusual characteristics. The abundance of plagioclase in this rock also deserves note. Leeman (1970) has reported a ^{87}Sr/^{86}Sr value of 0.7035 for a basaltic andesite sample (WPL-91) from the Sentinel area.

A3009

Name: Basaltic andesite

Megascopic description: Dark gray, mostly unvesicular, contains an occasional olivine phenocryst altered to iddingsite

Coordinates: 112°48'55"W - 32°27'39"N

Township: 800'W, 250'S, NE corner sec 19, R5W, T11S, Ajo 15' quad, Pima Co., AZ

Locality: SW flank, Batamonte Mtns, ∿2 mi N and E of Childs

Field relations: Sample from Batamonte Andesite formation of Gilluly (1946)

Age: K/Ar 15 ± 2.2 my (Eberly and Stanley, 1978)

Reference: Gilluly (1946)

Minerals:

5%	Plagioclase, phenos, stubby to irregular in shape, 1-2 mm in size, universally rounded, occasionally embayed, wormy textured cores or rings, zoned, twinned
15%	Olivine, phenos and grdmass, 20 μ - 1 mm, subhedral to anhedral, larger grains replaced in large part by iddingsite, but unaltered crystals clear
10%	Clinopyroxene, grdmass, equant, 100-500 μ , B+, lt gray-green color
40%	Plagioclase,grdmass, lath like, 50-150 μ in length, ∿An40?
15%	Oxides, grdmass, equant, euhedral, 100 μ
15%	Glass, interstitial, 20 μ blebs, brown colored and containing microlites
1%	Calcite, weathering product, found lining vesicles and in some cracks

Texture: Groundmass plagioclase laths are subparallel to one another.

Comment: This sample is unlike the Quaternary alkaline olivine basalts that characterize much of the Basin and Range province. The presence of wormy plagioclase crystals suggest a similarity to the basaltic andesites of the Colorado Plateau.

M3012

Name: Basalt

Megascopic description: Black, vesicular volcanic rock with plagioclase phenocrysts

Coordinates: 113°30'W - 32°02'N

Locality: 1 mi E and S of black ash quarry on Mexico Route 2, between Sonoita and San Luis, several mi E of the microwave relay station on top of Cerro de Las Lavas, northern part of Pinacate volcanic field

Field relations: From a morphologically recent flow

Age: Quaternary

Reference:

Minerals:

10%	Plagioclase, phenocrysts to microphenocrysts, euh to subh but generally lath like, 0.3-6 mm in length
5%	Olivine, microphenos, subh, usually around 300 μ in size but occasionally as large as 1 mm
25%	Oxides, grdmass, anh, equant
20%	Plagioclase, grdmass, laths
15%	Glass
20%	Vesicles, irregular in shape, but approximately a mm or two across
5%	Clays and calcite, vesicle filling

Texture: Under low power this rock appears to have black glass matrix. Higher power reveals a groundmass composed almost entirely of fine grained crystals

Comment: Two features are especially noteworthy about this rock. The first is the abundance of oxides in the groundmass. The second is the abundance of clays and calcite as fillings in vesicles. Although these are not really weathering products - the rock itself appears quite fresh - their occurrence suggests that the isotopic results on this rock be interpreted with caution.

C3013

Name: Olivine-augite basalt

Megascopic description: Lt. gray, unvesicular basalt with abundant olivine phenocrysts

Coordinates: 117°57'52"W - 37°24'48"N

Township: Central W 1/2, sec 19, R37E, T6S, Soldier Pass 15' quad Inyo Co., CA

Locality: In arroyo cliff, just S of California 63, W of Piper Mtn, on the NE part of Deep Springs valley

Field relations: Basalt outcrop lies on top of Mesozoic granite

Age: K/Ar 10.8 ± 1.0 my (Dalrymple, 1963)

Reference: Mariposa Sheet, Geologic Map of California (Strand, 1962)

Minerals:

25%	Olivine, phenocrysts to grdmass grains, typical olivine cross-sections, subhedral, 20 μ - 2 mm in size, crystal rims often show incipient oxidation, larger crystals often contain oxide inclusions
25%	Augite, phenocrysts and grdmass crystals, equant, subh-anh, 50 μ - 1 mm in size, lt brownish or greenish tint, 2V∿60°
35%	Plagioclase, grdmass, elongated laths, ∿50-250 μ in length, An45
15%	Oxides, equant, 10-100 μ in size, perhaps a bimodal size distribution

Texture: Intergranular

Comment: A remarkably fresh sample, which shows no petrographic evidence of contamination. However, Hedge and Noble (1971) have reported a $^{87}Sr/^{86}Sr$ ratio of 0.7080 for a sample from the same general locality.

C3014

Name: Olivine basalt

Megascopic description: Light gray, unvesicular basalt with reddish brown iddingsite "phenocrysts"

Coordinates: 118°36'27"W - 37°33'16"N

Township: SE 1/4, sec 36, R30E, T4S, Casa Diablo Mtn 15' quad, Mono Co., CA

Locality: Owens River gorge, ∿4 mi E of Tom's Place

Field relations: Sample from upper part of the flow. The basalt in Owens Gorge lies on top of Mesozoic granitic rocks and beneath the Bishop tuff

Age: K/Ar 3.2 ± 0.1 my (Dalrymple, 1963)

Reference: Mariposa Sheet, Geologic Map of California (Strand, 1967)

Minerals:

5%	Olivine, phenos, sub, ∿1 mm in size, larger grains rimmed by reddish alteration, smaller grains completely consumed
20%	Augite, microphenos-grdmass, subh-anh, ∿200 μ in size, B+, intermediate 2V, lt brown tint
10%	Olivine grdmass, an., 50 μ in size, almost completely converted to iddingsite
45%	Plagioclase, grdmass, elongate laths, 100 μ in length, ∿An45
15%	Oxides, grdmass, equant, 20 μ in size
3%	Vesicles, up to 4 mm in size, completely free of alteration

Texture: Orientated plagioclase laths give this rock a trachytic appearance.

Comment: This rock is transitional between an olivine-augite basalt and a feldspathic basalt.

N3015

Name: Basaltic andesite

Megascopic description: Purplish gray, aphanatic, aphyric

Coordinates: 117°36'55"W - 38°58'42"N

Township: T13N, R39E, Ione 15' quad, Nye Co., NV

Locality: Top of a NW trending ridge, ∿2½ mi NW of Ione, ∿1/4 mi E of National Forest boundary

Field relations: Stratigraphically above Toiyabe quartz latite (∿20 my) but morphologically older than one would expect for a Quaternary or Late Pliocene rock

Age: Between 5? and 20 my in age

Reference: Vitaliano (1963), Vitaliano and Vitaliano (1972)

Minerals:

55%	Plagioclase, pheno-grdmass, short laths, 50 μ - 2 mm, twinned, zoned
7%	Olivine, pheno-grdmass, sub, 1 mm - 100 μ in size, larger grains almost completely converted to iddingsite and contain oxide inclusions
13%	Clinopyroxene, grdmass, sub-an, often elongate, 100-400 μ in size, commonly twinned, B+, intermediate 2V
15%	Oxides, grdmass, granular, ∿50 μ in size
10%	Glass, grdmass, interstitial blebs, lt brown color
1%	Quartz, xenocrystic, 1 mm, rounded, surrounded by clinopyroxene and glass reaction rim
1%	Oxidation, weathering, especially along cracks

Texture: Randomly orientated plagioclase laths set in a glassy matrix

Comment: Mineralogically this rock is similar to the basaltic andesites of the Colorado Plateau. Isotopically it is indistinguishable from the other volcanics of the Great Basin.

N3016

Name: Feldspathic basalt

Megascopic description: Med gray, generally unvesicular basalt with "rusted" olivine phenocrysts and larger but less common feldspar phenocrysts

Coordinates: 118°27'04"W - 39°16'41"N

Township: ∿12000' S75 E of NW corner, T16N, R32E, 2° Reno quad, Churchill Co., NV

Locality: Just N of U.S. 50, W side of the Stillwater Range, ∿7 mi W of Frenchman

Field relations: Youngest volcanic rock in the section, overlies Pliocene? sediments and tuffs

Age: Plio-Pleistocene, according to Page (1965)

Reference: Page (1965)

Minerals:

3%	Olivine, pheno, subh, characteristic olivine cross sections, ∿1 mm in size, rimmed by reddish and/or black oxidation, 11 ext, B+, 2V∿80, clear color, contain some oxide inclusions
2%	Plagioclase, pheno, subh, often lath like, ≤1 mm sized crystals clump together in 3 mm sized aggregates (glomeroporphyritic texture)
10%	Olivine, grdmass, anh, 50 μ in size
15%	Clinopyroxene, grdmass, anh, 50 μ in size
20%	Oxides, grdmass, blocky, 50-100 μ in size
4%	Vesicles, 300 μ in size, irregular in shape
1%	Glass, interstitial blebs, 30 μ in size
45%	Plagioclase, grdmass, lath like, 200-400 μ in length, ∿An50

Texture: Basically intergranular, but plagioclase laths are locally subparallel. Rock is characterized by glomeroporphyritic plagioclase megacrysts, and rare patches of fine grained, mostly clinopyroxene, material

Comment: The abundance of oxide in this rock may suggest a tholeiitic affinity. The occurrence of plagioclase phenocrysts is untypical of alkaline olivine basalts, suggesting that this sample be labelled a feldspathic basalt.

N3018

Name: Andesite

Megascopic description: Lt gray, aphanatic, unvesicular volcanic rock containing hornblende, biotite, and feldspar phenocrysts

Coordinates: 116°50'27"W - 39°23'30"N

Township: E side sec 30 (unsurveyed), R46E, T18N, Spencer Hot Springs 15' quad, Lander Co., NV

Locality: ∿150 m N of U.S. 50, on hill to E of Cape Horn, Simpson Park range

Age: K/Ar 35 ± 4 my (McKee and Silberman, 1970)

Reference: McKee and Silberman (1970), McKee (1968)

Minerals:

5%	Biotite, pheno, euh, ∿700 μ in size, pleochroic olive-green to brown to lt brown, occasionally seen replacing clinopyroxene
10%	Hornblende, pheno, subh, ≤2 mm in size, pleochroic lt brown to brown to olive-green
3%	Augite, pheno, subh-anh, 0.4-1.0 mm, clear color, usually occurring with other pyroxene grains in aggregates
2%	Bronzite, pheno, anh, 0.4-1.0 mm, pleochroic pink to green, found in aggregates with other pyroxene crystals, in some cases partially replaced by hornblende and biotite
5%	Oxides, μpheno, 50-300 μ, small grains subh while larger grains often pseudomorphs after biotite and/or hornblende
20%	Plagioclase, pheno, subh, ∿2 mm, zoned twinned, a few grains with sieve-like (wormy) textures, ∿An58
15%	Plagioclase, grdmass, acicular, 30 μ long, crystallizing from glassy matrix, ∿An20
40%	Glass, white translucent

Texture: Phenocrysts set in a partially devitrified glassy matrix

Comment: The coexistence of several nonequilibrium ferromagnesium phenocryst phases is notable, but not uncommon in intermediate, calc-alkaline volcanics. Although this sample has been labelled an andesite, it might easily be a dacite.

N3021

Name: Dacite or andesite

Megascopic description: Flinty, chocolate brown, aphanatic volcanic rock with abundant plagioclase phenocrysts

Coordinates: 115°08'59"W - 39°25'52"N

Township: N 1/2, sec 18, R61E, T18N, Riepetown 15' quad, White Pine Co., NV

Locality: 450 m N of U.S. 50 and 300 m W of lower Thirtymile Road, W of Robinson Summit, Egan Range

Age: K/Ar 32.9 ± 0.7 my (Armstrong, 1970)

Reference: Armstrong (1970)

Minerals:

5%	Biotite, pheno, subh, ∿400 μ, largely replaced by opaques, and in some cases also completely redissolved in matrix material
1%	Clinopyroxene, pheno, 0.4 mm grains in 1 mm aggregates, rounded and embayed, reacting with grdmass
15%	Plagioclase, pheno, subh, generally equant, ∿1 mm sizes, zoned, twinned
1%	Oxides, pheno, subh, ∿0.5 mm, usually found partially included in plagioclase
2%	Oxides, grdmass, anh, 5 μ size grains, differential abundances of these minute grains in different parts of the thin section give a marbled texture
50%	Plagioclase, grdmass, anh, irregular or acicular in shape
25%	Glass, translucent

Texture: Porphyritic with phenocrysts set in an originally glassy but now largely devitrified matrix

Comment: This sample is probably dacitic or andesitic in composition.

N3023

Name: Tholeiite

Megascopic description: Med gray, aphanatic, aphyric, unvesicular basalt

Coordinates: 116°23'00"W - 40°04'27"N

Township: NE 1/4, sec 14, T25N, R49E, Horse Creek Valley 15' quad, Eureka Co., NV

Locality: 1150 m due S of Cadet Trough Spring, Rocky Hills, Simpson Park Mtns

Age: K/Ar 14.7 ± 1.0 my (Armstrong, 1970)

Reference: Armstrong (1970)

Minerals:

35%	Plagioclase, µpheno-grdmass, 20 µ - 1 mm, lath like, twinned, zoned, ~An54
40%	Clinopyroxene, grdmass, subh, ~50 µ
12%	Orthopyroxene?, grdmass, subh, ~50 µ
10%	Oxides, blocky, 50-200 µ
2%	Glass
1%	Apatite, acicular, hexagonal to anh in cross section, ~5 x 40 µ

Texture: Relatively coarse grained groundmass, ophitic texture

Comment: The lack of olivine in this sample is unusual. This lack suggests a tholeiitic affinity for this sample, even though orthopyroxene was not positively identified.

N3027

Name: Diabase

Megascopic description: Med gray volcanic rock containing numerous small vesicles

Coordinates: 116°51'49"W - 40°44'54"N

Township: NE 1/4, SE 1/4, sec 11, R45E, T33N, Battle Mtn 15' quad, NV

Locality: ∿6600' elevation, W side of Sheep Creek Range, NE of Battle Mtn

Field relations: Bottom of the basalt flow capping the Sheep Creek Range

Age: 14.8 ± 1.5 my (McKee and Silberman, 1970)

Reference: McKee and Silberman (1970), McKee and Mark (1971)

Minerals:

15%	Olivine, subh, rounded, ∿300 μ, rims commonly converted to iddingsite, not distributed evenly through section, but rather in multigranular patches
25%	Augite, anh, interstitial, ∿400 μ sizes, lt green tint, partially include plagioclase laths, and some oxides
1%	Plagioclase, pheno, glomeroporphyritic aggregates of several large crystals, up to 6 mm in size
35%	Plagioclase, laths, ∿500 μ, zoned, twinned, An58
	Oxides, generally acicular crystals, found in interstitial areas occupied by mesostasis, ≤200 μ in length
15%	Glass, interstitial, ∿200 μ sizes, brown-black coloration, largely devitrified
10%	Vesicles, irregular in shape, ∿400 μ in size

Texture: Uniformally coarse grained groundmass, ophitic-subophitic texture

Comment: From its mineralogy, it is not clear whether this rock is alkaline or tholeiitic in character. However, chemical analyses by McKee and Mark (1971) on basalts from the same area indicate a tholeiitic affinity. These authors also report ^{87}Sr/^{86}Sr values of 0.7058 and 0.7056 for basalts from the same general locality.

N3029

Name: Olivine basalt

Megascopic description: Med gray aphanatic volcanic containing olivine phenocyrsts and an occasional pipe vesicle

Coordinates: 114°37'04"W - 39°29'16"N

Township: NE 1/4, NW 1/4, sec 17, R21E, T14N, Virginia City 15' quad, Storey Co., NV

Locality: Near dump, Long Valley, Lockwood area

Field relations: Isolated remnant of McClellan Peak basalt capping a ridge

Age: K/Ar 1.14 ± 0.04 my (Schilling, 1965)

Reference: Thompson and White (1964)

Minerals:

15%	Olivine, μpheno, subh, rounded, ∿700 μ, rimmed by reddish material, some crystals are noticeably embayed, commonly contain angular oxide inclusions
3%	Augite, μpheno, subh-anh, generally tabular, ≤2 mm in size, lt brown color, many crystals have a sieve-like texture, especially in crystal coves
5%	Plagioclase, μpheno, subh, ≤700 μ, zoned, twinned, ∿An52?
25%	Augite, grdmass, anh, 100 μ
5%	Olivine, grdmass, subh, 100-200 μ
15%	Oxides, grdmass, both equant and elongate crystals, 50 μ
30%	Plagioclase, grdmass, laths, 100 μ in length
1%	Apatite, grdmass, acicular, 100 μ in length
1%	Vesicles, 100-300 μ
Tr	Glass, interstitial, ≤100 μ, largely devitrified

Texture: Intergranular

Comment: Leeman (1970) has reported an ^{87}Sr/^{86}Sr ratio of 0.7052 for a nearby flow while Hedge and Noble (1971) found an ^{87}Sr/^{86}Sr of 0.7048 for a McClellan Peak basalt sample.

C3032

Name: Alkali-rich feldspathic basalt

Megascopic description: Lt gray, unvesicular volcanic rock which sparkles in the sunlight. Contains small olivine and feldspare phenocrysts

Coordinates: 120°08'41"W - 39°10'04"N

Township: N 1/2, NE 1/4, sec 12, T15N, R16E, Tahoe 15' quad, Placer Co., CA

Locality: Near top of Truckee River canyon (∼6760' elevation), Twin Crags area, ∼2 mi W of Tahoe City on California 89

Field relations: Lousetown Formation

Age: K/Ar 1.9 ± 0.1 my (Dalrymple, 1964)

Reference: Burnett and Jennings (1962), Geologic Map of California, Chico Sheet

Minerals:

15%	Olivine, μpheno-grdmass, anh, 700-100 μ, partially altered to iddingsite, larger grains have oxide inclusions
20%	Augite, grdmass, subh, 100-300 μ, lt greenish-brown tint
15%	Oxides, grdmass, anh, 50-200 μ
5%	Vesicles, often angular, 100-400 μ in size, interstitial holes, especially between feldspar laths
1%	Glass, interstitial, ∼50 μ
45%	Plagioclase, laths, 300 μ in length, twinned, zoned, ∼An65?
1%	Alkali feldspar, interstitial, ≤70 μ in length, v low refraction index

Comment: Dalrymple (1964) called this rock an olivine latite. Although alkali feldspar is present, it does not appear to be abundant enough to justify the term "latite." The basalt-like character of the mafic minerals would instead indicate that this rock is merely an alkali rich feldspathic basalt.

C3034

Name: Feldspathic basalt

Megascopic description: Dark gray, aphanitic, aphyric volcanic which sparkles in the sunlight (suggesting microphenocrysts of plagioclase are present)

Coordinates: 120°20'56"W - 39°19'37"N

Township: NE 1/4, sec 24, R14E, T17N, Donner Pass 15' quad, Nevada Co., CA

Locality: Crest of Boreal Ridge, at 7400' elevation, near National Forest boundary line

Age: K/Ar 7.4 ± 0.2 my (Dalrymple, 1964)

Reference: Dalrymple (1964); Chico Sheet, California State Geologic Map (Burnett and Jennings, 1962).

Minerals:

50%	Plagioclase, grdmass, long laths, ≤500 μ in length, twinned, zoned, An62
15%	Augite, grdmass, anh, equant, ~70 μ across, B+, intermediate 2V
10%	Olivine, grdmass, subh, characteristic olivine habit, ll ext, large 2V, clear color
10%	Oxides, grdmass, subh, equant
15%	Glass, grdmass, interstitial, 40-70 μ, purple brown when frozen, and yellow-brown when devitrified to clayey alteration products

Texture: Trachytic texture

Comment: The abundance of glass in this thin section prohibits the characterization of this rock as a tholeiite or an alkaline-olivine basalt. However, the plentitude of plagioclase indicates that it can be called a feldspathic basalt.

C3035

Name: Andesite

Megascopic description: Dark gray, unvesicular volcanic rock containing abundant plagioclase phenocrysts

Coordinates: 122°34'03"W - 38°08'08"N

Township: Unsurveyed township, Petaluma River 7.5' quad, Marin Co., CA

Locality: Small quarry, SE side of Burdell Mtn, ∿400 m W of U.S. 101, near Marin County Airport

Field relations: Sample taken from a quarried block

Age: K/Ar 11.8 ± 0.8 my (Mankinen, 1972)

Reference: Geologic Map of California, Santa Rosa Sheet (Koenig, 1963)

Minerals:

25%	Plagioclase, pheno, anh, irregular in outline, often with rounded corners, individual grains <1 mm, commonly found in glomeroporphyritic aggregates (with pyroxene) up to 4 mm in size
10%	Hypersthene, pheno, euh-subh, 500 μ, B-, occasionally twinned, little or no pleochroism
5%	Augite, pheno, subh-anh, 300 μ, B+, 2V∿50-60
30%	Plagioclase, grdmass, lath like, 50 μ in length
3%	Oxides, grdmass, equant, 20 μ
17%	Glass, interstitial, pale brown in color
10%	Pyroxene, grdmass, 30 μ, occurring in multigranular clumps

Texture: Glomeroporphyritic aggregates and individual phenocyrsts set in a partially devitrified glassy matrix

Comment: This is a typical andesite.

A3037

Name: Feldspathic basalt

Megascopic description: Black, somewhat vesicular, aphanitic volcanic rock with scattered (altered) olivine phenocrysts

Coordinates: 112°19'06"W - 32°51'06"N

Township: N 1/2, sec 1, T7S, R1W, Estrella 15' quad, Maricopa Co., AZ

Locality: Base of low mesa, just N of Freeman Road Exit on I-8

Field relations: Basalt is overlain by andesitic flows

Age: The Geologic Map of Arizona (Wilson et al., 1969) indicates that flow from which this basalt sample was taken has a Quaternary age. The degree of erosion and degree of weathering of the basalt flow suggests an older age. K/Ar dates from other volcanics in the same general area of Arizona (e.g., Eberly and Stanley, 1978) suggest the rock is probably ≤20 my in age.

Minerals:

1%	Olivine, pheno, 700 μ, euh, often completely replaced by alteration
15%	Olivine, grdmass, 100 μ, anh, completely oxidized
20%	Clinopyroxene, grdmass, subh, 100 μ, lt green coloration, 2V∿60
40%	Plagioclase, grdmass, anh, 150 μ, zoned
10%	Alteration, mainly serricitic and calcitic, found throughout thin section, but mostly concentrated in vesicles
2%	Vesicles
10%	Oxides, grdmass, anh, ∿30 μ, opaque

Texture: Ferromagnesium minerals set randomly in a plagioclase matrix. A poikoblastic texture?

Comment: This rock is probably too weathered to be suitable for isotopic analysis.

A3038

Name: Feldspathic basalt

Megascopic description: Med gray, aphanatic basalt. Contains both plagioclase and iddingitized olivine phenocrysts, neither in abundance. Also contains a few pipe vesicles

Coordinates: 111°05'03"W - 33°05'02"N

Township: E boundary, sec 14, T4S, R10E, Florence SE 7.5' quad, Pinal Co., AZ

Locality: E side China Wash, ∼1/4 mi S of gaging station on the Florence Canal

Field relations: Interfingers with Quaternary alluvium

Age: Quaternary according to Geologic Map of Arizona (Wilson _et al_., 1969)

Reference: Geologic Map of Arizona (Wilson _et al_., 1969)

Minerals:

1%	Olivine, pheno, euh-anh, 1 mm, predominately altered to iddingsite, 2V∼80
Tr	Clinopyroxene, pheno, anh, 1 mm, lt brown coloration
3%	Plagioclase, pheno, subh, laths, 2 mm, zoned, twinned, ∼An68
20%	Olivine, grdmass, subh, considerably less susceptible to iddingsite replacement
45%	Plagioclase, grdmass, elongate laths, 150 μ in length, ∼An51
15%	Clinopyroxene, anh, 50 μ, greenish coloration
15%	Oxides, blocky, 30 μ
1%	Glass, interstitial, 20 μ
Tr?	Alkali feldspar, interstitial, 30 μ, v low refractive index
Tr	Apatite, acicular, 50 μ in length

Texture: The consistent orientation of plagioclase laths gives this rock a pilotaxitic texture

Comment: The presence of plagioclase phenocrysts and the trachytic texture in this rock suggest that this rock be called a feldspathic basalt.

A3041

Name: Feldspathic basalt

Megascopic description: Med gray, aphanatic, unvesicular mafic volcanic with partially oxidized olivine phenocrysts

Coordinates: 110°59'24"N - 31°12'53"W

Township: Sec 14, T24S, R13E, Tucson 7.5' quad, Pima Co., AZ

Locality: Quarry, NE side of Sentinel Peak ("A" Mtn), just outside of Tucson city limits, in the Tucson Mts

Age: K/Ar 27.0 ± 1.2 my (Bikerman and Damon, 1966)

Reference: Tolman (1909)

Minerals:

2%	Olivine, pheno, subh, 0.5-1.5 mm, iddingsite rims
40%	Plagioclase, grdmass, laths, 150-600 μ in length, twinned, zoned, ∿ An54
20%	Olivine, grdmass, subh-anh, 100 μ, brownish color from weathering
15%	Clinopyroxene, grdmass, subh-anh, 70 μ, pale green in color
13%	Oxides, grdmass, angular but irregular in shape, ≤100 μ
10%	Glass, grdmass, interstitial blebs, <100 μ in size, dotted brown color, largely devitrified
Tr	Apatite, grdmass, acicular, 100 μ in length

Texture: Plagioclase laths show a preferred direction of orientation throughout the section. However, this preferred orientation is not so well defined to be considered a pilotaxitic texture. The presence of interstitial glass suggests an intersertal texture.

Comment: Bikerman and Damon (1966) has labelled his sample from the same locality a basaltic andesite. This thin section looks a lot more like a basalt than an andesite, although there might be a slightly higher proportion of feldspar here than in many basalts.

A4003

Name: Alkaline olivine basalt

Megascopic description: Med gray, aphanitic, unvesicular basalt. Contains common but relatively small (≤1 mm) olivine phenocrysts, and larger but less common plagioclase and oxide phenocrysts

Coordinates: 109°18'33"W - 31°39'29"N

Township: SW 1/4, sec 29, R30E, T20S, Pedregosa 15' quad, Chochise Co., AZ

Locality: Stream cut cliff, Tex Canyon, San Bernardino volcanic field, SE edge of the Chiricahua Mtns

Field relations: Flow deposited on a fairly modern drainage surface, overlies a young looking conglomerate

Age: Quaternary?

Reference: Cooper (1960)

Minerals:

1%	Plagioclase, pheno, anh, round, 6 mm in length
5%	Olivine, μpheno, subh, 400 μ in size, a few, generally without any trace of oxidation, do not include oxides
20%	Olivine, grdmass, subh, 50-200 μ, some oxidation gives a brownish color to rims, no reaction with other grdmass minerals
20%	Oxides, grdmass, granular, 50 μ
20%	Clinopyroxene, grdmass, anh, ≤100 μ, pale purplish brown coloration
35%	Plagioclase, grdmass, 100 μ lath like crystals and larger anh crystals which appear to poikilitically include other 30 μ grdmass, grains, zoned, twinned, ∿An53
Tr	Glass, interstitial
Tr	Apatite, grdmass, acicular, 30 μ in length
Tr	Oxide, xeno?, equant, subh with rounded corners, encloses a large hypersthene crystal
Tr	Hypersthene xeno?, subh, ∿1 mm long, ⊥ cleavage, low birefrigence, parallel extinction, unpleochroic, inclusion in a large oxide

Texture: Intergranular, relatively fine grained groundmass. Some foliation in the orientation of plagioclase laths, but it is not well pronounced. Some groundmass feldspars poikilitically enclose other crystals.

A4003 (continued)

Comment: Despite the plagioclase phenocryst, this is not a feldspathic basalt. And, although one hypersthene crystal (a xenolith?) was observed, the purplish (titaniferous?) groundmass clinopyroxene suggests that this basalt has alkaline affinities.

A4005

Name: Basanitoid

Megascopic description: Dark gray, aphanatic basalt. Contains microphenocrysts of olivine. Also contains ultramafic nodules and some kaersutite. Slightly vesicular.

Coordinates: 109°18'44"W - 31°26'41"N

Township: NW 1/4, sec 8, T23S, R30E, College Peak, 15' quad, Chochise Co., AZ

Locality: Near flow scarp, ∿1 mi N of Cinder Hill, San Bernardino volcanic field

Field relations: Sample taken from a flow with a sharp, uneroded front and irregular, only partially sediment-covered surface

Age: The fresh morphology of this flow demands a Quaternary, and probably Recent age.

Reference: Cooper (1960)

Minerals:

5%	Olivine, pheno and μpheno, subh, ≤1 mm, 2V≈90°, only occasional oxide inclusions
2%	Clinopyroxene (titanaugite) pheno and μpheno, subh, avg size ∿600 μ, pale purplish brown, slightly pleochroic coloration, B+, 2V∿60, one larger grain shows a Shiller-like texture in its oxide inclusions.
20%	Titaniferous augite, subh-anh, 30-100 μ, pale purplish brown coloration
15%	Olivine, subh, 50-150 μ, v slight oxidation staining
15%	Oxides, both blocky crystals and acicular crystals growing in glassy interstices, ≤50 μ sizes
25%	Plagioclase, elongate laths, ∿100 μ in length, An65
20%	Glass, interstitial, ≤100 μ in diameter, distinctive purple brown coloration
1%	Vesicles, rounded, ∿500 μ

Texture: Intersertal

Comment: The mineralogy of this rock is indistinguishable from other Quaternary basanitoids and alkaline olivine basalts in the Mohave desert, the Potrillo volcanic field, and the Jornada del Muerto volcanic field.

NM4007

Name: Basanitoid

Megascopic description: Med gray, aphanitic, slightly vesicular rock containing abundant olivine microphenocrysts

Coordinates: 108°51'06"W - 31°56'38"N

Township: E 1/2, sec 23, R20W, T27S, Pratt 15' quad, Hidalgo Co., NM

Locality: Small road cut, ~1.6 mi W of Animas on N.M. 9

Field relations: Sample taken from a boulder unearthed by road excavation

Age: Quaternary according to Geologic Map of New Mexico (Dane and Bachman, 1965)

Minerals:

5%	Olivine, pheno, euh-subh, <1 mm - 4 mm, contains small euh oxide inclusions, some embayment
30%	Titanaugite grdmass, subh-anh, 500 μ, purplish slightly pleochroic coloration
35%	Plagioclase, grdmass, long laths, 300 μ in length
10%	Olivine, grdmass, subh-anh, 100 μ, no reaction relations observed
15%	Oxides, grdmass, anh, occasionally skeletal, more commonly blocky and acicular, ~150 μ in size
3%	Vesicles, 100 μ - 3 mm in size, smaller vesicles somewhat angular or irregular in shape, longer vesicles round
3%	Glass, interstitial, ~40 μ sizes, purple-brown color, largely devitrified

Texture: Subophitic texture. Plagioclase laths show a real but rough preferred orientation direction. The groundmass of this rock is quite coarse-grained, and almost entirely crystallized.

Comment: The mineralogy of this rock bespeaks a basanitic or alkaline-olivine basalt.

NM4010

Name: Alkaline-olivine basalt or basanitoid

Megascopic description: Dark gray basalt containing abundant olivine phenocrysts and infrequent plagioclase phenocrysts. Basically unvesicular

Coordinates: 106°46'11"W - 32°01'07"N

Township: SE 1/4, sec 30, T24S, R2E, Afton 15' quad, Doña Ana Co., NM

Locality: N side, semicircular identation in lava cliff adjacent to Rio Grande river alluvial plain, Potrillo volcanic field

Field relations: Flow #2 (Hoffer, 1969) from the Santo Thomas volcano

Age: K/Ar 2.35 ± 0.2 my (Hawley and Kottlowski, 1969; quoted by Hoffer, 1969), 0.116 ± 0.116 my (R.E. Denison, quoted by Renault, 1970)

Reference: Hoffer (1969)

Minerals:

10%	Olivine, pheno, subh, rounded, ∿1 mm, oxide inclusions, minor embayment
2%	Titanaugite, pheno, subh, ∿700 μ, purplish brown, slightly pleochroic color, B+, 2V∿50°
1%	Plagioclase, pheno, subh-anh, ∿1 mm, interiors infrequently contain abundant oxide inclusions
30%	Plagioclase, grdmass, laths, and oddly shaped grains which poikolitially enclose other grdmass minerals, ≤300 μ in length, An73?
10%	Olivine, grdmass, subh, 150 μ, no reaction rims
25%	Titaugite, grdmass, anh, 150 μ, purplish brown color
15%	Oxides, grdmass, subh-anh, equant to acicular, ≤50 μ
5%	Glass, grdmass, interstitial, brown color, largely devitrified
2%	Vesicles, irregular in shape, 300 μ long

Texture: Random orientation of crystals

Comment: The apparently high An content of the plagioclase is unusual. Otherwise this sample could easily be described as a typical alkaline olivine basalt or basanitoid. Renault (1970) gives a chemical analysis on a basalt from the Santo Thomas volcano which supports this conclusion.

NM4015

Name: Basanitoid

Megascopic description: Dark gray, aphanitic, basaltic rock containing abundant olivine phenocrysts. Vesicular with mm sized sized, rounded vesicles and a network of smaller sized, irregular shaped voids

Coordinates: 106°58'12"W - 31°57'30"N

Township: N 1/2, SW 1/4, sec 17, T27S, R1W, Noria 15' quad, Doña Ana Co., NM

Locality: SW portion of Kilbourne Hole, Potrillo volcanic field

Field relations: Basaltic dike exposed in side of Kilbourne Hole maar

Age: K/Ar 0.103 ± 0.084 my (R.E. Denison in Renault, 1970)

Reference: Reeves and De Hon (1965)

Minerals:

10%	Olivine, pheno, subh, rounded corners, 0.5-1.0 mm, euh oxide inclusions, some embayment, 2 ∿90
2%	Titanaugite, pheno, subh, 700 μ, purple-brown slightly pleochroic coloration, B+, 2V∿50
25%	Plagioclase, μpheno and grdmass, laths, 60-300 μ, twinned, An73?
10%	Olivine, grdmass, subh, 150 μ, no reaction observed
20%	Titanaugite, grdmass, subh, 150 μ, purplish brown color
10%	Oxides, some 50 μ granular crystals, but mostly crpto-crystalline dusting in glass
15%	Glass, interstitial blebs, 50 μ in diameter, nearly opaque because of oxide dustings
10%	Vesicles, irregular in shape, ≤200 μ in size, a network of holes intimately involved in the rock's fabric

Texture: Intersertal and almost dikytaxitic

Comment: The titanaugite in this rock indicates its alkaline character. The abundance of mafic phases suggests a basanitic rather than a basaltic composition. The apparently high An content of the plagioclase is a puzzlement.

Additional note: Renault has published a chemical analyses on the basalt from Kilbourne Hole. Leeman (1970) has reported a $^{87}Sr/^{86}Sr$ ratio of 0.7038 for a sample from the Hole.

NM4016

Name: Basanitoid

Megascopic description: A dense, unvesicular, aphanatic, dark gray volcanic rock

Coordinates: 106°55'W - 32°03'N

Township: sec 14 (?), T26S, R1W, Afton 15' quad, Doña Ana Co., NM

Locality: Sample collected a few mi E of the intersection of two roads, one running N-S between Kilbourne Hole and Aden and the second running E-W from Black Mountain and La Mesa, Potrillo volcanic field

Field relations: Morphologically very young. Flow from Aden Crater

Age: Simons and Alexander (1964), quoted by Renault (1970), indicate an age in excess of 11,000 years

Reference: Renault (1970)

Minerals:

10%	Olivine, pheno, euh-subh, 0.5-2.5 mm, 2V 90, contains oxide inclusions
10%	Olivine, grdmass, subh-anh, 100 μ, no obvious reaction relations
30%	Titanaugite grdmass, subh-anh, purplish-brown, slightly pleochroic coloration
15%	Glass, grdmass, interstitial blebs, ≤100 μ in size, brownish color
10%	Oxides, grdmass, 70 μ granules and acicular microlites and dust in glass
25%	Plagioclase, grdmass, elongate laths, 50-500 μ in length, zoned, twinned
1%	Vesicles, irregular shapes, 300 μ lengths

Texture: Intersertal and ophitic textures

Comment: The sample is petrographically similar to the Kilbourne Hole sample (NM4015). Both are unsilicic and alkaline in character. Renault (1970) has published a chemical analysis on an Aden Crater flow.

C4017

Name: Olivine basalt

Megascopic description: Med gray basalt containing a few small (≤1 mm), rounded vesicles, and microphenocrysts of olivine

Coordinates: 117°14'48"W - 33°32'06"N

Township: R4W, T7S, Murrieta 7.5' quad, Riverside, Co., CA

Locality: N tip of Mesa de Burro, ~300 m S of Tenaja Road, 3.3 road miles SW of Murrieta

Field relations: Sample from below the top of the mesa, a sample of the Santa Rosa basalts

Age: K/Ar 8.3 ± 0.5 my (Hawkins, 1970)

Reference: Hawkins (1970), and Santa Ana Sheet, Geologic Map of California (Rodgers, 1966)

Minerals:

2%	Olivine, phenos, euh-subh, ≤1 mm, usually mantled by iddingsite rims
20%	Augite, grdmass, anh, 400 μ, B+, 2V~50, slight purplish brown to pale green coloration, occasionally ophitically intruded by plagioclase
37%	Plagioclase, grdmass, laths, 200-500 μ, An68
12%	Olivine, grdmass, anh, 70 μ, almost all converted to iddingsite
15%	Oxides, grdmass, anh and irregular in shape, 100 μ in size
10%	Glass, grdmass, interstitial, 50 μ, almost completely altered to yellow green, cryptocrystalline hydrous minerals
Tr	Apatite, acicular, 50 μ in length
3%	Hematite, alteration
1%	Vesicles, semi-round, 700 μ

Texture: Intersertal. Some pyroxenes enclose plagioclase laths, giving a local ophitic texture. The groundmass here is coarse grained

Comment: It is not clear whether this rock has tholeiitic or alkaline affinities, although I would guess the latter. Chemical analyses by Hawkins (1970) indicate that both tholeiitic and alkaline rocks are present in the Santa Rosa volcanics.

C4020

Name: Feldspathic basalt

Megascopic description: Med gray, basically unvesicular, volcanic rock. Contains "rusted" olivine phenocrysts and an occasional plagioclase phenocryst

Coordinates: 116°11'56"W - 32°37'29"N

Township: N boundary, sec 7, R8E, T18S, Jacumba 7.5' quad, San Diego, Co., CA

Locality: Summit Jacumba Peak, ∿1 mi NW of Jacumba

Age: K/Ar 18.7 ± 1.3 my (Hawkins, 1970)

Reference: San Diego Sheet, Geologic Map of California (Strand, 1962), and Hawkins (1970)

Minerals:

2%	Olivine, pheno, subh, 0.5-1 mm, most partially altered to iddingsite, or occasionally to serpentinitic material, euh, oxide inclusions
1%	Augite, pheno, subh-anh, 400 μ, clear off-white color, B+, 2V∿60
5%	Olivine, grdmass, anh, 100 μ, no obvious reaction with grdmass
25%	Clinopyroxene, grdmass, anh, 100 μ, clear to slightly brownish color
45%	Plagioclase, grdmass, euh laths and anh equant grains, with wavy extinction, ∿100 μ sizes, ∿An55
1%	Apatite, grdmass, acicular, ≤150 μ in length
2%	Vesicles, irregular in shape but not really interstitial, 100-200 μ
1%	Calcite, found in some vesicles, not present throughout thin section

Texture: Locally pilotaxitic, but more often mafic phases appear set in an unoriented granular feldspar matrix

Comment: Hawkins (1970) has called a sample from the same locality as this one an alkalic basaltic andesite based on a chemical analysis. Although this report has reserved the name "basaltic andesite" for volcanics with quartz and/or wormy plagioclase xenocrysts, C4020 is certainly more felsic than most basalts. Consequently, the feldspathic basalt label has been applied.

C4022

Name: Alkaline olivine basalt

Megascopic description: Dark gray, aphanitic rock. Generally dense but contains a few eliptical vesicles and more common crack vesicles. Phenocrysts of olivine

Coordinates: 116°19'23"W - 34°41'24"N

Township: NW 1/4, sec 23, T7N, R6E, Lavic 15' quad, San Bernardino Co., CA

Locality: Basalt flow front adjacent to NE portion of Lavic Lake

Field relation: This basalt from Pisgah crater overlies sediments of the pluvial Lavic Lake, morphologically a young flow

Age: Recent

Reference: Dibblee (1966)

Minerals:

5%	Olivine, phenocrysts, euh-anh, 0.3-1.5 mm, 2V∼80, contains minute oxide inclusions
30%	Plagioclase, μpheno and grdmass, elongate laths ≤800 μ in length and more equant crystals ≤400 μ in size, An45
15%	Olivine, grdmass, anh, ≤200 μ, no reaction rims
25%	Titanaugite, grdmass, anh-subh, blocky, 100 μ, purple brown color
15%	Oxides, grdmass, blocky and acicular, 40 μ
4%	Glass, grdmass, interstitial, partially devitrified
6%	Vesicles, irregular in shape, ∼1 mm in size, often in trains

Texture: The ground mass is ophitic to subophitic. Plagioclase laths show a rough but clear preferred orientation

Comment: This rock has the distinctive characteristics of an alkaline-olivine basalt or basanitoid

Additional note: Peterman et al. (1970) has published several ^{87}Sr/^{86}Sr measurements on Pisgah Crater basalts. These range from 0.7037 to 0.7043 in value. Both Smith and Carmichael (1969) and Wise (1969) have published chemical analyses on basalts from the Pisgah Crater field.

C4025

Name: Alkaline olivine basalt or basanitoid

Megascopic description: Dark gray volcanic rock. Contains olivine phenocrysts and an occasional large, elongate phenocryst of pyroxene. Vesicles are present but not especially abundant

Coordinates: 115°43'22"W - 35°17'15"N

Township: NW 1/4, sec 20, T14N, R12E, Mescal Range 15' quad, San Bernardion Co., CA

Locality: 100 m E of Black Tank, in the vicinity of the Halloran Summit Cinder Mine

Field relations: From a squeeze up near the edge of a morphologically recent flow

Age: Holocene

Reference: Kingman Sheet, Geologic Map of California (Jennings, 1961)

Minerals:

2%	Titanaugite, pheno, anh-subh, 6 mm, and ≤1 mm, slightly pleochroic purplish brown, B+, intermediate 2V, cores commonly display a sieve like texture, larger grains have serrated edges
10%	Olivine, µpheno, subh-anh, 0.8-0.3 mm, minute oxide inclusions, some large grains have a skeletal appearance, embayment
30%	Plagioclase, µpheno, laths, 150-700 µ in length, a few large, equant crystals have wormy interiors, zoned, twinned, An55
Tr	Quartz, xenocryst?, rounded, 500 µ, surrounded by a perpendicular pyroxene corona
20%	Titanaugite, grdmass, anh, ≤300 µ, purple-brown color
10%	Olivine, grdmass, subh, 100 µ
15%	Oxides, grdmass, subh, granular to blocky to acicular in shape, 150 µ
10%	Glass, grdmass, interstitial, 150 µ in size, deep purple brown color, often embedded by oxide crystals, or dusted by opaque powder
3%	Vesicles, larger (>1 mm sized) vesicles have rounded outlines, smaller (∿0.5 mm sized) vesicles are much more irregular in shape

Texture: Intersertal

C4025 (continued)

Comment: The mineralogy of this rock is typical of Quaternary basanitoids and alkali-olivine basalts from the southwestern United States. The presence of two quartz xenocrysts and several wormy feldspar megacrysts is remarkable. Their interpretation is, however, unclear. Certainly the lead isotopic composition of this rock shows little record of crustal contaminants.

Additional note: Leeman (1970) found the $^{87}Sr/^{86}Sr$ isotopic ratios of two basalts from the Halloran Summit-Cima Dome area to be .7034 and .7033. Peterman et al. (1970) have reported a value of .7029. Smith and Carmichael (1969) have published a chemical analysis on a basalt from the same field.

A4027

Name: Olivine-augite basalt

Megascopic description: Med gray basalt with iddingsite (olivine) phenocrysts and dark green pyroxene phenocrysts

Coordinates: 112°28'17"W - 34°52'09" N

Township: SW 1/4, sec 9, T17N, R2W, Pauldin 15' quad, Yavapai Co., AZ

Locality: W of Sullivan Lake, ∿1 mi S of Pauldin, close to U.S. 89

Field relations: Sample from boulder unearthed during dirt road excavation, from the Perkinsville formation

Age: K/Ar 4.5 ± 0.2 my (McKee and Anderson, 1971)

References: McKee and Anderson (1971), Krieger (1965)

Minerals:

7%	Olivine, pheno, subh, 0.5-1.5 mm, contain minute oxide inclusions, in large part converted to iddingsite
3%	Augite, pheno, anh, 0.5 mm crystal, ≤2 mm grains, pale brown-green color, B+, 2V∿60
10%	Olivine, grdmass, anh-subh, 70 μ, usually reddish-brown from oxidation, no reaction
30%	Augite, grdmass, anh, granular, 50 μ, pale green color
10%	Oxides, grdmass, subh, blocky, subh-anh
35%	Plagioclase, grdmass, laths, ≤400 μ in length, zoned, twinned, An53, largest (600 μ) crystals occur in glomeroporphyritic aggregates
2%	Glass, interstitial, 30 μ, deep brown color
1%	Apatatite, acicular, 40 μ in length
2%	Vesicles, 30 μ - 1 mm
Tr	Calcite, coating borders of some vesicles

Texture: Plagioclase laths are locally subparallel, being separated from one another by pyroxene crystals. However, augite crystals never really enclose feldspar laths so the texture is not ophitic

Comment: The abundance of olivine and augite in this rock relative to plagioclase indicates that this is an olivine-augite basalt in the classification scheme of Chapter 5. A chemical analysis on a nearby sample (PA3 of McKee and Anderson) showed that sample to be an alkaline-olivine basalt. Classification of A4027 as an alkaline-olivine basalt is compatible with its petrographic characteristics. However, it might be noted that A4027 lacks the distinctive alkaline characteristics (e.g., titanaugite) displayed by alkaline-olivine basalts and basanitoids of the Basin and Range province.

A4028

Name: Feldspathic tholeiite

Megascopic description: Med gray, aphanitic, essentially unvesicular volcanic rock. Contains a few megascopic black pyroxene (?) crystals, which occur in clots. Rock sparkles in the sunlight, suggesting abundant microphenocrysts of feldspar

Coordinates: 112°08'30"W - 34°42'15"N

Township: N central portion T15N, R2E, Mingus Mtn 15' quad, Yavapai Co., AZ

Locality: Road cut, ∿3/4 mi from U.S. 89A along dirt road to Mingus Mtn campground, in Haywood Canyon

Field relations: Hickey Formation

Age: K/Ar 12 ± 1 my (McKee and Anderson, 1971; samples MM1 and MM2)

Reference: McKee and Anderson (1971), Anderson and Creasey (1971)

Minerals:

3%	Olivine, pheno, subh-anh, 0.3-1.0 mm, several optically continuous grains are topologically distinct, extensive embayment in several of the larger crystals, rimmed by opaque oxides, not iddingsite?
5%	Hypersthene pheno, rounded, anh-subh, 600 μ, slight pink green pleochroism, B-, 2V∿60
15%	Hypersthene grdmass, subh-anh, 100 μ, slight pleochroism
50%	Plagioclase, grdmass, 200 μ subh laths, and 50 μ grains of irregular shape, zoned, twinned, An56
20%	Oxides, grdmass, granular, equant, 20 μ
2%	Glass, small undevitrified remnants of a glassy matrix
1%	Apatite, acicular, 50 μ in length
2%	Vesicles, rounded, 200 μ

Texture: Randomly oriented feldspar laths set in a granular oxide-plagioclase matrix. Texture has an hyalophitic appearance, even though the glass matrix is essentially all crystallized.

Comment: Several characteristics of this thin section are noteworthy. 1) This is one of the very few samples of this study found to contain hyperstene phenocrysts. 2) Like several other tholeiite samples, this rock contains an abundance of opaque oxides. 3) Opaque oxides, not iddingsite rim the olivine phenocrysts. 4) The hyalophitic texture observed in this rock is almost always observed in volcanics more silicic than basalt. This and the abundance of plagioclase suggests A4028 has andesitic affinities. Two chemical analyses on nearby rocks (McKee and Anderson, 1971) support the conclusion that A4028 has the chemistry of a basaltic andesite.

A4029

Name: Olivine tholeiite

Megascopic description: A med gray basalt. Contains partially oxidized olivine phenocrysts and "lacy" network of small vesicles

Coordinates: 111°38'06"W - 35°12'13"N

Township: E central sec 15, T21N, R7E, Flagstaff West 7.5' quad, Coconino Co., AZ

Locality: Blasted road cut near Pinecliff Apartments on Pinecliff Road, on W side of Switzer Mesa, Flagstaff, San Francisco volcanic field

Field relations: Approximately correlative to the basalt of Cedar Mesa

Age: K/Ar 5.8 ± 0.34 my (Daman *et al*., 1974)

Reference: Moore *et al*. (1974)

Minerals:

5%	Olivine, pheno, subh-anh, rounded, 600 μ, rimmed by iddingsite, minute oxide inclusions
5%	Olivine, grdmass, subh-anh, no reaction rims observed
25%	Augite, grdmass, anh, almost skeletal because of inclusions of plagioclase laths, 500 μ, B+, 2V∿60, pale brown-green color, slightly pleochroic?
30%	Plagioclase, laths, 600 μ
15%	Oxides, 5 μ granular dusting and anh, elongate grains up to 300 μ long
5%	Glass, interstitial areas up to 300 μ in size, brown color, often containing opaque microlites
15%	Vesicles, irregular in shape, 100-500 μ in size

Texture: Ophitic and subophitic to intersertal textures. Despite the abundance of small vesicles, the texture is not quite dikytaxitic

Comment: This is an olivine augite basalt, according to the classification scheme of Chapter 5. A chemical analysis of a Switzer Mesa flow sample (E. Wolfe and R. Moore, written communication) has the chemical composition of an olivine tholeiite. It is also interesting to note the abundance of oxides in this tholeiitic rock, a characteristic that has been observed in other tholeiites too.

Additional note: Brookins and Moore (1975) have reported a ^{87}Sr/^{86}Sr ratio of .7030 on the basalt of Switzer Mesa.

A4030

Name: Basaltic andesite

Megascopic description: Dark gray, aphanitic volcanic rock. Contains abundant but rather small (<1 mm), pale green (pyroxene) phenocrysts. Moderately vesicular with persistent, irregularly shaped, generally small (≤2 mm) voids

Coordinates: 111°36'30"W - 35°36'36"N

Township: NE 1/4, sec 26, R7E, T26N, SP Mtn 15' quad, Coconino Co., AZ

Locality: E side of SP basalt flow, N of crater V168 and W of crater V225, San Francisco volcanic field

Field relations: Sample from a small squeeze up; a morphologically very young, blocky lava flow (Merriam)

Age: K/Ar 0.071 ± 0.004 my (Baksi, unpublished data, reported in Damon et al., 1974)

Reference: Ulrich and Bailey (1974), Moore et al. (1974)

Minerals:

2%	Augite, pheno, 600 μ anh grains in aggregates up to several mm in size, very pale coloration, B+, 2V∿50
5%	Olivine, μpheno-grdmass, euh, 50-300 μ in size, clear, 2V∿80, no obvious reaction
20%	Augite, grdmass, 50 μ, subh, B+, 2V∿55
Tr	Plagioclase, pheno, wormy texture
35%	Plagioclase, grdmass, elongate laths, typically 100 μ in length, and 10 μ across, ∿An42
20%	Glass, interstitial between feldspar laths, spotty brown color
5%	Oxides, equant, euh, 20 μ size (a larger percentage as dusting in glass)
15%	Vesicles, 50 μ - 3 mm, irregular but generally rounded shapes

Texture: Intersertal to hyalophitic, and quite vesicular (although vesicles are too large to give a dikytaxitic texture)

Comment: According to Moore et al. (1976), two pyroxenes are commonly found in the basaltic andesites of the San Francisco volcanic field. Only augite was observed in the A4030 sample. This thin section also lacks quartz xenocrysts and contains only a single wormy plagioclase grain. Both phases are common in most other basaltic andesite samples from the Colorado Plateau. However, a number of chemical analyses on the SP flow (Wolfe and Moore, written communication) indicate that it is chemically similar to the other basaltic andesite of the San Francisco volcanic field.

A4031

Name: Feldspathic basalt

Megascopic description: Med gray, aphanitic, unvesicular volcanic with large (up to 1 cm sized) plagioclase phenocrysts and small, euhedral olivine phenocrysts

Coordinates: 111°30'56"W - 35°37'09"N

Township: E central sec 23, R8E, T26N, SP Mtn 15' quad, Coconino Co., AZ

Locality: Just E of U.S. 89, 2 mi N of Hank's Trading Post, San Francisco volcanic field

Field relations: Black Point flow of Woodhouse age

Age: K/Ar 2.39 ± 0.32 my (Damon _et_ _al_., 1974)

Reference: Ulrich and Bailey (1974), Moore _et_ _al_. (1974)

Minerals:

5%	Plagioclase, pheno, 0.5-4 mm, subh-anh, smaller crystals are lath like, larger crystals rounded, twinned and zoned, ≥An54
1%	Olivine, pheno, 700 μ, subh, contains minute oxide inclusions, 2V∿90, v. slight iddingsite on rims
20%	Olivine, grdmass, ≤200 μ, smaller grains often a rust color
15%	Clinopyroxene, grdmass, 80 μ
20%	Oxides, grdmass, 40 μ, subh, block
40%	Plagioclase, grdmass, laths, ≤400 μ in length
Tr	Apatite
Tr	Glass

Texture: Intergranular texture with feldspar laths aligned subparallel to their neighbors. Ferromagnesium and oxide phases appear set in feldspar matrix

Comment: The plagioclase phenocrysts and the abundance of plagioclase indicate that this rock be labelled a feldspathic basalt.

A4033

Name: Basaltic andesite

Megascopic description: Lt gray, aphanitic, unvesicular. Contains an occasional large (1-3 mm) translucent quartz and/or feldspar megacryst and more commonly, smaller (<1 mm), elongate, blackish colored olivine and/or pyroxene phenocrysts

Coordinates: 109°34'42" W - 34°15'59"N

Township: Center, sec 15, R26E, T10N, Cerro Hueco 7.5' quad, Apache Co., AZ

Locality: 40 m W state highway facility, N of U.S. 60, across from Cerro Montoso, White Mountains volcanic field

Age: Quaternary

Reference: Ackers (1964)

Minerals:

2%	Augite, pheno, subh-an , 0.6-3 mm, pale green-brown color, B+, $2V\sim50$, sometimes associated with olivine phenocrysts, some crystals have concentrations of oxide inclusions along their rims
5%	Olivine, pheno, rounded euh-subh, 0.4-2 mm, small oxide inclusions, thin iddingsite rim ubiquitous, $2V\sim80$
Tr	Quartz, xenocryst?, rounded, 1 mm, surrounded by a corona of clinopyroxene and glass, U+
1%	Plagioclase, pheno, subh, equant laths, 0.5-1.5 mm, wormy (sieve textured) cores or rings, zoned, some twinning
Tr	Sodic Augite?, 1mm, anh crystals in a pyroxene-feldspar (gabbroic) xenolith, striking green color, B+, $2V\sim60$, unpleochroic
Tr	Plagioclase, 1 mm, anh, crystals in a pyroxene-feldspar xenolith, some twinning
50%	Plagioclase, grdmass, subh laths, 100-300 μ, An63, zoned, twinned
20%	Olivine, grdmass, subh-anh, iddingsite alteration nearly ubiquitous
5%	Augite, grdmass, subh-anh, 100 μ, light green color, B+
15%	Oxides, grdmass, anh, blocky, 50 μ
Tr	Apatite, grdmass, acicular, 150 μ in length
Tr	Calcite, alteration
Tr	Vesicles, 0.5 mm in size, irregular in shape
Tr	Glass, interstitial, 30 μ

A4033 (continued)

Texture: Intergranular with a fairly coarse grained groundmass. Plagioclase laths are somewhat subparallel to one another, but this is hardly a trachytic texture

Comment: An interesting rock. Obviously a basaltic andesite.

NM4035

Name: Tholeiite

Megascopic description: Med gray, vesicular baslat containing microphenocrysts of olivine

Coordinates: 107°47'17"W - 35°04'40"N

Township: SE 1/4, sec 21, T10N, R9W, Grants SE 7.5' quad, Valencia Co., NM

Locality: Near powerline perpendicular to La Ventana Road, NE side of flow

Field relations: McCartys basalt, morphologically a very fresh flow

Age: Holocene

Reference: Nichols (1946), Thaden et al. (1967), Lipman and Moench (1972), Carden and Laughlin (1974)

Minerals:

1%	Olivine, pheno, 0.5-1 mm, subh-anh, minute oxide inclusions
35%	Plagioclase, pheno-grdmass, 1.5 mm - 100 μ, long laths, twinned, An56
15%	Clinopyroxene, grdmass, 100 μ, anh, slight brownish coloration
10%	Olivine, grdmass, anh, 100 μ, no obvious reaction rims
25%	Oxide and glass, interstitial brown to black areas, 100 μ in size
15%	Vesicles, rounded voids up to 4 mm across, and 400 μ, irregularly shaped holes, which are not really interstitial in this rock

Texture: Intersertal, vesicular, and dikytaxitic. Relatively coarse grained

Comment: The petrographic properties tabulated above do not uniquely specify this sample to be tholeiitic. However, these properties (especially coarse grain sizes, porous nature, dikytaxitic texture, and the abundance of oxide charge glass) are distinctive characteristics of the Late stage, tholeiitic basalts of the Mt. Taylor volcanic field. In addition, chemical analyses on the McCartys basalt (e.g., Carden and Laughlin, 1974) show it to be hypersthene normative.

NM4036

Name: Tholeiite

Megascopic description: Med gray, aphanitic, basalt containing abundant, small olivine phenocrysts

Coordinates: 107°47'20"W - 35°04'40"N

Township: SE 1/4, sec 21, T10N, R9W, Grants SE 7.5' quad, Valencia Co., NM

Locality: ∿30 m SW of NM4035 locality

Field relations: Flow morphology not quite as fresh as that of the McCartys basalt. Qbza on the Thaden *et al.* (1967) map

Age: Quaternary

Reference: Thaden *et al.* (1967), Lipman and Moench (1972)

Minerals:

2%	Olivine, pheno, subh-anh, ≤3 mm in size, embayed often to the point of disaggregation
15%	Olivine, grdmass, subh-anh, 100 μ in size, no obvious reaction
20%	Clinopyroxene, grdmass, anh, 100-200 μ, light brown color
25%	Plagioclase, grdmass, elongate laths, ≤1 mm in length, twinned
15%	Oxide-glass, interstitial, ≤400 μ in size, glass heavily dusted with oxides so as to be opaque, as oxide grains
20%	Vesicles, some large, mm sized rounded vesicles but predominantly small (300 μ) sized irregularly shaped voids, small holes commonly have plagioclase laths growing in them.

Texture: Intersertal and dikytaxitic

Comment: This rock, like NM4035, has texture reported to be characteristic of the late stage, Quaternary tholeiites of the Mt. Taylor volcanic field.

NM4038

Name: Alkaline-olivine feldspathic basalt

Megascopic description: Med gray, essentially unvesicular. Clean surfaces shine in the sunlight, suggesting the presence of abundant plagioclase microphenocrysts. Contains an occasional large (2 mm) phenocryst of olivine

Coordinates: 107°25'31"W - 35°07'06"N

Township: S boundary sec 1, R6W, T10N, Laguna 7.5' quad, Valencia Co., NM

Locality: E of Encimal, on W flank of Wheat Mtn, Mt. Taylor volcanic field

Field relations: A basalt of the high mesas, flow QTB6 of Moench (1963)

Age: ∼Pleistocene

Reference: Moench (1963), Lipman and Moench (1972)

Minerals:

Tr	Olivine, pheno, 2 mm, euh, v slight iddingsite alteration
15%	Olivine, μpheno-grdmass, subh, 300-30 μ, no reaction rim observed
20%	Clinopyroxene, grdmass, anh, ≤400 μ, a brown color somewhat reminiscent of titanaugite but less intense in its purplish tint than basanitic titanaugite, crystals occur in clots and partially enclose feldspar laths
45%	Plagioclase, grdmass, anh-subh, laths, An50?
15%	Oxides, grdmass, anh, blocky, 50 μ
1%	Vesicles, 200-600 μ in size
Tr	Apatite, grdmass,acicular
Tr	Glass, grdmass, interstitial, 20 μ

Texture: Intergranular, pilotaxitic, and locally subophitic

Comment: Chemical analysis of this flow indicates that it is a silicic alkali olivine basalt (Lipman and Moench, 1972). This conclusion is consistent with the occurrence of purplish titanaugite in thin section. However, the abundance of plagioclase in this rock suggests it be labelled a feldspathic basalt or a hawaiite.

NM4039

Name: Tholeiite

Megascopic description: Med gray volcanic rock lacking large vesicles and containing olivine phenocrysts with reddish rims

Coordinates: 106°14'38"W - 35°46'31"N

Township: R7E, T18N, White Rock 7.5' quad, Los Alamos Co., NM

Locality: ∿1/4 mi down canyon of N.M. 4, in Ancho Canyon, E side of Jemez Mtns bordering the Rio Grande rift

Field relations: Lies beneath the Bandilier tuff

Age: Late Pliocene (?)

References: Griggs (1964)

Minerals:

2%	Olivine, pheno, ≤2.5 mm, subh, contains minute oxide inclusions, thin reddish oxidation rims
Tr	Plagioclase, pheno, ≤1.5 mm, zoned, twinned
25%	Plagioclase, grdmass, elongate laths, typically 300 μ in length, ∿An54
30%	Augite, grdmass, ahn, 50-700 μ, often ophitically include plagioclase laths, tan color
20%	Oxides, grdmass, anh, granular and acicular, 1 μ-200 μ in size
20%	Vesicles, irregularly shaped, typically with dimensions around 300 μ
2%	Glass, interstitial, 300 μ blebs
1%	Olivine, grdmass, anh, 50-100 μ, no observable reaction

Texture: Ophitic, dikytaxitic, relatively coarse grained

Comment: A chemical analysis has indicated that this rock is a tholeiite (W.S. Baldridge, personal communication). This categorization appears compatible with the petrographic observations above. First, like other tholeiites observed in this study (e.g., NM4036, NM4035, A4029, A4028), this rock contains a notable abundance of oxides. In addition, a dikytaxitic texture has yet to be observed in an alkaline basalt, while it commonly occurs in tholeiitic ones. There is practically no groundmass olivine in this rock, and the total amount of olivine is quite small - these two observations also suggest a tholeiit affinity. It is interesting, however, that the groundmass olivine that does occur does not appear to possess reaction rims.

NM4040

Name: Basaltic andesite

Megascopic description: A lt gray, unvesicular volcanic rock with a relatively coarse grained groundmass. Contains few observable phenocrysts

Coordinates: 105°42'32"W - 36°32'06"N

Township: NW 1/4 sec, 31, T27N, R12E, Arroyo Hondo 7.5' quad, Taos Co., AZ

Locality: Rio Grande Gorge on the W side of Dunn Bridge

Field relation: Bottom flow in the exposed sequence

Age: The data of Ozima et al. (1967) suggest an age of approximately 4.0±0.3 my.

Reference: Aoki (1967)

Minerals:

20%	Olivine, μpheno-grdmass, subh, 500-30 μ, larger grains embayed, partial alteration to iddingsite common, no obvious reaction of grdmass grains
45%	Plagioclase, pheno-grdmass, laths to anh, 0.1-1 mm, a few larger grains have sieve-textured interiors
20%	Augite, grdmass, anh, 100 μ, grayish-green coloration, granular habit, minute oxide inclusions common, occasionally found in clumps 1 mm in size
15%	Oxides, grdmass, anh, ≤100 μ, acicular - blocky,
Tr	Biotite, alteration in pyroxene aggregate
Tr	Calcite, alteration in pyroxene aggregates
Tr	Apatite, grdmass, acicular, ≤100 μ long

Texture: Intergranular, perhaps a bit more coarse grained than is typical, an asterix-like arrangement of plagioclase laths occurs rarely

Comment: The wormy plagioclase and the higher than normal percentage of plagioclase suggest that this rock be called a basaltic andesite.

NM4044

Name: Alkaline olivine basalt

Megascopic description: A dark gray, flinty, aphanitic volcanic rock containing large but infrequently occurring pipe vesicles. Also contains a few olivine phenocrysts, and at least three different types of ultramafic inclusions

Coordinates: 107°08'51"W - 33°08'21"N

Township: SE portion of Elephant Butte 7.5' quad, Sierra Co., NM

Locality: Mesa N of Jose Cyn and E of Elephant Butte Res., approximately 3/4 mi N of N.M. 52

Field relations: Mesa capping flow

Age: Quaternary according to the Geologic Map of New Mexico (Dane and Bachman, 1965) but could easily be Pliocene in age

Reference: Dane and Bachman (1965)

Minerals:

1%	Olivine, pheno, subh-anh, ≤1 mm, often with an iddingsite rim, varying degrees of embayment
15%	Olivine, grdmass, euh-anh, 100 μ, reddish color because of oxidation
15%	Oxides, grdmass, blocky, equant, 30 μ
20%	Clinopyroxene, grdmass, anh, 50 μ, brown coloration
25%	Glass, brown color
20%	Plagioclase, laths, 200 μ in length, An55
5%	Vesicles, 400 μ in size, generally rounded

Texture: Fine grained groundmass. Hyalophitic, but there is really too much glass for the glass to be called interstitial. Plagioclase laths are oriented subparallel to one another.

Inclusions: This rock has three types of mafic and ultramafic inclusions. The first is peridotitic The second is gabroic, consisting of anhedral grains of orthopyroxene, clinopyroxene, and plagioclase (≥An45). The third is made up of centimeter sized, amphibole crystals, in which subhedral, millimeter sized oxide grains are embedded.

Comment: The fined grained and glassy nature of this rock prohibits an unambiguous conclusion on whether it is alkaline or tholeiite in nature. However, the occurrence of ultramafic and mafic inclusions indirectly suggests an alkaline affinity.

A4046

Name: Mafic andesite

Megascopic description: A med gray, aphanitic, aphyric volcanic rock possessing only an occasional small vesicle

Coordinates: 109°11'41"W - 32°40'54"W

Township: Center, sec 5, R31E, T9S, Duncan 15' quad, Greenlee Co., AZ

Locality: E side of Flattop, on slope into Woods Canyon, Peloncillo Mountains

Field relations: Tay (younger basaltic andesite) of Morrison (1965)

Age: K/Ar 27.5 ± 0.8 my (Elston *et al.*, 1973)

Reference: Morrison (1965), Elston *et al.* (1973)

Minerals:

55%	Plagioclase, grdmass, subh-anh, equant to lath-like, 300 μ, zoned, twinned, An46
10%	Olivine, grdmass, anh, 150 μ, only slightly oxidized
10%	Augite, grdmass, anh, 400 μ, pale gree-brown color, B+, $2V \sim 60$
10%	Oxides, grdmass, anh-subh, 20-200 μ, dust in interstitial glass
15%	Glass, interstitial, brownish color, spotted appearance
1%	Vesicles, 700 μ, rounded

Texture: Intersertal. Plagioclase laths are oriented in a random fashion.

Comment: The abundance of plagioclase in this rock testifies to its andesitic character. The additional presence of olivine would suggest that the rock be labelled a basaltic andesite. However, this rock lacks the wormy plagioclase and quartz xenoliths used to define basaltic andesites of the Colorado Plateau. Consequently, I have used the name "mafic andesite."

C5001

Name: Alkalii(?)-olivine basalt

Megascopic description: A nonvesicular, med gray basalt with plagioclase and altered (iddingsite) olivine phenocrysts

Coordinates: 117°08'22"W - 35°06'28"N

Township: N 1/4, sec 34, R45E, T32S, Opal Mountain 15' quad, San Bernardino Co., CA

Locality: Tip of a hilly prong extending into the alluvium from Black Mountain

Field relations: Black Mountain basalt of Dibblee (1968)

Age: Pleistocene

Reference: Dibblee (1968)

Minerals:

7%	Olivine, pheno, subh, 700 μ, rounded to embayed, 10-100% converted to iddingsite, 2 ~90, some olivine-feldspar glomeroporphyritic aggregrates
5%	Plagioclase, pheno, subh laths, 1.5 mm in length, An73
1%	Augite, μpheno, anh, pale brown-green color, B+, 2V~50
7%	Olivine, grdmass, anh, 50-150 μ, partially altered to iddingsite, no noticeable reaction rims
20%	Augite, grdmass, anh, 100 μ, pale color
10%	Oxides, grdmass, ≤100 μ, needles to blocky, anh grains
32%	Plagioclase, grdmass, laths, 200 μ, twinned, An51
15%	Glass, grdmass, brown interstitial blebs
Tr	Apatite, grdmass, acicular, 70 μ long
1%	Vesicles, rounded 300 μ in size

Texture: Intersertal, coarse grained

Comment: This rock lacks the titanaugite common in Quarternary alkaline volcanics of the Mohave desert. Nonetheless, it is probably alkaline in character. In addition, this sample is somewhat more feldspar rich than most the nearby basanitoids; that is, it is more basaltic than basanitic

Additional notes: Leeman (1970) analyzed a sample of the Black Mountain basalt for its strontium isotopic composition; he found his rock to have ^{87}Sr/^{86}Sr ratio of .7035.

C5003

Name: Feldspathic basalt

Megascopic description: A chocolate gray basalt, containing a network of small (usually ≤1 mm) sized vesicles, and plagioclase phenocrysts

Coordinates: 116°05'38"W - 34°50'56"N

Township: N central sec 25, T9N, R8E, Broadwell Lake 15' quad, San Bernardino Co., CA

Locality: Entrance to an unnamed canyon in the Bristol Mountains, ∿1/2 mi S of a ruined cabin

Field relations: Mapped as Tb by Dibblee (1967), one of the oldest Tertiary volcanics in the Mohave desert

Age: K/Ar 22.2 ± 1.1 my (Armstrong and Higgins, 1973)

Reference: Dibblee (1967)

Minerals:

15%	Plagioclase, pheno, equant to lath-like, ≤2 mm in length twinned, zoned, An58
1%	Olivine, pheno, subh, 700 μ, minute oxide inclusions, 2V∿70, B-
1%	Oxides, μpheno, equant, subh, 200-800 μ
10%	Oxides, grdmass, subh, 20-100 μ in size
30%	Plagioclase, grdmass, elongate laths, ≥20 μ in length, ∿An50, zoned, twinned
15%	Olivine, grdmass, anh-euh, 100 μ
3%	Clinopyroxene, anh, 30 μ
20%	Glass, interstitial, light brown color, bubbly
Tr	Apatite, grdmass, acicular, 50 μ in length
7%	Vesicles, irregular shaped pipes, up to 3 or 4 mm but usually around 0.5 mm in length

Texture: Intersertal, almost hyalophitic texture. Vesicular. Plagioclase phenocrysts show a preferred orientation throughout the thin section

Comment: The abundance of plagioclase and almost hyalophitic texture of this rock suggests that it be labelled a basaltic andesite. However, to avoid confusion with the xenolith bearing basaltic andesites of the Colorado Plateau, it has been called a feldspathic basalt.

A5006

Name: Feldspathic basalt

Megascopic description: Very dark gray, aphanitic, unvesicular. Essentially aphyric

Coordinates: 114°38'44"W - 35°57'00"N

Township: Sec 33 (unsurveyed), R22W, T30N, Black Canyon 15' quad, Mohave Co., AZ

Locality: Road cut for an unpaved road running parallel to U.S. 93 from a roadside rest just below BM2257 on topographic map and approximately N of U.S. 93 from a roadside rest area. Rock belongs to the Fortification Basalt member of the Muddy Creek Formation

Field relations: Basalt caps a surface which slopes down toward the Colorado River.

Age: K/Ar 4.9 ± 0.04 my (Anderson *et al.*, 1972), 4.7 ± 0.3 my (Scott *et al.*, 1969)

Reference: Longwell (1963), Anderson *et al.* (1972)

Minerals:

2%	Olivine, pheno, ahn-subh, 700 μ, intensively corroded and embayed, a small to large degree of alteration to serpentinite
1%	Augite, μpheno, subh-anh, pale brown color
5%	Olivine, grdmass, euh-subh, 200 μ, often partially altered to serpentinite
20%	Augite, grdmass, subh-anh, ≤100 μ, slight brownish tint, smaller grains nearly colorless and often euh
1%	Apatite, grdmass, euh, acicular to elongate, ≤50 μ in length
20%	Oxides, grdmass, anh, blocky, 20 μ in size
5%	Chorite (?), grdmass, interstitial, ≤150 μ in size; often found associated with olivine grains; unpleochroic blue-green color; birefringence low,anomalously blue, fan-like extinction, moderate relief; sometimes contains microlites, suggesting that this phase has replaced glass
45%	Plagioclase, grdmass, stubby laths, 300 μ in size, and irregularly shaped but more equant crystals which poikiliticallyenclose other groundmass minerals

Texture: Essentially intergranular. Iron and magnesium bearing groundmass grains are found interstitial to plagioclase laths, or as inclusions in regularly shaped plagioclase grains

A5006 (continued)

Comment: This is the only rock examined in this study which contains chlorite. This chorite does not seem to be a weathering product but rather associated with deuteric alteration of originally glass material. It is also somewhat unusual for olivine to alter to serpentinite rather than iddingsite. The abundance of plagioclase noted above suggests that the term feldspathic basalt be applied to this rock.

C5009

Name: Feldspathic basalt

Megascopic description: A very dark gray, unvesicular volcanic rock. Contains microphenocrysts of oxidized (reddish) olivine and plagioclase

Coordinates: 116°35'51"W - 36°20'06"N

Township: R3E, T25N, Ryan 15' quad, Inyo Co., CA

Locality: From a northward-trending promontory which sticks out toward Calif. 90 from the Greenwater Range, about 12 mi W of Death Valley Junction, near BM3040 on the topographic map

Field relations: Interfingers with the Funeral Fanglomerate

Age: Pliocene or Pleistocene

Reference: Geologic Map of California, Death Valley Sheet (Drewes, 1963) and Fleck (1970)

Minerals:

5%	Olivine, μpheno., euh-subh, several crystals are being replaced by opaques
20%	Oxides, grdmass, blocky, usually 30 μ but occasionally up to 200 μ in size
15%	Olivine, grdmass, anh, 20-100 μ, iddingsite alteration
15%	Clinopyroxene, euh-anh, 30 μ, clear with pale green tint
45%	Plagioclase, anh, 50-200 μ in size, zoned, little twinning
Tr	Clinopyroxene (?) xenolith, anh, serrated edges, 2 mm in size, heavily altered to a green fine grained mineral (epidote or chlorite?) and hematite
Tr	Apatite, grdmass, acicular, ≤80 μ long
v.Tr	Biotite, grdmass, near clinopyroxene (?) xenolith, 100 in size, pleochroic brown

Texture: Intergranular. Small mafic minerals appear to be embedded in large, anhedral plagioclase grains rather than interstitial to them

Comment: An unusual rock, somewhat similar in its appearance to A5006. The abundance of plagioclase in the thin section is notable and suggests that the rock be called a "feldspathic basalt." If this rock is potassic like other volcanics from the California border, it may be a trachybasalt.

Additional note: Leeman (1970) reported a ^{87}Sr/^{86}Sr ratio for a trachybasalt in the same general area.

C5010

Name: Feldspathic basalt

Megascopic description: This is a medium gray, unvesicular, flinty, volcanic rock. It contains abundant plagioclase microphenocrysts, which give the sample a shiny appearance in the sunlight.

Coordinates: 117°38'26"W - 36°21'11"N

Township: Sec 21 (unsurveyed), T18S, R40E, Darwin 15' quad, Inyo Co., CA

Locality: Collected in a gully W of Calif. 190, about a mile to the S and W of Saline Valley turnoff

Age: Quaternary

Reference: Hall and MacKevett (1962)

Minerals:

Tr	Plagioclase, pheno, equant and rounded, ∿1.5 mm in size, holey
25%	Olivine, grdmass, euh-subh, 150-20 μ, unaltered, 2V∿80, no reaction rims
10%	Clinopyroxene, grdmass, 20 μ, anh, light green-brown color
15%	Oxides, grdmass, subh-anh, blocky, 50 μ in size
50%	Plagioclase, grdmass, elongate laths, up to 700 μ long, An54
Tr	Apatite, grdmass, acicular to elongate, ≤40 μ in length
1%	Glass, interstitial to interstitial grdmass grains, 20 μ, light brown color

Texture: Intergranular, with mafic minerals interstitial to feldspar laths. Plagioclase laths are randomly orientated.

Comment: Texturally and mineralogically this rock and C5009 are quite similar. (They differ, however, in their concentration of oxides. In addition, mafic minerals in this rock are interstitial between plagioclase laths while in C5009 they appear to be embedded in anhedral plagioclase.) Isotopically they are quite distinct.

C5011

Name: Feldspathic basalt

Megascopic description: A medium gray aphanitic volcanic rock containing abundant and occasionally large (3 mm) phenocrysts of plagioclase and less common waxy green olivine phenocrysts. Somewhat vesicular with network of fine (0.5 mm) vesicles

Coordinates: 117°52'35"W - 35°57'06"N

Township: NE 1/4, sec 9, R38E, T23S, Little Lake 15' quad, Inyo Co., CA

Locality: ∿100 m from distal end of the Volcano Peak flow, and ∿1½ mi E of Little Lake

Field relations: Morphologically a Recent flow

Age: Later Quaternary

Reference: Babcock (1975)

Minerals:

20%	Plagioclase, pheno, subh laths, 300 μ-2 mm in length ∿An64
5%	Olivine, pheno, euh-anh, ≤1 mm, no oxide inclusions or reaction rims
1%	Augite, pheno, subh, 1 mm, pale green-brown color, B+, 2V∿50
10%	Olivine, grdmass, euh-anh, ≤200 μ, no reaction rims
10%	Augite, grdmass, euh, 30 μ
20%	Oxides, grdmass, equant blocks, 20 μ
25%	Plagioclase, grdmass, roughly equant but anh, 30 μ
Tr	Glass, grdmass, interstitial, 10 μ
10%	Vesicles, rounded but usually not round, typically around 700 μ in size

Texture: Although the matrix of this rock is nearly 100% crystalline, it is very fine grained, and under low power the thin section has a hyalophitic appearance. Plagioclase laths display a rough but clear direction of orientation. One area of this thin section is mineralogically similar but texturally very different from the rest. This is about 4 mm across and composed entirely of phenocrysts arranged in a pronounced dikytaxitic texture. Indeed, vesicles makeup some 30% of this area, are often angular in outline, and comparable in size to the solid phases

Comment: This is feldspathic basalt characterized by an abundance of oxides.

A5014

Name: Basaltic andesite

Megascopic description: An aphanitic, dark gray volcanic rock with a few feldspar phenocrysts. About 20% vesicles, with vesicles irregularly shaped and generally small (<1 mm) in size

Coordinates: 111°27'53"W - 35°26'19"N

Township: NE 1/4, NW 1/4, sec 29, R8E, T42N, Strawberry Crater 7.5' quad, Coconino Co., AZ

Locality: Prominent face in flow front, ∿500 m S and E of Strawberry Crater, San Francisco volcanic field

Field relations: A flow of Merriam age

Age: K/Ar 0.46 ± 0.046 my (Damon et al., 1974)

Reference: Moore *et al.* (1974)

Minerals:

2%	Plagioclase, pheno, anh-subh, wormy (sieve) texture due to microcrystalline alteration. Some crystals are surrounded by rims of unaltered material, while others have clear, unaltered cores. Infrequent twinning. Embayed exteriors
Tr	Quartz, pheno, rounded shape, 700 µ, surrounded by a clinopyroxene corona
1%	Hypersthene, pheno, subh-anh, 400-700 µ, pinkish brown to pale green pleochroism, B-
15%	Hypersthene, grdmass, anh, 70-200 µ, often patches containing multiple crystals
10%	Clinopyroxene, grdmass, subh, 100 µ, 2V≤30
5%	Olivine, grdmass, euh, 50 µ, in part altered to iddingsite
15%	Glass, grdmass, interstitial, 50 µ, brown color, bubbly appearance
5%	Oxides, grdmass, blocky to powdery, 20-100 µ
30%	Plagioclase, grdmass, euh laths, typically about 100 µ in length, An52
Tr	Pigeonite, pheno, anh, 700 µ, light green-brown, 2V<30, embayed
Tr	Serricite, alteration, usually along vesicle sides
20%	Vesicles, somewhat rounded in shape, 200 µ-2 mm in size

Texture: Intersertal, vesicular

A5014 (continued)

Comment: Plagioclase and quartz megacrysts are definitely out of equilibrium with the groundmass minerals. The uncommon pigeonite phenocrysts also appear to be in disequilibrium. The association of two pyroxenes, olivine, quartz "xenoliths," and wormy plagioclase occurs commonly in the basaltic andesites of the San Francisco volcanic field (Moore *et al.*, 1976).

U5016

Name: Basaltic andesite

Megascopic description: A med gray, aphanitic, essentially unvesicular volcanic rock containing clear plagioclase phenocrysts, occasionally up to 5 mm in size

Coordinates: 113°33'16"W - 37°07'25"W

Township: NE 1/4, sec 20, T42S, R15W, St. George 15' quad, Washington Co., UT

Locality: Black Ridge, ∿500 m N of I-15, within St. George city limits

Field relations: A stage II flow (Hamblin, 1963)

Age: Probably ≤3 my (see Best and Brimhall, 1974)

Reference: Hamblin (1963) and Best and Brimhall (1974)

Minerals:

3%	Olivine, pheno, euh, 0.3-1 mm, very thin iddingsite rims, 2V∿80
3%	Plagioclase, pheno, equant-laths, 2 mm, wormy textured patches, zoned, twinned
50%	Plagioclase, μpheno and grdmass, laths, not wormy, twinned, An47
Tr	Quartz, pheno anh, rounded, 700 μ, surrounded by a reaction rim of radiating clinopyroxene crystals and brown glass
20%	Olivine, grdmass, anh-subh, ≥30 μ, no alteration or reaction
15%	Clinopyroxene, grdmass, anh, 50 μ, pale coloration
10%	Oxide, grdmass, skeletal to blocky, 100 μ
Tr	Apatite, grdmass, euh, acicular, ≤50 μ in length
Tr	Vesicles, 1 mm in size
Tr	Glass, grdmass, interstitial, 20 μ, nearly clear

Texture: Relatively coarse grained groundmass. Intergranular with mafic minerals occupying positions interstitial to feldspar laths. Plagioclase laths show a consistent orientation throughout the thin section

Comments: The wormy plagioclase and partially resorbed quartz crystals found in this rock indicate that this is a basaltic andesite

Additional note: This sample was collected near the Leeman (1974) SG-15 sample locality. Leeman (1974) has reported a ^{87}Sr/^{86}Sr ratio of .7040 for his sample.

U5017

Name: Hawaiite

Megascopic description: Med gray, aphanitic, with rare mm sized vesicles and microphenocrysts of olivine

Coordinates: 113°16'54"W - 37°13'31"N

Township: Center, N 1/2, sec 14, T14S, R31W, Hurricane, 15' quad, Washington Co., UT

Locality: Stream cliff, ∿1&3/4 mi N of La Verkin on Utah 15

Field relations: Stage II (Hamblin, 1963)

Age: Probably ≤1 my (see Best and Brimhall, 1974)

Reference: Hamblin (1963), Best and Brimhall (1974), and Leeman (1974)

Minerals:

5%	Olivine, pheno, subh, 300 μ-1.5 mm, very slight iddingsite alteration
15%	Olivine, grdmass, subh-anh, 75 μ, slight iddingsite alteration, no reaction rims
25%	Titanaugite, grdmass, subh-anh, purple brown color, slightly pleochroic
40%	Plagioclase, grdmass, laths to irregular shapes, 150 μ, An48
15%	Oxides, grdmass, euh-anh, both acicular and blocky, interstitial, 100 μ in size
2%	Vesicles, amoebic, rounded shapes, 300 μ sizes
Tr	Apatite, grdmass, acicular, ≤70 μ in length
Tr	Calcite, alteration
Tr	Glass, interstitial

Texture: Intergranular, with augite situated between feldspar laths

Comment: This is the only Colorado Plateau sample studied in this report which contains purple clinopyroxene. This titanaugite suggests an alkaline affinity for the rock. Petrographically this rock is somewhat transitional between an alkaline olivine basalt and a feldspathic basalt. For the moment "hawaiite" appears to be an adequate label.

Additional note: Leeman (1970) has a ^{87}Sr/^{86}Sr ratio of .7046 on a sample from the same vicinity as U5017.

A5019

Name: Basaltic andesite

Megascopic description: A lt gray, aphanitic volcanic rock with small (<1 mm) but abundant olivine phenocrysts. It also contains small vesicles, but it is not really a vesicular rock

Coordinates: 113°03'50"W - 36°28'02"N

Township: NE 1/4, sec 32, T35N, R7W, Mt. Trumbell NE 7.5' quad, Mohave Co., AZ

Locality: W side of Toroweap Valley, near the Mt. Trumbell Road

Field relations: Stage IV (Hamblin, 1974)

Age: Quaternary

Reference: Hamblin (1974) and Best and Brimhall (1974)

Minerals:

Tr	Quartz, xenolith, rounded, anh shape, 0.3 mm in size, surrounded by a clinopyroxene corona
1%	Augite, pheno, anh, 500 μ, lt brown color, 2V∿60
10%	Olivine, pheno, subh, ≤2.5 mm, oxide inclusions, sometimes embayed
10%	Olivine, grdmass, subh-anh, ≥50 μ, no reaction rims
25%	Augite, grdmass, subh-anh, 40 μ, pale green-brown coloration
45%	Plagioclase, grdmass, subh laths to equant anh grains, 100 μ, An64
10%	Oxides, grdmass, blocky, skeletal, and acicular, 50 μ
Tr	Apatite, grdmass, acicular, ≤100 μ in length
Tr	Glass, interstitial, 20 μ

Texture: Intergranular. Plagioclase laths are locally subparallel to one another

Comment: The partially resorbed quartz megacryst found in thin section suggests that this is a basaltic andesite. (It might be mentioned, however, that the thin section does not contain wormy plagioclase, which is a commonly occurring mineral in basaltic andesites.) The large percentage of plagioclase also suggests that this rock has andesitic tendencies.

U5020

Name: Feldspathic diabase

Megascopic description: A lt gray volcanic rock, with a dikytaxitic texture. Feldspar laths of mm size compose about 40% of the rock

Coordinates: 112°37'46"W - 38°52'19"N

Township: NW 1/4, sec 27, T22S, R7W, Tabernacle Hills 15' quad, Millard Co., UT

Locality: Near Hole in the Rock on Beaver Ridge, Black Rock Desert volcanic field

Field relations: A Pre-Lake Bonneville flow

Age: Pleistocene

Reference: Condie and Barsky (1972), Pushkar and Condie (1973)

Minerals:

20%	Plagioclase, pheno, lath-like, 5 mm long, zoned, twinned, An70
25%	Augite, "μpheno," anh, 700-100 μ, lt brown color, B+, $2V \sim 45$
10%	Olivine, μpheno, rounded, subh, 200-700 μ, slight iddingsite alteration
10%	Oxides, μpheno, anh, blocky
25%	Plagioclase, subh laths, 500-100 μ, An63
10%	Vesicles, complex in shape, ≤2 mm in size, in some cases interstitial
Tr	Glass, interstitial

Texture: Quite coarse grained. Clinopyroxene crystals are always interstitial to plagioclase laths but in some areas clinopyroxene is so abundant as to give an ophitic texture. Plagioclase crystals grow out into voids, giving vesicles their irregular to angular shapes, and the rock a dikytaxitic texture in some areas.

Comment: A remarkably beautiful feldspar-rich diabase

Additional note: Pushkar and Condie have reported a $^{87}Sr/^{86}Sr$ ratio of .7044 on a sample from the same general locality as this one.

U5022

Name: Feldspathic basalt

Megascopic description: Med gray, aphanitic, aphyric. Contains pipe vesicles up to several cm in length

Coordinates: 112°27'42"W - 38°58'48"N

Township: S boundary, SW 1/4, sec 18, R5W, T21S, Filmore 15' quad, Millard Co., UT

Locality: ~1.7 mi W of Flowell, on E side Recent flow, Ice Springs field

Field relations: One of the youngest flows in the Black Rock desert

Age: Holocene

Reference: Condie and Barsky (1972) and Pushkar and Condie (1973)

Minerals:

Tr	Olivine, pheno, euh, 1 mm
17%	Olivine, grdmass, euh-subh, 100 μ, no reaction rims
43%	Plagioclase, grdmass,euh, 100-200 μ long, An55
5%	Clinopyroxene, grdmass, subh-anh, 30 μ
15%	Oxides, grdmass, blocky to acicular, anh, 30 μ
10%	Glass, interstitial, 40 μ, black to brown in color
10%	Vesicles, round to rounded elongate, 0.5 mm - 1 cm
Tr	Calcite, weathering, thin lining on the walls of some vesicles

Texture: Intersertal and fine grained

Comment: Condie and Barsky (1972) report that basalts from the Ice Springs volcanic field contain orthopyroxene as microphenocrysts and as a groundmass phase, that they do not contain olivine, and that rare partial resorbed plagioclase phenocrysts occur in most samples. This sample from the Ice Springs field does contain olivine, and does not contain orthopyroxene or wormy plagioclase. The contradiction is quite glaring because U5022 was collected at essentially the same locality as two of Condie and Barsky's samples.

Additional note: Samples from the Ice Springs volcanic field show a range in $^{87}Sr/^{86}Sr$ between .7052 and .7059 (Pushkar and Condie, 1973).

N5023

Name: Basaltic andesite

Megascopic description: Med gray, aphanitic. Contains a few large (≥1 mm) vesicles but essentially unvesicular. Also contains small brown (iddingsite) olivine phenocrysts and microphenocrysts of plagioclase

Coordinates: 114°27.6'W - 37°15.9'N

Township: Sec 11, R67E, T8S, Lincoln Co., NV

Locality: ∿1 km N of Leith Station, on W side of Meadow Valley wash

Field relations: On top of a thick sequence of Tertiary volcanic tuffs

Age: K/Ar 8.5 ± 0.3 my (Armstrong, 1970)

Reference: Tschanz and Pampeyan (1970) and Armstrong (1970)

Minerals:

3%	Olivine, pheno, euh, 1.5 mm, iddingsite rims, B-, 2V∿80
5%	Plagioclase, pheno and μpheno, laths and equant, ≤1 mm, annular areas characterized by sieve-like texture (worminess)
Tr?	Orthopyroxene (hypersthene and bronzite), grdmass, subh, ≤100 μ, green-pink pleochroism, B- and B+
25%	Clinopyroxene, grdmass, subh, 50 μ, light green color
15%	Olivine, grdmass, subh, 70 μ, no reaction rims
40%	Plagioclase, μpheno and grdmass laths, 100 μ, An68
7%	Oxides, grdmass, anh, 50-100 μ
5%	Glass, interstitial, colored by opaque dust
Tr	Apatite, grdmass, acicular, 70 μ in length

Texture: Essentially intergranular. Consistent orientation of elongate plagioclase laths

Comment: The presence of wormy feldspars would indicate that this rock is a basaltic andesite.

Additional note: Scott *et al*. (1969) have reported a ^{87}Sr/^{86}Sr ratio of .7061 ± .0006 on a sample from the same locality as N5023.

N5024

Name: Basanitoid

Megascopic description: Med gray, unvesicular, aphanitic. Contains abundant, large mafic and feldspathic megacrysts

Coordinates: 116°00'44"W - 38°28'47"N

Township: T6N, R53E (unsurveyed), Lunar Crater 15' quad, Nye Co., NV

Locality: Just E of Sandy Springs wash, $\sim$1 mi N of U.S. 6, Lunar Crater volcanic field

Field relations: Taken from a morphologically fresh flow

Age: Holocene

Reference: Scott and Trask (1971) and Snyder *et al*. (1972)

Minerals:

1%	Olivine, megacryst, anh-subh, 7 mm, completely unweathered, devoid of oxide inclusions
Tr	Plagioclase, megacryst, anh, 3 mm, twinned, embayed
1%	Augite, megacryst, anh, 2 mm, purplish tint, 2V$\sim$60, B+
5%	Olivine, μpheno, subh, $\leq$0.8 mm, 2V$\sim$90, clear
25%	Titanaugite, μpheno and grdmass, subh, 400 μ, gray-purple brown color, 2V$\sim$60
15%	Olivine, grdmass, subh-anh, 100-200 μ, clear color
15%	Oxides, grdmass, blocky, 50 μ
15%	Plagioclase, grdmass, laths, 100 μ
20%	Glass, interstitial, brown in color
3%	Vesicles, irregular in shape, 200 μ

Texture: Intersertal, but interstitial areas are poorly defined

Comment: A very mafic rock, with a remarkable dearth of feldspar.

Additional note: Scott and Trask (1971) have published a chemical analysis on this flow and Leeman (1970) has reported two ^{87}Sr/^{86}Sr analyses (.7032 and .7034) of Lunar Crater basalt flows.

N5026

Name: Feldspathic basalt

Megascopic description: Med gray, aphanitic. Contains ≤1 mm sized vesicles and microphenocrysts of olivine and feldspar

Coordinates: 117°01'38"W - 38°11'23"N

Township: NE 1/4, sec 22, T4N, R44E, Tonopah 15' quad, Nye Co., NV

Locality: N side of Thunder Mountain, $\sim$3 mi E of Rye Patch and Nev. 8A

Field relations: This basaltic flow overlies white tuff

Age: K/Ar 18.9 ± 1.5 my (Armstrong *et al.*, 1972)

Reference: Armstrong *et al.* (1972), Bonham and Garside (1974)

Minerals:

2%	Olivine, pheno, subh, 0.7 mm, partially altered iddingsite, 2V$\sim$80
40%	Plagioclase, μpheno and grdmass, tabular laths, 300 μ, zoned, twinned, An42
25%	Augite, grdmass, μpheno, anh, 150 μ, 2V$\sim$60
5%	Olivine, grdmass, anh, 50-100 μ, no reaction rims
10%	Oxides, grdmass, blocky, ≤200 μ
15%	Glass, grdmass, brown color, bubbly texture

Texture: Fine grained to glassy matrix set between oriented laths of microphenocryst size plagioclase

Comment: Armstrong called this rock an olivine trachyandesite. Although this term or "basaltic andesite" are both acceptable, I have labelled it a feldspathic basalt to be consistent with the terminology used in the text.

Additional note: Armstrong (1972) reports a ^{87}Sr/^{86}Sr ratio of .7052 for his Thunder Mountain sample.

C6002

Name: Basaltic andesite

Megascopic description: Dark gray, aphanitic, and essentially unvesicular. Contains phenocrysts of oxidized olivine and plagioclase, and some, generally small (<0.5 mm) vesicles

Coordinates: 114°50'44"W - 34°07'01"N

Township: SE 1/4, NE 1/4, sec 2, T1S, R20E, Rice 15' quad, San Bernardino Co., CA

Locality: SW corner of the Turtle Mtns, ∿2½ mi due N of Rice

Field relations: A dissected flow

Age: Pleistocene according to map but probably older

Reference: Geologic Map of California, Needles Sheet (Bishop, 1964)

Minerals:

5%	Olivine, pheno, rounded subh, 500 μ, iddingsite rims, occasionally surrounded by clinopyroxene
5%	Augite, pheno, euh and subh, ≤1 mm, pale green color, sieve-like texture
5%	Plagioclase, pheno, subh laths, 0.2-2.5 mm, rarely wormy
10%	Oxides, grdmass, anh, 30 μ
20%	Clinopyroxene, grdmass, anh, 30 μ, light green color
1%	Olivine, grdmass, subh-anh, almost entirely altered to iddingsite
45%	Plagioclase, grdmass, laths, 100 μ, An50?
5%	Glass, interstitial, 100 μ
3%	Vesicles, irregular to round in shape, 0.3-3 mm in size
Tr	Apatite, grdmass, acicular, 50 μ in length

Texture: Intergranular and pilotaxitic

Comment: The occurrence of large, mottled clinopyroxene phenocrysts is unusual.

A6003

Name: Andesite

Megascopic description: Aphanitic, gray with a slight red-brown tint

Coordinates: 114°12'58"W - 34°07'20"N

Township: Central E edge, sec 15, T9N, R19W, Yuma Co., AZ

Locality: Road cut in concrete paved jeep road up to Black Peak, ∿4 mi SE of Parker

Age: K/Ar 15.1 ± 4.4 my, 16.4 ± 0.7 my (Damon, 1970)

Reference: Geologic Map of Arizona (Wilson *et al.*, 1969)

Minerals:

50%	Plagioclase, laths, 700 μ, An66
15%	Clinopyroxene, anh, rounded 50-600 μ, brown color
15%	Oxides, subh, interstitial, 300 μ
5%	Oxides, anh, weathering, 20 μ
1%	Apatite, euh, acicular, 10 x 200 μ
15%	Vesicles, irregular to angular in shape, interstitial, 100 μ

Texture: Coarse grained. Oxides and clinopyroxene crystals (intergranular texture) and vesicles (dikytaxitic texture) are interstitial to plagioclase laths.

Comment: Texturally an unusual rock. The abundance of plagioclase indicates the rock's andesitic affinities.

A6004

Name: Basaltic andesite

Megascopic description: Black, aphanitic, essentially unvesicular. Small olivine and plagioclase phenocrysts. Rare quartz in vesicles

Coordinates: 114°04'21"W - 33°40'34"N

Township: SE 1/4, NW 1/4, sec 24, R18W, T4N, Quartzite 15' quad, Yuma Co., AZ

Locality: ~200 m S of I-10, on Golden Nugget Road in Plomosa Pass, ~8½ mi E of Quartzsite

Age: Quaternary according to map, but could easily be older

Reference: Geologic Map of Arizona (Wilson *et al*., 1969)

Minerals:

5%	Olivine, pheno, euh, 200-700 µ, iddingsite rims
2%	Plagioclase, µpheno, equant to tabular, euh-subh, 500 µ, zoned, twinned, An75
30%	Augite, grdmass, anh, 50-200 µ, pale green color, B+, 2V~60
5%	Olivine, grdmass, subh-anh, 100 µ
15%	Oxides, grdmass, blocky, subh and euh, 50 µ
10%	Glass, interstitial, 70 µ, brownish color, contains microlites
33%	Plagioclase, grdmass, elongate laths, 200 µ in length, An55
1%	Vesicles, 0.5-2 mm, rounded by irregular shapes
Tr	Calcite, alteration in some vesicles
Tr	Quartz, xenolith, 2 mm, rounded clinopyroxene reaction rim, U+, embayed

Texture: Intersertal and pilotaxitic

Comment: This rock is rather mafic. The occurrence of a quartz xenolith is unusual and lacks an obvious explanation. The quartz could be a xenolith, or a high pressure phenocryst.

A6005

Name: Feldspathic tholeiite

Megascopic description: Med gray, aphanitic, and essentially aphyric. Some elongate vesicles up to 2 mm in length

Coordinates: 112°56'04"W - 33°27'15"N

Township: SW 1/4, sec 1, R7W, T1N, Arlington 15' quad, Maricopa Co., AZ

Locality: Palo Verde Hills, 2½ mi S of Tonopah and I-10

Age: Quaternary according to state geologic map. A K/Ar date on a basalt from the Palo Verde Hills has a 16.7 my age (Miller *et al.*, 1977)

Reference: Geologic Map of Arizona (Wilson *et al.*, 1969)

Minerals:

2%	Hypersthene,pheno, euh-subh, ≤1 mm, lt green to pink pleochroism, B-
5%	Plagioclase, pheno, tabular-equant, subh-anh, <1 mm, some twinning, zoned, embayed, reaction with grdmass
5%	Hypersthene, grdmass, 20 μ, euh-subh microlites
1%	Clinopyroxene (?), grdmass, 20 μ, euh-subh microlites
15%	Oxides, grdmass, euh, equant, 20 μ
25%	Plagioclase, grdmass, laths, 70 μ, An55
43%	Glass, lt brown color, contains abundant microlites
Tr	Calcite, weathering
5%	Vesicles, amoeboid in shape, ≤3 mm in size

Texture: The groundmass has a pilotaxitic and hyalophitic texture.

Comment: It is unusual to find a Basin and Range basalt which contains hypersthene phenocrysts.

A6008

Name: Diabase

Megascopic description: Med gray, aphanitic basalt with olivine and plagioclase microphenocrysts. Possesses a fine network of very small vesicles.

Coordinates: 113°22'03"W - 34°29'04"N

Township: NW 1/4, sec 12, T11W, R13N, Arrastra Mountain 7.5' quad, Mohave Co., AZ

Locality: Road cut on U.S. 93, ~10 mi SE of Burro Creek-Kaiser Spring Canyon bridge

Field relations: Basalt lies directly on top of Precambrian granite

Age: Pliocene (?) or Pleistocene (?)

Reference: Geologic Map of Arizona (Wilson et al., 1969)

Minerals:

5%	Olivine, rounded subh, 700 μ, 2V~80, partially converted to iddingsite
30%	Augite, skeletal, poikilitic, 700 μ, lt green-brown color
5%	Glass, interstitial, 100 μ, brown color, often contains microlites
5%	Oxides, blocks to needles, anh, 50 μ
25%	Plagioclase, laths, 0.2-1 mm, An61, very rarely with wormy interiors
25%	Vesicles, irregular in shape, 50 μ-2 mm in size

Texture: Ophitic, intersertal, and dikytaxitic textures are found in this rock. Uniformly coarse grained.

Comment: Despite the (very rare) occurrence of a sieve textured plagioclase, this rock is too feldspar poor to be considered a basaltic andesite.

C6009

Name: Feldspathic basalt

Megascopic description: A lt gray rock containing plagioclase microphenocrysts, rare olivine microphenocrysts, and small (≤1 mm) vesicles

Coordinates: 115°03'27"W - 34°54'36"N

Township: Central E side, sec 36, T10N, R18E, Fenner 15' quad, San Bernardino Co., CA

Locality: Hill, ∿1500 m S and E of Goffs

Field relations: A dike

Age: Pleistocene according to state geologic map but easily older

Reference: Geologic Map of California, Needles Sheet (Bishop, 1964)

Minerals:

15%	Clinopyroxene, μpheno and grdmass, subh-anh, ≤400 μ, lt brown-green color, B+, 2V∿60
2%	Olivine, μpheno-grdmass, subh-anh, ≤300 μ, partially converted to iddingsite
20%	Plagioclase, μpheno, short laths, 400 μ, zoned, twinned, An56
30%	Plagioclase, grdmass, microlites, ≤100 μ in length
10%	Oxides, grdmass, anh, blocky, 5-70 μ
20%	Glass, pale brown in color, contains many small microlites
3%	Vesicles, 0.3-1 mm in size, irregular in shape

Texture: Hyalophitic

Comment: The dearth of olivine in this rock is noticeable, suggesting that the rock is not very unsaturated.

A6011

Name: Andesite

Megascopic description: Med gray volcanic rock containing abundant plagioclase laths up to several mm in length

Coordinates: 114°06'06"W - 35°12'30"N

Township: Center, sec 15, T21N, R17W, Kingman 7.5' quad, Mohave Co., AZ

Locality: Road cut on U.S. 93-466, ~2½ mi NW of high school in Kingman

Field relations: At least as old as the Peach Springs tuff

Age: Qb, according to Geologic Map of Arizona, but at least 17 my in age because of field relations and K/Ar dates on Kingman ignimbrite (Damon, 1966)

Reference: Geologic Map of Arizona (Wilson *et al.*, 1969)

Minerals:

10%	Augite, pheno, and μpheno, subh, rounded, 0.2-2 mm, commonly twinned, B+, 2V~55, lt brown color
10%	Hornblende, pheno and μpheno, subh, rounded 0.2-2 mm, B-, brown-green pleochroism
25%	Plagioclase, pheno and μpheno, usually euh-subh laths, 0.2-3 mm in length, a few of the larger grains are anh and possess an wormy texture
55%	Glass, matrix, black, nearly opaque, contains some microlites

Texture: Glassy matrix containing randomly orientated phenocrysts (hypocrystalline and porphyritic)

Comment: Not a basalt, as was believed in the field, but an andesite or dacite.

A6014

Name: Feldspathic basalt

Megascopic description: A med gray basalt containing only rare, small (<1 mm) olivine phenocrysts. Essentially unvesicular

Coordinates: 112°46.7'W - 35°16.8'N

Township: NE corner, sec 24, R5W, T22N, Yavapai Co., AZ

Locality: Road cut along I-40, approximately 7 mi E of Seligman, Mt. Floyd volcanic field

Age: Probably younger than the Hickey Formation (≤10 my) (D. Neeley, personal communicaton)

Reference: Geologic Map of Arizona (Wilson et al., 1969)

Minerals:

2%	Clinopyroxene, monomineralic inclusion consisting of many anhedral crystals, 6 mm long, angular shape
5%	Olivine, pheno, subh, 1 mm, iddingsite rims common
5%	Clinopyroxene, pheno, anh, granular patches made up of a mosaic of finer grains, individual crystals sometimes arranged as a corona
15%	Olivine, grdmass, subh-anh, 100 μ, in part altered to iddingsite
20%	Clinopyroxene, grdmass, anh-subh, 200 μ, gray-green color
Tr	Apatite, grdmass, acicular, 100 μ long
10%	Oxides, grdmass, blocky 50 μ
40%	Plagioclase, grdmass, anh to lath-like, twinned
2%	Vesicles, round, ∿0.7 mm
Tr	Glass, interstitial, 30 μ, pale brown in color

Texture: The texture is dominated by interlocking, often irregularly shaped subparallel plagioclase crystals, occasionally in fan-like motifs.

Comment: The abundance of plagioclase in this rock indicates that it is a feldspathic basalt. The "coronas" of clinopyroxene suggest that quartz xenocrysts were present at one time.

A6015

Name: Rhyolite

Megascopic description: White, glassy volcanic rock containing minute biotite crystals. Glass shards are observable.

Coordinates: 111°57'27"W - 35°17'59"N

Township: NE 1/4, NW 1/4, sec 10, T22N, R4E, Park 7.5' quad, Coconino Co., AZ

Locality: Top of Wright Hill, western San Francisco volcanic field

Age: Approximately 2 my in age (E. Wolfe, personal communication)

Minerals:

15%	Orthoclase, pheno-grdmass, equant, euh-anh, 50 μ-1 mm, occasionally with myrmekitic rims, B-, 2V~70
1%	Biotite (?), grdmass, anh, 200 μ, pleochroic green-brown, often altered to oxides
3%	Oxides, grdmass and deuteric alteration, anh, 50 μ, opaque and reddish in color
80%	Glass, clear color, occasionally found in shards, contains microlites, sperulitic cracks
1%	Vesicles, round 400 μ

Texture: Glassy and porphyritic

Comment: This is one of the very few rhyolitic rocks analyzed in this study.

A6018

Name: Dacite vitrophere

Megascopic description: A dark gray, porphyritic volcanic rock containing abundant plagioclase phenocrysts

Coordinates: 111°28'00"W - 35°26'34"N

Township: SW 1/4, sec 20, R9E, T24N, Strawberry Crater 7.5' quad, Coconino Co., AZ

Locality: Eastern side Strawberry Crater, San Francisco volcanic field

Field relations: Contains an occasional, partially fused granulitic xenolith

Age: Quaternary, younger than the Strawberry Crater basalt (0.046 ± 0.046 my)

References: Moore et al. (1974)

Minerals:

5%	Orthoclase, pheno, anh, equant, 1 mm, often partially cloudy, especially along rims, commonly embayed, refractive index < balsam, B- with a fairly large 2V
1%	Olivine, pheno-grdmass, subh-anh, ≤0.8 mm, B-, 2V∼70, clear color
1%	Hornblende, pheno, subh-anh, ≤1 mm, brown color, slightly pleochroic, small angle, often associated with opaques, B-, 2V∼70, embayed
Tr	Oxides, pheno, anh, 0.6 mm
10%	Olivine, grdmass, subh-anh, 50-100 μ
20%	Feldspar, grdmass, euh-subh laths, 100 μ in length
3%	Opaques, grdmass, blocky 10 μ
60%	Glass, brown color
1%	Vesicles, rounded and somewhat elongate in form, 50-700 μ

Texture: Intersertal

Comment: It seems unusual to have orthoclase and olivine together in the same thin section.

A6021

Name: Basanitoid

Megascopic description: A dense, essentially unvesicular, aphyric volcanic which contains rare but large pipe-like vesicles

Coordinates: 111°12'12"W - 35°25'36"N

Township: T24N, R12E (unsurveyed), Grand Falls 7.5' quad, Coconino Co., AZ

Locality: Grand Falls on the Little Colorado River, San Francisco volcanic field

Field relations: Flow dammed the Little Colorado River

Age: Merriam age (<0.1 my)

Reference: Moore *et al*. (1974)

Minerals:

20%	Olivine, μpheno and grdmass, euh-subh, ≤400 μ, some oxide inclusions
15%	Clinopyroxene, grdmass, anh, 70 μ, brownish color
20%	Glass, interstitial, 50 μ, brown color
10%	Oxides, grdmass, blocky, 70 μ
30%	Plagioclase, grdmass, elongate laths, ∿An76
5%	Vesicles, rounded shapes, 0.1-3 mm in size

Texture: Intersertal. Plagioclase laths are subparallel throughout the thin section

Comment: The abundance of glass in this rock prohibits a definitive classification. However, a chemical analysis (E. Wolfe, written communication) indicates that A6021 is a basanitoid.

A6022

Name: High alumina basalt

Megascopic description: A med gray basalt containing a few olivine phenocrysts and abundant plagioclase microphenocrysts. Contains a fine network of crack vesicles

Coordinates: 111°19'45"W - 35°17'55"N

Township: NE 1/4, sec 16, T22N, R10E, Merriam 7.5' quad

Locality: Near BM5742, Leupp Road, near Junction Crater

Field relations: The Jumpoff Crater flow

Age: Tappan age - 0.7-0.7 my, Pleistocene

Reference: Moore et al. (1974)

Minerals:

1%	Plagioclase, pheno, equant, subh, 1 mm, An70 (?)
5%	Olivine, μpheno and grdmass, ≤400 μ, euh-subh, very slight oxidation
10%	Clinopyroxene, grdmass, anh, 50 μ, brownish color, B+, 2V∼50
45%	Plagioclase, grdmass, elongate laths, 50-300 μ in length, An58
15%	Oxides, grdmass, blocky, 50 μ
10%	Glass, interstitial, 50 μ, gritty texture, brown color
15%	Vesicles, irregular in shape but often elongate, 0.2-2 mm

Texture: Plagioclase laths are oriented subparallel to one another, giving the thin section a sort of pilotaxitic appearance. The vesicles in this rock are small and irregular in shape, but not so much so as to be called a dikytaxitic texture.

Comment: Petrographically this rock is a feldspathic basalt. A chemical analysis of a sample from that flow (E. Wolfe, written communication) indicates that this is an alkali-rich high alumina basalt.

A6023

Name: Alkaline-olivine basalt

Megascopic description: A med gray basalt containing microphenocrysts of olivine and plagioclase. Somewhat vesicular with large (up to 5 mm in size) rounded vesicles.

Coordinates: 111°31'40"W - 35°22'52"N

Township: SE 1/4, NE 1/4, sec 15, T23N, R8E, O'Leary Peak 7.5' quad, Coconino Co., AZ

Locality: Near NW boundary of Sunset Crater National Monument, San Francisco volcanic field

Field relations: Sample taken near edge of the Bonito lava flow

Age: 1064 A.D. (Smiley, 1958, as quoted by Moore et al., 1974)

Reference: Moore et al. (1974)

Minerals:

15%	Olivine, μpheno to grdmass, subh, 100-700 μ, contains oxide inclusions, 2V~80
15%	Clinopyroxene, μpheno-grdmass, anh-subh, 800-50 μ, pale green in color, B+, 2V~50
30%	Plagioclase, grdmass, elongate laths, 200 μ in length
15%	Oxides, grdmass, anh, 70 μ
15%	Glass, interstitial, 20 μ, brown color, also along the borders of some vesicles, partially devitrified
10%	Vesicles, rounded, elongate and amoeboid in shape, 1-7 mm in size

Texture: Both glass (intersertal texture), clinopyroxene, and oxides (intergranular texture) are interstitial to plagioclase laths in this rock. Plagioclase laths are locally subparallel.

Comment: Petrographically this rock would be labelled an olivine-augite basalt. A chemical analysis (E. Wolfe, written communication) indicates that it is an alkaline-olivine basalt.

A6025

Name: Feldspathic basalt

Megascopic description: A dark gray, aphanitic volcanic rock possessing a moderate amount of olivine phenocrysts. Some millimeter-sized vesicles.

Coordinates: 112°22'27"W - 34°34'43"N

Township: Central part, sec 21, R1W, T14N, Prescott 15' quad, Yavapai Co., AZ

Locality: S side of Glassford Hill, in the Prescott area

Age: K/Ar 13.4 ± 0.5 my (McKee and Anderson, 1971)

Reference: Krieger (1965), McKee and Anderson (1971)

Minerals:

10%	Olivine, pheno, euh to anh (because of embayment), 1 mm, thin iddingsite rims
5%	Augite, pheno, subh, 1 mm, brownish color, B+, $2V \sim 60$
40%	Plagioclase, grdmass, laths, ≤300 μ, An55
10%	Olivine, grdmass, subh-anh, ≤150 μ, some iddingsite alteration but no obvious reaction rim
15%	Augite, grdmass, anh, 30 μ
10%	Oxides, grdmass, blocky, anh-subh, 50 μ
7%	Glass, interstitial, 40 μ, brown color
2%	Vesicles, ellipsoidal in shape, 0.5-3 mm in size

Texture: Plagioclase laths are locally oriented subparallel to one another, giving the thin section a pilotaxitic appearance.

Comment: Petrographically this rock is somewhat transitional between a feldspathic basalt and an olivine-augite basalt. A chemical analysis on a sample from a nearby locality (McKee and Anderson, 1971) is also transitional in a number of its characteristics.

A6026

Name: Basaltic andesite

Megascopic description: A med gray, aphanitic, volcanic rock containing olivine phenocrysts, which, in large part, have been altered to iddingsite.

Coordinates: 112°02'29"W - 34°16'30"N

Township: NE 1/4, sec 4, T10N, R3E, Mayer 15' quad, Yavapai Co., AZ

Locality: Approximately 1½ mi N of Horseshoe Ranch on Indian Creek

Field relations: Hickey formation

Age: K/Ar 10.4 ± 0.4 my (McKee and Anderson, 1971)

Reference: Anderson and Blacet (1972), McKee and Anderson (1971)

Minerals:

Tr	Quartz, megacryst, anh, rounded, 0.8 mm, U+, surrounded by a pyroxene reaction rim
2%	Olivine, pheno, euh but rounded corners, iddingsite rims, an occasional serpentinitic core, 2V∿80
15%	Clinopyroxene, grdmass, anh, 30 μ, individual grains and granular aggregates, very pale coloration
10%	Olivine, grdmass, subh-anh, 100 μ, some iddingsite alteration
55%	Plagioclase, grdmass, laths, 100 μ, twinned
10%	Oxides, grdmass, euh-subh, blocky 50 μ
5%	Glass
3%	Vesicles, round 100 μ vesicles, and elongate 2 mm vesicles

Texture: A trachytic texture with glass usually interstitial to plagioclase (intersertal texture).

Comment: This rock is petrographically similar to many feldspathic basalts. However, the presence of quartz "xenocrysts" indicates that the "basaltic andesite" label should be applied.

A6027

Name: Diabase

Megascopic description: A med gray volcanic rock containing rare olivine phenocrysts and more abundant plagioclase microphenocrysts. It contains numerous but minute (≤3 mm) vesicles.

Coordinates: 113°05'34"W - 34°19'25"W

Township: SE 1/4, sec 3, T11N, R8W, Malpais Mesa 7.5' quad, Yavapai Co., AZ

Locality: Malpais Mesa SE of Black Canyon Wash

Field relations: Basalt caps mesa, overlies sandstone and conglomerate of Late Tertiary (?) age.

Age: Quaternary according to Geologic Map of Arizona, but might easily be Pliocene in age

Reference: Geologic Map of Arizona (Wilson _et al_., 1969)

Minerals:

15%	Olivine, subh, rounded corners, average size about 300 μ, iddingsite rims common, B+, 2V∿80, contains minute oxide inclusions
20%	Augite, anh, 400 μ, interstitial to and including plag. laths pale brown in color, B+, 2V∿45
25%	Plagioclase, euh-subh laths, 500 μ long, ∿An66
5%	Oxides, blocky and elongate crystals ≤400 μ in size, and dust
10%	Glass, interstitial, 400 μ, brown to black in color, depending on the amount of opaque microlites
25%	Vesicles, angular and nearly interstitial, 100-400 μ in size
1%	Calcite, alteration, fills an occasional vesicles

Texture: Uniformly coarse grained. Subophitic, ophitic, intersertal, and dikytaxitic textural relationships can be found in this rock.

Comment: The mineral assemblage displayed by this rock is not diagnostic.

A6028

Name: Basaltic andesite

Megascopic description: A dark gray, aphanitic volcanic rock. Contains rare, partially altered, yellowish olivine phenocrysts and abundant but small phenocrysts of plagioclase . Unvesicular in appearance but contains some subparallel vesicle trains.

Coordinates: 113°37'20"W - 34°19'31"N

Township: W central portion, sec 4, R13N, T11N, Artillery Peak 15' quad, Mohave Co., AZ

Locality: S tip of Black Mountain, across from Plancha Mountain

Field relations: Basalt caps a faulted mesa, and overlies Tertiary sedimentary rocks

Age: Armstrong et al. (1976) dated a mesa capping flow S and W of Bill Williams River at 9.7 ± 0.3 my

Reference: Lasky and Weber (1949)

Minerals:

1%	Plagioclase, pheno, equant, anh, 3 mm, wormy, sieve-like texture, embayed
Tr	Olivine, pheno, euh, 1 mm, largely altered to iddingsite
10%	Olivine, grdmass, subh, 100 μ, some iddingsite alteration, no obvious reaction rims
15%	Clinopyroxene, grdmass, granular, anh, ≤100 μ, pale brown color, B+, 2V∿60
Tr	Amphibole, μpheno, columnar, subh, 0.2 x 3 mm, parallel extinction, B-, yellow-green pleochroism
10%	Oxides, grdmass, blocky 100 μ crystals and dust particles in glass
15%	Glass, interstitial, nearly black, spotted appearance
25%	Plagioclase, grdmass, subh-anh, often lath-like
20%	Vesicles, angular, 200 μ

Texture: Intersertal. The network of minute vesicles might be called a dikytaxitic texture if the groundmass was a little coarser grained.

Comment: It is unusual to find amphibole in a basalt. The occurrence of wormy plagioclase indicates that the term "basaltic andesite" should be applied to this rock.

A6030

Name: Feldspathic basalt

Megascopic description: A med gray basalt which possesses a few, small brownish olivine phenocrysts. It also contains vesicles; these are ≤3 mm in size and constitute only a very small percentage of the rock.

Coordinates: 113°54'01"W - 35°39'31"N

Township: NW 1/4, sec 34 (unsurveyed), T38N, R15W, Cane Springs 15' quad

Locality: Prominent mesa, just S of Jacobs Well, and W of Cottonwood Wash

Field relations: Mesa capping flow

Age: K/Ar 6.70 ± 0.20 my (Damon, 1968)

Reference: Best and Brimhall (1974)

Minerals:

1%	Olivine, pheno, subh, 5-2 mm, slight iddingsite alteration
15%	Olivine, grdmass, anh, 40 μ, brown color because of iddingsite
20%	Clinopyroxene, grdmass, anh, 40 μ, pale brown coloration
20%	Oxides, grdmass, blocky, equant, subh, 40 μ
42%	Plagioclase, grdmass, subh, often lath-like, 150 μ in length, An54
2%	Glass, interstitial, 20 μ, pale brown in color
Tr	Vesicles, round, 2 mm

Texture: Rather fine grained. Intergranular with mafic minerals interstitial to plagioclase laths. Plagioclase laths are subparallel to one another, giving the thin section a trachytic appearance.

Comment: Like many other basalts from the southwest this rock doesn't have an obvious alkaline or tholeiite character. It is somewhat rich in feldspar, and has consequently been labelled a feldspathic basalt for the purposes of this report. Chemical analyses on two rocks form the same general area as A6030 (Leeman, 1974) have been classified as hawaiites and it is reasonable to believe that A6030 is also a hawaiite.

A6031

Name: Ankaramite

Megascopic description: A med gray basalt containing olivine microphenocrysts. Moderately vesicular.

Coordinates: 113°35.1'W - 36°49.4'N

Township: Sec 33, R12W, T40N, Grand Canyon 1:250,000 quad, Mohave Co., AZ

Locality: SW side of hill protruding from the NE portion of Wolf Hole Mountain into the saddle with Seegmuller Mountain

Age: K/Ar 5.2 ± 1.3 my (Damon, 1968)

Reference: Best and Brimhall (1974), Leeman (1974)

Minerals:

20%	Olivine, μpheno, 0.1-2 mm, euh-subh but rounded, iddingsite and opaque oxide rims
25%	Augite, μpheno and grdmass, anh-subh, 50-400 μ, pale brown-green color, B+, 2V∿60
15%	Oxides, grdmass, blocky, anh, 100 μ
30%	Plagioclase, grdmass, laths, 80 μ
10%	Vesicles, round ≤2 mm in size
3%	Glass, interstitial, 10 μ

Texture: Basically intergranular although some glass is present. Somewhat coarse grained. Not ophitic, despite the abundance of clinopyroxene to plagioclase.

Comment: This rock is characterized by abundant olivine and clinopyroxene and relatively unabundant plagioclase. It is easily classified as an olivine-augite basalt, according to the algorithm of Chapter 5. However, the abundance of mafic phases might also allow this rock to be called an ankaramite. Indeed, Leeman (1974) called a basalt from the same general locality as A6031 an ankaramite on the basis of a chemical analysis. His isotopic analysis on the same sample gave a ^{87}Sr/^{86}Sr ratio of .7035.

U6032

Name: Feldspathic basalt

Megascopic description: A med gray, aphanitic, unvesicular volcanic rock, which contains minute olivine phenocrysts.

Coordinates: 112°46'44"W - 37°52'36"N

Township: NW 1/4, sec 5, T34S, R8W, Pargonah 7.5' quad, Iron Co., UT

Locality: Near Black Rock Cave, ∿1 km S of Pargonah

Field relations: Morphologically a very young flow

Age: K/Ar 0.44 ± 0.04 my (Fleck et al., 1975)

Reference: Geologic Map of Southwestern Utah (Hintz, 1963)

Minerals:

10%	Olivine, pheno and μpheno, 0.1-1 mm, euh-subh, no alteration, B-, 2V∿75
10%	Augite, μpheno, subh-anh, 200 μ, pale green color, B+, 2V∿50
60%	Plagioclase, grdmass, usually lath-like, euh-anh, 20-200 μ
10%	Oxides, grdmass, blocky, subh, 20 μ
10%	Clinopyroxene?, grdmass, subh, 20 μ
Tr	Biotite, grdmass, subh, 40 μ, brown pleochroism

Texture: Unvesicular. Intergranular. Plagioclase laths are subparallel to one another throughout the thin section; nonetheless, the texture is really not trachytic.

Comment: This rock is so feldspar rich that it is close to being an andesite. However, it has been labelled a feldspathic basalt.

N6034

Name: Feldspathic tholeiite

Megascopic description: Lt gray, aphanitic, unvesicular. Contains olivine and plagioclase microphenocrysts.

Coordinates: 115°05'36"W - 37°47'21"W

Township: SW 1/4, White River Narrows 7.5' quad, Lincoln Co., NV

Locality: SE part of mesa lying to the W side of White River, 17 mi N of Hiko on Nevada 38

Age: Pliocene (?)

Reference: Tschanz and Pampeyan (1970)

Minerals:

5%	Olivine, μpheno, anh, <1 mm, largely converted to iddingsite, extensively embayed, usually surrounded by a clinopyroxene rich zone (a corona)
45%	Plagioclase, μpheno and grdmass, subh-anh, ≤800 μ, zoned
10%	Oxides, grdmass, blocky, 50 μ
20%	Clinopyroxene, grdmass, ≤200 μ, granular, pale green color
5%	Orthopyroxene (?), grdmass, subh, 40 μ, parallel extinction, low birefringence
10%	Glass, interstitial, pale brown color

Texture: Intersertal. Large feldspars have a fairly consistent orientation throughout the thin section.

Comment: The reaction rims associated with olivine crystals and the orthopyroxene in the grdmass indicate that this rock has tholeiitic affinities. The abundance of plagioclase suggests that the term feldspathic basalt should be applied.

N6035

Name: Andesite

Megascopic description: A very dark gray volcanic rock containing abundant pyroxene phenocrysts. The groundmass gives a concoidal fracture, suggesting that it is glassy.

Coordinates: 115°53'04 W - 37°43'44"N

Township: E central part, sec 34, R54E, T2S, White Blotch Springs 15' quad, Lincoln Co., NV

Locality: Approximately 1 mi W of Lincoln Co. line, and 1 mi N of Nevada 25, and approximately 50 mi W of the junction of Nevada 25 with U.S. 93. From the SE side of a large hill in the Benoyer Valley

Age: Pliocene (?)

Reference: Tschanz and Pampeyan (1970)

Minerals:

5%	Hypersthene, pheno, subh-anh, 0.8 mm, pink-green pleochroism, parallel extinction, B-, 2V∿60
5%	Augite, pheno, anh, 1 mm, B+, 2V∿60, pale green, often found in glomerporphyritic aggregates with orthopyroxene
20%	Plagioclase, pheno and μpheno, larger grains are a and equant, while smaller grains are more euh and lath-like, 0.2-3 mm, some larger crystals have wormy interiors, zoned, twinned, An68
20%	Plagioclase, grdmass, subh laths and microlites, 30 μ
15%	Pyroxene, grdmass, subh, 30 μ
5%	Oxides, grdmass, subh, blocky, 10-200 μ
30%	Glass, clear color, largely devitrified, contains abundant microlites

Texture: Hyalophitic, even though much of the glass has devitrified.

Comment: The texture and mineralogy of this rock are typical of andesites.

N6036

Name: Feldspathic basalt

Megascopic description: A shiny , med gray rock containing microphenocrysts of olivine and plagioclase. Essentially unvesicular but does contain vesicles up to 1 cm in size

Coordinates: 118°03'08"W - 37°59'57"N

Township: Sec 26 (unsurveyed), R35E, T2N, Davis Mountain 15' quad, Esmeralda Co., NV

Locality: Approximately 1 mi S of U.S. 6, on the NW side of the Volcanic Hills

Age: Pliocene or Pleistocene. Ages on similar rocks in the same general area are around 5 my by K/Ar methods.

Reference: Albers and Stewart (1972)

Minerals:

2%	Olivine, pheno, euh-subh, rounded, 1 mm
Tr	Augite, pheno, subh, 0.8 mm, lt green color
55%	Plagioclase, grdmass, space-filling anh shapes to euh laths, An55
15%	Olivine, grdmass, subh, 100 μ, clear color, iddingsite on edges
15%	Clinopyroxene, grdmass, subh, 30 μ
12%	Oxides, grdmass, blocky, skeletal, and elongate, anh, 50 μ
4%	Glass, grdmass, interstitial, 30 μ, brown color, spotty texture
1%	Apatite, grdmass, acicular, 50 μ in length
1%	Vesicles, round, 1 mm

Texture: Basically an intergranular texture dominated by plagioclase crystals, which alternately surround and include mafic phases. Plagioclase grains are not especially lath-like in this rock and exhibit no consistent orientation.

Comment: Petrographically this is a feldspathic basalt. Petrologic and chemical work on volcanics from nearby areas would suggest that this basalt is potassic and might easily be a trachybasalt (Robinson, 1972). Leeman (1970) reported a ^{87}Sr/^{86}Sr ratio of .7061 on a trachybasalt from a nearby locality.

N6040

Name: Feldspathic basalt

Megascopic description: A med gray basalt. Essentially aphyric but rare olivine microphenocrysts and a sparkly appearance which bespeaks plagioclase microphenocrysts.

Coordinates: 116°30'33"W - 36°40'47"N

Township: NW 1/4, sec 1 (unsurveyed), R48E, T15S, Big Dune 15' quad, Nye Co., NV

Locality: Front of a flow deriving from a cinder cone, ∿6 mi NW of Lathrop Wells on U.S. 95

Field relations: Morphologically, a very fresh flow

Age: K/Ar 2.0 ± 0.6 my (P. Orkild, quoted by Marvin *et al.*, 1973)

Reference: Cornwall (1972)

Minerals:

3%	Olivine, pheno, subh, rounded, 0.6 mm, minute oxide inclusions
15%	Oxides, grdmass, subh-anh, $\leq 50\ \mu$
45%	Plagioclase, grdmass, subh laths and anh, 20-400 μ, An55
10%	Olivine, grdmass, subh, 80 μ
15%	Clinopyroxene, grdmass, subh, 30 μ
5%	Glass, interstitial, 30 μ
7%	Vesicles, rounded, 1 mm

Texture: Fine grained. Plagioclase laths are oriented subparallel to one another but this is not quite a pilotaxitic texture.

Comment: A feldspar rich basalt. Leeman (1970) called his sample from the same locality a trachy basalt. The ^{87}Sr/^{86}Sr ratio on his rock was .7075.

C6041

Name: Feldspathic basalt

Megascopic description: Med gray, relatively coarse grained, unvesicular. Contains olivine, plagioclase, and pyroxene phenocrysts

Coordinates: 116°16'30"W - 35°58'50"N

Township: SW 1/4, NW 1/4, sec 30, R7E, T22N, Shoshone 15' quad, Inyo Co., CA

Locality: Very near Shoshone Spring, which is on the edge of the Dublin Hills, and ∿1/4 mi N of central Shoshone

Field relations: Volcanics rest on top of poorly consolidated, white colored conglomerate

Age: Pliocene according to State Gelogic map

Reference: Trona Sheet, Geologic Map of California (Jennings *et al.*, 1962)

Minerals:

20%	Plagioclase, pheno, euh-subh laths, 1-4 mm, An58
3%	Olivine, pheno, rounded, very slight iddingsite alteration, 2V∿85°
2%	Augite, pheno, anh, 1 mm, light brown color, B+, 2V∿40, sometimes found in multi-grain aggregates with olivine
10%	Olivine, grdmass, subh, 100-200 μ
20%	Augite, grdmass, subh-anh, 50-100 μ
25%	Plagioclase, grdmass, euh-subh, laths, 100-400 μ in length
10%	Oxides, grdmass, anh, 10-100 μ
10%	Glass, interstitial, brown to black in color, spotted appearance
Tr	Apatite, grdmass, acicular, 100 μ in length

Texture: Relatively coarse grained throughout thin section, but still a distinct bimodal distribution in grain sizes. This porphyritic texture indicates a two stage cooling history. The groundmass has an intersertal texture.

Comment: The abundant and large plagioclase phenocrysts would suggest that this is a feldspathic basalt.

A6053

Name: Andesite

Megascopic description: Med gray, aphanitic, unvesicular. Contains abundant plagioclase phenocrysts and less common pyroxene phenocrysts

Coordinates: 111°40'38"W - 35°20'47"N

Township: Central part, sec 29, R7E, T23N, Humphreys Peak 7.5' quad, Coconino Co., AZ

Locality: Summit of Humphreys Peak, San Francisco volcanic field

Field relations: Stratigraphically the uppermost flow on Humphrey's Peak

Age: Pleistocene

Reference: Robinson (1913), Wolfe et al. (in preparation)

Minerals:

3%	Augite, pheno, subh-anh, 1 mm, pale brown color, B+, 2V∼60
2%	Hypersthene, pheno, subh-anh, light green to light brown pleochroism
15%	Plagioclase, pheno, subh-anh, stubby laths, An68
2%	Olivine, μpheno, euh-subh, 100-400 μ, clear color, unaltered
15%	Oxides, μpheno and grdmass, subh-anh, blocky, 10-400 μ
50%	Plagioclase, grdmass, subh-anh, lath-like and irregular in shape, 100 μ
10%	Pyroxene, grdmass, anh-subh microlites, 20 μ
3%	Glass, interstital, 20 μ, light brown color, spotted
Tr	Apatite, grdmass, acicular, 30 μ in length

Texture: Felted. Porphyritic. Basically intergranular.

Comment: This rock is similar to what one would expect if olivine and some clinopyroxene were settled from a high alumina basalt from the San Francisco volcanic field.

A6054

Name: Dacite

Megascopic description: A porphyritic black and white rock. Contains abundant, large (2 mm) plagioclase phenocrysts, and smaller, less abundant pyroxene phenocrysts in a black matrix

Coordinates: 111°40'31"W - 35°20'46"N

Township: S central portion, sec 29, R7E, T23N, Humphreys Peak 7.5' quad, Coconino Co., AZ

Locality: E side of Humphreys Peak, near the 12,400 foot contour

Field relations: Sample from the upper part of the massive dacite flow underlying the andesite of the Humphreys Peak summit

Reference: Robinson (1913)

Minerals:

15%	Plagioclase, pheno, subh-anh, 1-2 mm, zoned, polysynthetic twinning, some embayment and reaction with matrix material, occasionally found in glomeroporphyritic aggregrates
5%	Hypersthene, pheno and μpheno, subh-anh, 0.2-1.5 mm, B-, 2V∿70, pink-green pleochroism, sometimes found in glomeroporphyritic aggregates with plagioclase, B-, 2V∿70
1%	Augite, μpheno, anh, 0.5 mm, green color, B+
2%	Oxides, μpheno, anh, blocky, 100-200 μ, often associated with pyroxene
50%	Glass, off-white color, largely devitrified - contains abundant microlites
15%	Plagioclase, microlites, 50 μ in length
10%	Oxides, microlites, ≤50 μ
5%	Pyroxene (?), microlites, 20 μ
1%	Vesicles, very irregular in shape, 0.2-2 mm

Texture: Hyalophitic and glomeroporphyritic

Comment: The characteristics of this rock are those of a dacite or andesite.

A6058

Name: Feldspathic basalt

Megascopic description: Lt brown color, unvesicular. Common plagioclase phenocrysts, less abundant mafic phenocrysts

Coordinates: 111°40'48"W - 35°20'04"N

Township: W central portion, sec 35, R7E, T23N, Humphreys Peak 7.5' quad, Coconino Co., AZ

Locality: 11,820 foot contour, near lowest point in the saddle between Humphreys Peak and Agassiz Peak

Field relations: Associated with the "Core Ridge" feeder system for the San Francisco stratovolcano, stratigraphically low in the volcanic pile

Age: Pleistocene

Reference: Robinson (1913), Wolfe *et al*. (in preparation)

Minerals:

15%	Plagioclase, pheno, subh, lath-like and equant, some embayment, An62
2%	Olivine, µpheno, subh, 100-400 µ, iddingsite rims
10%	Olivine (?), grdmass, anh, 10 µ, reddish color due to oxidation
10%	Pyroxene (?), grdmass, anh, embedded in a plagioclase-glass matrix
10%	Oxides, grdmass, blocky, 10 µ, embedded in a plagioclase-glass matrix
35%	Plagioclase, grdmass, irregularly shaped wedges and laths, ≤70 µ
10%	Glass, brown color, largely devitrified

Texture: Variable concentrations of oxide relative to plagioclase give this rock a streaked appearance. Under low power the thin section has a texture quite reminiscent of a hyalophitic andesite.

Comment: Petrographically this rock is similar to many andesites. However, an unpublished chemical analysis (Wolfe and Moore, written communication) indicates that it is a feldspathic basalt.

A6060

Name: Olivine basalt

Megascopic description: A med gray, somewhat vesicular basalt, which contains olivine phenocrysts and rare plagioclase phenocrysts

Coordinates: 109°21'22"W - 34°15'13"N

Township: NW 1/4, sec 23, T10N, R28E, Lyman Lake 7.5' quad, Apache Co., AZ

Locality: Just W of U.S. 180-666, 9 mi N of Springerville and 5 mi S of Lyman Lake

Field relations: From a squeeze-up in a morphologically very fresh flow

Age: Holocene?

Reference: Geologic Map of Arizona (Wilson *et al*., 1969)

Minerals:

1%	Augite, pheno, euh but rounded, 2 mm, pale brown color, B+, 2V∿60
15%	Olivine, pheno and μpheno, subh-euh, 0.1-1 mm
35%	Plagioclase, μpheno and grdmass, euh laths and anh, 20-500 μ
25%	Pyroxene and olivine, grdmass, elongate-equant microlites, 30 μ
20%	Oxides, grdmass, blocky, 20 μ
5%	Vesicles, round, 200 μ
Tr	Glass (?)

Texture: A very fine grained groundmass.

Comment: Although the fine grained groundmass is difficult to deal with, I would tentatively classify this as an olivine augite basalt.

A6062

Name: Olivine-augite diabase

Megascopic description: A lt gray volcanic rock distinguished by its dikytaxitic texture. Hand specimen contains brownish (iddingsitized) olivine phenocrysts and microphenocrysts of plagioclase

Coordinates: 110°09'11"W - 34°06'22"N

Township: Central N 1/2, sec 7, T8N, R21E (unsurveyed), Showlow 15' quad, Navajo Co., AZ

Locality: Intersection of Corduroy Creek and U.S. 60, W side of bridge, near BM5856

Field relations: Flow in the Corduroy Creek drainage

Age: K/Ar 11.8 ± 0.6 my (McKee and McKee, 1972)

Reference: McKay (1972), Shakel (1976)

Minerals:

10%	Vesicles, angular in shape, 0.3-0.8 mm, bounded by crystal faces, some plagioclase laths actually extend into voids
15%	Olivine, subh-anh, 0.1-3 mm, partially altered to iddingsite, no reaction rims
28%	Augite, anh, 0.5 mm, interstitial to plagioclase, but commonly partially enclosing or including plagioclase laths, lt brown color with a slight purple (?) tint, B+, 2V∿50
35%	Plagioclase, lath-like, subh, ≤2 mm long, An64
2%	Glass, 100 μ, devitrified cryptocrystalline material in angular well-defined intertices
10%	Oxides, blocky to interstitial, 100 μ
Tr	Clay, found lining some vesicles

Texture: Uniformly coarse grained. Dikytaxitic. Locally ophitic.

Comment: This is a diabase which should probably be classified in the olivine augite basalt category.

A6063

Name: Olivine basalt

Megascopic description: A dark gray, unvesicular, aphanitic volcanic rock containing olivine phenocrysts $\leq$1 mm in size

Coordinates: 111°27'51"W - 33°55'41"N

Township: Eastern part, N boundary, sec 30, T7N, R9E, Reno Pass 7.5' quad, Maricopa Co., AZ

Locality: SW of Iron Dike and approximately 400 m S of Arizona 87

Field relations: A columnar jointed dike

Age: Late Miocene (?) or Pliocene (?)

Reference: Geologic Map of Arizona (Wilson *et al.*, 1969)

Minerals:

5%	Olivine, pheno and μpheno, euh-anh, 0.1-3 mm, some embayment, minor resorption
1%	Augite, pheno, euh but rounded corners, 2 mm, B+, 2V∼60, unpleochroic, pale brown
35%	Augite, grdmass, euh, elongate, 200 μ, pale brown or green in color
15%	Oxides, grdmass, blocky, 10-70 μ, opaque
5%	Olivine, grdmass, subh, 70 μ, clear
40%	Plagioclase, grdmass, laths, 20-100 μ in length, An56
Tr	Glass, interstitial pockets, 20 μ
Tr	Alteration, ferromagnesium hydrous minerals, anh, 30 μ, associated with cracks

Texture: Fine grained groundmass. Trachytic, intergranular texture

Comment: This rock is somewhat transitional between olivine-augite basalt and feldspathic basalt categories.

A6064

Name: Olivine-augite diabase

Megascopic description: A med gray basalt distinguished by abundant brown, iddingsitized olivine phenocrysts and a network of small, almost microscopic vesicles

Coordinates: 111°24'59"W - 34°19'17"N

Township: SE 1/4, sec 3, T11N, R9E, Pine 15' quad, Gila Co., AZ

Locality: Buckhead Mesa, ∿4 mi S of Pine, AZ on Arizona 87

Field relations: Mesa capping flow

Age: Late Miocene (?) or Pliocene (?)

Reference: Geologic Map of Arizona (Wilson *et al.*, 1969)

Minerals:

10%	Olivine, subh-anh, 0.1-2 mm, in part (and occasionally totally) altered to iddingsite
30%	Augite, anh, poikilitic-ophitic, 0.2-1 mm, pale brown-green-gray color, B+, 2V∿60
10%	Oxides, euh-anh blocks, 100 μ
10%	Glass, interstitial, 100 μ, heavily dusted with oxide microlites
25%	Plagioclase, laths, 0.5 mm, An60
25%	Vesicles, often angular, with crystal faces often defining boundaries, 0.4 mm

Texture: Uniformly coarse grained. Both ophitic and dikytaxitic

Comment: The abundance of olivine and clinopyroxene in this rock relative to plagioclase indicates that this is an olivine-augite diabase.

C7001

Name: Olivine basalt

Megascopic description: A med gray, aphanitic volcanic rock. Contains large (≥1 mm) olivine (largely oxidized) and plagioclase phenocrysts and a few vesicles

Coordinates: 116°24'00"W - 34°10'31"N

Township: NW 1/4, sec 14, T1N, R5E, Joshua Tree 15' quad, San Bernardino Co., CA

Locality: ∿100 m W of Lucerne-Yucca Valley Rd (Calif. 27), 4½ mi N of Yucca Valley

Age: Late Pliocene (?) or Early Pleistocene (?)

Reference: Dibblee (1967)

Minerals:

2%	Olivine, pheno, subh, 0.4-2 mm, slightly to almost totally altered to iddingsite and opaque oxides
3%	Plagioclase, pheno, subh, usually lath-like, 0.5-2 mm, often in aggregates of several crystals
1%	Augite, pheno, subh, 2 mm, pale green-brown color, shiller structure, B+, 2V∿60
10%	Olivine, grdmass, subh-anh, 30-150 μ, almost totally converted to iddingsite
25%	Augite, grdmass, subh, 50 μ, pale green color
15%	Oxides, grdmass, anh, blocky, 50 μ
40%	Plagioclase
2%	Oxides, weathering, red-orange color
1%	CC, weathering, found in vesicles
1%	Vesicles, round 0.8 mm
Tr	Apatite, grdmass, acicular, ≤50 μ in length

Texture: A felted texture. Intergranular

Comment: This rock is transitional between a feldspathic and an olivine-augite basalt.

NM7005

Name: Alkaline-olivine basalt

Megascopic description: A med gray basalt containing small olivine phenocrysts and plagioclase microphenocrysts. Abundant but very small vesicles

Coordinates: 108°17'21"W - 31°55'20"W

Township: N boundary, NE 1/4, sec 32, T27S, R14W, Hachita 15' quad, Grant Co., NM

Locality: SW corner of mesa, ∿2 mi E of Hachita on New Mexico 9

Field relations: Basalt capping a low mesa

Age: Quaternary (?)

Reference: Geologic Map of New Mexico (Dane and Bachman, 1965)

MInerals:

5%	Olivine, μpheno, subh-anh, 0.5 mm, iddingsite rims, some embayment and rounding
35%	Titanaugite, grdmass, anh, ≤30 μ, lt brown color with a purplish tint, often found partially including plagioclase laths, B+, 2V∿60
30%	Plagioclase, grdmass, euh, elongate laths, 400 μ in length, An55
5%	Olivine, grdmass, subh, 50-200 μ, partially oxidized
15%	Oxides, grdmass, subh-anh, blocky to elongate, 50 μ
5%	Glass, interstitial, 30 μ, brownish color, spotted appearance
5%	Vesicles, irregular in shape, ≤300 μ in size

Texture: Abundant, small vesicles give this rock almost a dikytaxitic texture. Ophitic and intersertal textures are also present.

Comment: Obviously, an alkaline and mafic rock. It might be either an alkaline-olivine basalt or a basanitoid.

NM7007

Name: Alkaline-olivine basalt

Megascopic description: A med gray, basically unvesicular basalt containing fresh olivine phenocrysts. The sparkly appearance of this rock in the sunlight suggests that plagioclase microphenocrysts are present. This sample contains rare, centimeter sized, coarse grained inclusions of gabbroic character.

Coordinates: 107°59'27"W - 32°55'11"N

Township: NW 1/4, sec 16, T16S, R11W, San Lorenzo 15' quad, Grant Co., NM

Locality: Mesa on NW side of East Canyon, E of Rio Mimbres Cafe, and ∿4½ mi N of Mimbres

Field relations: Basalt capping a deeply dissected mesa. Stratigraphically near the top of the Gila Conglomerate

Age: K/Ar 6.29 ± 0.41 my (Elston *et al.*, 1973)

Reference: Elston *et al.* (1973), Elston *et al.* (1976), Fodor (1978)

Minerals:

3%	Olivine, pheno, subh, rounded corners, ≤3 mm, very thin iddingsite rims
1%	Augite, pheno, anh, 0.5-1 mm, green cores and purple rims, probably derive from mafic inclusion
15%	Olivine, grdmass, subh, 100-200 μ, slight oxidation, no reaction rims
30%	Titanaugite, grdmass, anh, purplish-brown color
10%	Oxides, grdmass, anh, 50-100 μ
30%	Plagioclase, grdmass, long laths, 500 μ in length, An54
10%	Vesicles, irregular in shape, ≥100 μ
1%	Glass, interstitial, 30 μ, pale brown in color, spotted texture

Texture: Almost ophitic in some local areas

Comment: This rock has the petrographic characteristics of an alkaline olivine basalt or a basanitoid. A chemical analysis by Fodor (1978) supports this conclusion.

Inclusion: A large inclusion in this rock is made up of 1-3 mm sized, anhedral grains of hypersthene, clinopyroxene, and plagioclase. It also contains smaller, less abundant oxide crystals and some reddish oxidation along grain boundaries.

NM7008

Name: Olivine basalt

Megascopic description: A black basaltic rock with rather small (≤1 mm) phenocrysts of olivine and plagioclase. It contains infrequent but large (≤1 cm) vesicles.

Coordinates: 107°30'08"W - 32°58'48"N

Township: NW 1/4, sec 30, R7W, T15S, Hillsboro 15' quad, Sierra Co., NM

Locality: Flow on SW side of volcano, 2 mi N of New Mexico 180, 5 mi E of Hillsboro

Age: Quaternary (?)

Reference: Geologic Map of New Mexico (Dane and Bachman, 1965)

Minerals:

5%	Olivine, pheno, subh, rounded, ≤1 mm, iddingsite rims
20%	Plagioclase, µpheno, laths, 500 µ long, An58
20%	Plagioclase, grdmass, laths and microlites, An45
30%	Oxides, grdmass, blocky, 50 µ
20%	Olivine, grdmass, anh, 50 µ, partially oxidized
10%	Clinpyroxene, grdmass, anh, 20 µ
Tr	Glass, interstitial
1%	Vesicles, elongate but rounded, 1 cm in length
Tr	Calcite, weatherings, lines the borders of some vesicles

Texture: Intergranular but fine grained

Comment: The most notable thing about this rock is its abundant concentration of oxides. There is little to suggest either an alkaline or tholeiitic nature.

NM7009

Name: Basanitoid

Megascopic description: A med gray, aphanitic volcanic rock with phenocrysts of olivine and microphenocrysts of plagioclase. Contains quartz xenoliths. Apparently unvesicular but small, nearly microscopic voids are present.

Coordinates: 106°52'26"W - 33°31'08"N

Township: Unsurveyed township, Val Verde 15' quad, Socorro Co., NM

Locality: Bat caves, ~1 mi SW of volcano, Jornada del Muerto volcanic field

Field relations: Sample from a collapsed lava tube

Age: Quaternary

Reference: Geologic Map of New Mexico (Dane and Bachman, 1965), Weber (1963)

Minerals:

5%	Olivine, pheno, subh, ≤4 mm in size, completely fresh
35%	Plagioclase, μpheno, elongate laths, 0.1-1.5 mm long, An54
20%	Titanaugite, grdmass, anh, 50-300 μ, interstitial to but sometimes partially including plagioclase laths, pronounced purple tint
15%	Olivine, grdmass, subh-anh, 100 μ, no reaction rims
10%	Oxides, grdmass, anh, blocky to skeletal
3%	Glass, interstitial, ≤70 μ, contains abundant micolites
12%	Vesicles, irregular in shape, 200 μ
1%	Quartz, xenocryst, 3 mm inclusion composed of anh, 0.8 mm sized quartz crystals, rimmed by a clinopyroxene-glass reaction rim, conspicuously embayed

Texture: Plagioclase laths are oriented randomly in the thin section Interstitial to these are glass, oxide, and titanaugite. Vesicles are small and irregular in shape but a little too large relative to groundmass grains to be interstitial. Thus the texture is not quite dikytaxitic.

Comment: Petrographically, this rock is nearly identical to other Quaternary alkaline basalts from the southwestern United States. The occurrence of large monomineralic quartz megacrysts is extraordinary and not easily explained.

NM7010

Name: Basanitoid

Megascopic description: A med gray basalt. About 20% vesicles, ranging in size from 1 cm to microscopic, which give the rock a dikytaxitic appearance. Olivine and plagioclase phenocrysts are abundant but small.

Coordinates: 106°54'21"W - 33°30'26"N

Township: Unsurveyed township, Pedro Armenda Grant, Val Verde 15' quad, Socorro Co., NM

Locality: Prominent S facing flow front, abutting a large closed depression, ∿½ mi E of Hackberry Well on dirt road

Field relations: Morphologically this is a very fresh (Holocene?) flow

Age: Quaternary

Reference: Geologic Map of New Mexico (Dane and Bachman, 1965), Weber (1963)

Minerals:

2%	Olivine, pheno, euh-subh, 0.5-1.5 mm
Tr	Plagioclase, pheno, ahn, equant, 1.5 mm, wormy cores
35%	Plagioclase, μpheno and grdmass, laths, 0.2-1 mm long, twinned, An59
15%	Olivine, grdmass, subh, 70-400 μ, no reaction rims
25%	Titanaugite, grdmass, anh and usually interstitial, purplish tint
7%	Oxides, grdmass, skeletal and interstitial, anh, 70 μ
3%	Glass, interstitial, 30 μ
13%	Vesicles, round holes, 2 mm in size; and irregular shaped voids, 200-400 μ in size

Texture: Large, randomly oriented plagioclase laths dominate the groundmass texture. Interstitial to these are pyroxene, oxides, glass, and vesicles (dikytaxitic texture).

Comment: Like rocks from the Potrillo volcanic field to the south, this is an alkali olivine basalt or a basanitoid. The occurrence of wormy plagioclase megacrysts in this rock is unusual; sieve-textured plagioclase is normally found in basaltic andesites, which tend to be silica rich.

NM7011

Name: Tholeiitic basalt

Megascopic description: A med gray basalt. Contains 5-10% 1 mm-sized vesicles and more, nearly microscopic holes. Abundant but usually small olivine and plagioclase phenocrysts.

Coordinates: 105°54'51"W - 33°41'03"N

Township: NW 1/4, SW 1/4, sec 21, R10E, T10S, Carrizozo 15' quad, Lincoln Co., NM

Locality: Collapse depression N of U.S. 380 from Valley of Fire State Park, ∿6 km NE of Carrizozo

Field relations: Morphologically a very young flow

Age: Recent

Reference: Geologic Map of New Mexico (Dane and Bachman, 1965), Weber (1964)

Minerals:

3%	Olivine, pheno and μpheno, euh-subh, 0.5-2 mm, 2V∿85
7%	Olivine, grdmass, subh, 100 μ, no reaction rims
30%	Plagioclase, μpheno and grdmass, elongate laths, 100-500 μ, An58
40%	Glass/oxides, interstitial, 100 μ, nearly black because of oxide dust
20%	Vesicles, round holes 1 mm in size, and irregular shaped voids, 150 μ in size

Texture: Intersertal and dikytaxitic

Comment: The abundance of glass in this rock prohibits an accurate petrological classification. However, chemical analyses on the Carrizozo basalt (Renault, 1970; and Weber, 1964) indicate that it is tholeiitic in composition.

Additional note: Leeman (1970) reported a $^{87}Sr/^{86}Sr$ ratio of .7053 for a sample from the Carrizozo flow.

NM7012

Name: Basalt

Megascopic description: A med gray volcanic rock characterized by abundant, mm-sized plagioclase phenocrysts and smaller, less common olivine phenocrysts. Contains some megascopic vesicles.

Coordinates: 106°42'39"W - 35°08'24"N

Township: SE 1/4, NE 1/4, sec 34, T11N, R2E, Los Griegos 7.5' quad, Bernallilo Co., NM

Locality: Highest point at tip of a promontory cliffs W of Albuquerque

Age: K/Ar 0.19 ± 0.04 my (Bachman et al., 1975)

Reference: Geologic Map of New Mexico (Dane and Bachman, 1965)

Minerals:

10%	Plagioclase, pheno, subh, lath-like, 1-3 mm, occasionally in glomeroporphyritic aggregates, An72
5%	Olivine, μpheno, subh, 200-700 μ, very slight iddingsite alteration
10%	Olivine, grdmass, anh-subh, 100 μ, thin iddingsite rims, no apparent reaction
20%	Clinopyroxene, grdmass, anh, 100 μ, very pale brown, B+, 2V∿50-60
25%	Plagioclase, grdmass, lath-like, 100 μ long, An54
15%	Vesicles, mostly small (200 μ) and irregular in shape
5%	Oxides, grdmass, anh, 70 μ
10%	Glass, interstitial, almost opaque because of oxide dust

Texture: Approaching a dikytaxitic texture. Intersertal, intergranular, and ophitic textures are found locally. Plagioclase laths are oriented randomly.

Comment: Plagioclase phenocrysts usually occur in rocks containing abundant groundmass plagioclase. Both characteristics have been used to distinguish feldspathic basalts (high alumina basalts, and hawaiites) from more mafic rocks. This sample has plagioclase phenocrysts but a rather plagioclase-poor groundmass. It is not easily fit in the Chapter 5 classification scheme.

NM7013

Name: Andesite

Megascopic description: A lt gray, aphanitic, aphyric, unvesicular volcanic rock. Contains various inclusions, including some of gabbroic texture.

Coordinates: 106°47'04"N - 34°47'06"W

Township: Unsurveyed township, San Clemente Grant, Dalies 7.5' quad, Valencia Co., NM

Locality: Tip of SE lobe, Cerro de Los Lunas, ∿0.6 mi E of I-25

Age: K/Ar 1.12 ± 0.04 my (Bachman et al., 1975)

Reference: Geologic Map of New Mexico (Dane and Bachman, 1965)

Minerals:

1%	Hypersthene, μpheno, subh, ≤0.8 mm, pink-green pleochroism, B-, 2V∿50
Tr	Olivine, grdmass, anh, 100-300 μ, partial resorption, 2V∿90
Tr	Quartz, megacryst, anh, 1 mm, surrounded by clinopyroxene corona
Tr	Clinopyroxene, μpheno, subh, 0.5 mm, pale green, B+, 2V∿60
Tr	Biotite, "pheno," anh, 0.9 mm, almost completely replaced by opaque oxides
60%	Plagioclase, μpheno-grdmass, lath-like 70-500 μ, An50
5%	Oxides, μpheno, pseudomorphs after biotite, 200-800 μ, opaque
3%	Oxides, grdmass, blocky, 30 μ
7%	Hypersthene and clinopyroxene, grdmass, anh, 100 μ
17%	Vesicles, amoeboid in shape, 200 μ
2%	Ghosts, granular regionals characterized by minute oxide and pyroxene (?) grains
5%	Glass, crptocrystalline material interstitial to feldspar laths

Texture: Pilotaxitic texture. The abundance of microscopic vesicles in this rock is notable.

Comment: The abundance of plagioclase, the texture, the occurrence of biotite and hypersthene all indicate that this rock is an andesite.

Inclusion: A gabbroic inclusion in this rock is approximately 6 mm in size. It contains anhedral grains of hypersthene, clinopyroxene, plagioclase, biotite, and oxides. Disaggregation of similar inclusions could give rise to the "phenocryst" phases observed in the rest of the rock.

NM7014

Name: Alkaline-olivine basalt

Megascopic description: Dark gray basalt containing abundant, fresh olivine phenocrysts. About 10% vesicles

Coordinates: 106°50'43"W - 34°49'27"N

Township: Sec 21, T7N, R1E (unsurveyed), San Clemente Grant, Dalies 7.5' quad, Valencia Co., NM

Locality: Front of flow, E of Sandia (site) and ∿700 m N of New Mexico 6, ∿5½ mi E of Los Lunas

Field relations: Morphologically a very youthful flow

Age: Quaternary

Reference: Bachman *et al*. (1975)

Minerals:

2%	Olivine, pheno, subh, 1.5 mm, some embayment, 2V~85, include oxides
1%	Plagioclase, pheno, euh, elongate laths, ≤1 mm, zoned, twinned, An66
30%	Plagioclase, μpheno-grdmass, laths, 100-400 μ, An66
8%	Olivine, grdmass, subh, 70 μ, very slight oxidation, no reaction rims
25%	Titanaugite, grdmass, anh, interstitial to plagioclase, 70 μ, purple-brown color
15%	Oxides, grdmass, anh, interstitial, commonly acicular, 70 μ in length
10%	Glass, interstitial, brown color, spotty texture, sometimes lining larger vesicles
10%	Vesicles, irregular shape, 200 μ

Texture: Intersertal. Locally dikytaxitic. Plagioclase laths randomly oriented.

Comment: The titanaugite in this rock would indicate that it is an alkaline olivine basalt.

NM7015

Name: Basaltic andesite?

Megascopic description: A med gray basalt containing a few small (≤ 1 mm) olivine phenocrysts. Megascopically, this rock is unvesicular, containing only a few mm sized vesicles. However, there are numerous near microscopic voids in this rock, hinting at a dikytaxitic texture.

Coordinates: 108°37'02"W - 33°49'29"N

Township: SE 1/4, NE 1/4, sec 33, T5S, R17W, Squirrel Springs Canyon 7.5' quad, Catron Co., NM

Locality: S side of mesa, S of New Mexico 12 at Apache Creek

Age: K/Ar 0.9 ± 0.2 my (Bikerman, 1972)

Reference: Elston *et al.* (1976)

Minerals:

1%	Olivine, pheno, anh, 1 mm, unoxidized, 2V∼85
10%	Olivine, μpheno, euh-subh, 200 μ, very slight iddingsite alteration
Tr	Plagioclase, pheno, rounded, 2 mm, wormy texture
35%	Clinopyroxene, grdmass, anh, 100-400 μ, brownish color, occasionally include plagioclase laths
10%	Vesicles, irregular in shape, 0.1-0.8 mm in size, not quite interstitial
30%	Plagioclase, grdmass, euh-subh, elongate and equant laths, 200 μ in length, An59
5%	Oxides, grdmass, discrete, angular grains, 30-100 μ
10%	Glass, interstitial, 20 μ, pale brown color spotted texture

Texture: Somewhat coarse grained. Locally ophitic and dikytaxitic. Intersertal.

Comment: The presence of wormy plagioclase is one of the characteristics used to identify basaltic andesites. However, this rock is quite rich in mafics and the term may not be appropriate.

C7021

Name: Andesite

Megascopic description: Black, unvesicular, aphanitic volcanic rock possessing abundant, mm sized plagioclase laths

Coordinates: 119°35'03"W - 37°01'33"N

Township: SE corner, sec 29, R22E, T10S, Millerton Lake 15' quad, Fresno Co., CA

Locality: Table Mountain, ∿1½ mi NW of Marshal Station

Fields relations: Table Mountain basalt of the San Joaquin

Age: K/Ar 9.5 ± 0.3 my (Dalrymple, 1963)

Reference: Dalrymple (1963); Geologic Map of California, Mariposa Sheet (Strand, 1967)

Minerals:

20%	Plagioclase, subh-anh, often lath-like 1 mm, zoned, embayed, An58
10%	Augite, grdmass, anh, 100 μ, B+, 2V∿40-60
20%	Glass, interstitial, 30 μ, brown to nearly opaque, bubbly texture
35%	Plagioclase, grdmass, subh-anh, equant and lath-like, 50-100 μ, ∿An45
15%	Oxides, grdmass, blocky, 30 μ
Tr	Hydrous minerals, fine grained alteration of interstitial glass

Texture: Intersertal to hyalophitic.

Comment: The abundance of plagioclase, dearth of mafic minerals, and the hyalophitic texture would indicate that this rock is an andesite rather than a basalt.

APPENDIX D: SAMPLE AGE, CHEMISTRY AND ISOTOPE RATIOS

Arguments presented in Chapter 4 suggest that sample age and chemical composition are not the factors most useful in characterizing the major Pb isotopic variations observed in late Cenozoic volcanic rocks from the southwestern United States. This does not mean that sample age and chemistry are unimportant; there are at least two lines of evidence that suggest that isotopic differences between older, calc-alkaline volcanic rocks and younger, often alkaline basalts do indeed exist, and that further work on the older, silicic volcanic rocks would be of substantial scientific value.

For instance, there are suggestions that older, calc-alkaline rocks tend to have higher $^{208}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ ratios than their younger basaltic counterparts. To illustrate this, Table D.1 tabulates data on samples having high $^{208}Pb/^{204}Pb$ ratios ($^{208}Pb/^{204}Pb \geq 39.0$). A disporportionate number (15 or 21) of these high $^{208}Pb/^{204}Pb$ rocks are relatively old and relatively felsic. Inspection of this table also indicates that the majority of these high $^{208}Pb/^{204}Pb$ rocks also have relatively high $^{207}Pb/^{204}Pb$ ratios. Figure 6.2 also shows that older, calc-alkaline volcanic rocks from the Basin and Range province display a tendency for higher $^{207}Pb/^{204}Pb$ ratios. Calc-alkaline rocks from volcanic arcs also exhibit this tendency (Figure 6.1). Understanding the reason for this behavior might help us understand the petrogenesis of the calc-alkaline suite, as well as the Tertiary volcanic and tectonic history of the western United States.

Table D.1: Samples with $^{208}Pb/^{204}Pb \geq 39.0$

No.	Age	Rock Type	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	References*
C3032	Late Pliocene	olivine latite	19.30	15.68	39.21	0
N3023	Middle Miocene	basalt	19.27	15.63	38.95	0
J264	Oligocene	quartz porphyry	19.32	15.70	39.12	1
J272	Oligocene	tuff	19.25	15.67	38.95	1
J254A	Oligocene	rhyolite	19.38	15.76	39.33	1
W302	Miocene	rhyolite	19.30	15.70	39.119	1
N3021	Oligocene	dacite	19.00	15.73	40.03	0
N3018	Oligocene	andesite	19.57	15.69	39.23	0
N6035	Pliocene?	andesite	19.06	15.65	39.02	1
67L204C	Late Miocene	rhyodacite	18.14	15.64	39.25	2
67L204D	Late Miocene	quartz latite	18.19	15.61	39.12	2
67L209-11	Late Miocene	rhyolite	18.07	15.63	39.07	2
67L209-14	Late Miocene	quartz latite	18.37	15.67	39.13	2
C6041	Pliocene?	basaltic andesite	19.04	15.68	39.19	0
Vasquez	Early Miocene?	rhyodacite	19.12	15.65	39.07	2
C5003	Miocene	basalt	19.32	15.66	38.99	2
A6011	Miocene	andesite	18.39	15.54	38.97	0
M3012	Quaternary	basalt	19.46	15.62	39.13	0
NM4044	Quaternary	basalt	19.61	15.58	39.31	0

Table D.1 (continued)

No.	Age	Rock Type	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	References*
NM7008	Quaternary	basalt	19.55	15.57	39.14	0
NM7010	Quaternary	basalt	19.500	15.63	39.05	0

*References: 0 = this work; 1 = Rye, Doe, and Wells (1974); 2 = Doe and Delevaux (1973).

Strontium isotopic studies also seem to argue for a connection between sample age, chemical composition, and isotopic attributes. For example, Scott et al. (1969) have concluded that "Cenozoic volcanism in the Great Basin is characterized by outward migration of volcanic centers from a centrally located core region, and a gradational decrease in the initial Sr^{87}/Sr^{86} ratio with decreasing age and increasing distance from the core, a progressive change from calc-alkalic core rocks to more alkalic basin margin rocks." In detail this conclusion does not appear to be completely true, for there are basaltic rocks with young ages and high $^{87}Sr/^{86}Sr$ ratios outside the Scott et al. (1969) core region (Hedge and Noble, 1971). However, in a general way this phenomenon of older rocks having calc-alkaline chemistries and high $^{87}Sr/^{86}Sr$ seems to extend beyond the limits of the great Basin. Bikerman and Damon (1966), for instance, have found that basaltic andesite to tuffaceous volcanic rocks, ranging from 14-70 my in age, in the Roskruge Mountains of south-central Arizona have very radiogenic $^{87}Sr/^{86}Sr$ ratios ($>$.707) while a late Pliocene basalt from the same area has a $^{87}Sr/^{86}Sr = .7038$. Strontium data on the Mogollon-Datil volcanic province of southwestern New Mexico also seem to indicate a correspondence between sample age, composition, and initial strontium ratio (see Bikerman, 1976; Elston, 1976). Basaltic andesites, andesites, quartz latites, and rhyolites from the Mogollon-Datil region, which are between 20 and 40 my in age, have $^{87}Sr/^{86}Sr$ ratios between .706 and .730. Younger ($\leq$15 my) basalts from the same area appear to have $^{87}Sr/^{86}Sr$ ratios between .703 and .704. It may also be noted that lead and strontium data from the San Juan volcanic field of Colorado may exhibit time-dependent isotopic variations (Lipman *et al.*, 1978). Lead, for example, appears to be relatively unradiogenic in the earliest, andesitic volcanics, rather more radiogenic in the tuffaceous rocks of intermediate age, and again less radiogenic in the late stage basalts from the volcanic field. These data suggest that it would be fruitful to deal in more detail with the isotopic properties of older calc-alkaline volcanic rocks from the southwestern United States. Unfortunately, this report was not able to give sufficient attention to this problem.

APPENDIX E: CHEMICAL ANALYSES AND NORMS

Table E.1a: Olivine-augite basalts from the Southwestern Colorado Plateau

Sample	A6021	A6031	A6063	A6060	A4027	A6062	A6023	A4029	A6064
Chemical Analyses									
SiO_2	44.6	44.72	45.89	45.98	46.1	47.40	48.2	50.0	50.39
TiO_2	2.34	1.94	2.16	2.39	1.3	1.53	1.91	1.27	1.03
Al_2O_3	14.8	11.87	15.95	15.06	14.2	14.56	14.4	15.6	14.52
Fe_2O_3	2.97		5.39	1.71	8.9	4.99	3.77	2.1	5.47
FeO	8.38	10.12	6.05	9.39	2.0	6.63	7.38	8.91	5.87
MnO	.20		.19	.22		.23	.19	.20	.21
MgO	9.23	12.97	6.18	8.97	6.3	7.83	8.7	9.0	7.06
CaO	11.59	12.17	10.30	9.81	12.7	9.86	10.3	9.6	9.36
Na_2O	3.59	2.42	3.07	3.17	2.7	3.16	3.3	2.9	2.74
K_2O	1.10	1.23	1.50	1.17	.67	.79	.8	.5	1.36
P_2O_5	.58	.67	1.20	.62		.35	.44	.22	.89
H_2O^+	.26		.74	.29	.59	.75	.20	.16	.62
H_2O^-	.28		16	.30	.41	2.08	.06	.27	.37
CO_2	.44				3.3		<.06	<.05	
Total	100.36	98.11	99.78	99.08	99.19	100.25	99.58	100.73	99.89
Barth Niggli Cation Norms[1]									
Q									
Or	6.48	7.31	9.14	6.98	4.30	4.80	4.75	2.94	8.23
Ab	9.99	4.26	24.33	20.79	19.93	28.28	27.06	25.87	25.20
An	20.98	18.02	26.12	23.66	25.93	24.14	22.22	27.90	23.89
Ne	13.30	10.57	2.46	4.78	3.37	.53	1.62		
Cpx	26.08	34.21	15.02	17.13	30.58	19.06	20.97	14.39	16.97
Opx								13.16	16.08
Ol	16.36	20.73	14.93	20.10	11.05	17.79	17.50	11.35	5.01
Mt	2.35	2.17	2.40	1.81	2.20	2.44	2.29	2.18	2.36
Il	3.25	2.72	3.10	3.36	1.91	2.19	2.67	1.76	1.47
Ap	1.21		2.50	1.31	.73	.75	.92	.46	.79
Plag. An.	67.7	89.9	51.8	53.2	56.5	46.0	45.1	46.5	48.7
Ref.[2]	3	4	6	6	2	6	3	3	6
Ref. No.	NM213	grn-8			PA3		NM801c	NM545	
Area[3]	SF	St. G.	T	WM	T	WM	SF	SF	T
Name[4]	Bas.	Ank	AOB	AOB	AOB	AOB	AOB	OT	OT

Table E.1b: Feldspathic basalts of the Southwestern Colorado Plateau

Sample	A4031	A6014	A6022	A6030	U5017	A6058	A6025	U6032	A4028
Chemical Analyses									
SiO_2	47.42	50.05	50.5	50.5	50.71	52.8	53.8	53.45	53.8
TiO_2	2.40	2.13	1.64	1.85	2.05	1.56	1.6	1.64	1.5
Al_2O_3	16.94	15.04	18.3	15.0	16.75	18.7	15.8	14.25	15.0
Fe_2O_3	4.98	2.51	3.0		3.89	1.8	3.0	3.17	3.55
FeO	6.93	6.41	6.66	11.25	5.67	7.3	6.6	5.20	6.9
MnO	.18	.19	.17		.21	.14	.10	.23	.24
MgO	5.99	6.75	5.1	7.35	6.99	3.9	6.7	7.24	6.6
CaO	8.71	9.14	8.1	8.15	7.72	8.1	8.4	8.00	8.2
Na_2O	3.64	3.75	3.9	4.10	4.19	4.2	3.1	3.62	2.85
K_2O	1.13	2.03	1.3	1.32	1.46	1.4	1.4	1.96	.62
P_2O_5	.52	.29	.58		.25	.27	.47	.32	.09
H_2O^+	.52	.58	.41		.32		.64	.41	.61
H_2O^-	.31	.65	.19		.65		.28	.63	.23
CO_2	.11		<.05			.02	.04		<.05
Total	99.78	99.52	99.85	99.52	100.86	100.17	100.93	100.12	100.73
Barth-Niggli Norm[1]									
Q							1.03		5.16
Or	6.79	12.13	7.73	7.75	8.54	7.86	8.29	11.60	3.72
Ab	31.05	28.17	35.25	32.81	37.18	36.71	27.90	32.55	26.00
An	27.03	18.43	28.79	18.60	22.37	17.36	25.13	16.88	26.74
Ne	1.33	3.53		2.33	.04	1.33			
Cpx	10.80	20.42	6.28	17.38	9.08	10.80	10.85	15.00	11.20
Opx			6.96				21.59	15.70	22.68
Ol	16.01	11.83	9.46	16.17	16.69	16.01		2.96	
Mt	2.48	1.87	2.01	2.39	2.71	2.48	1.99	1.72	2.19
Il	3.40	3.00	2.30	2.57	3.89	3.40	2.23	2.29	2.12
Ap	1.11	.61	1.22		1.56	1.11	.99	1.32	.19
Plag. An.	46.5	39.5	45.0	36.2	48.3	46.5	47.4	34.1	50.7
Ref.[2]	3	6	3	4	6	3	2	6	2
Ref. No.	Avg of 8		MN307	GW17& GW32		SF054& SF021	PR2		MM1& MN3
Area[3]	SF	SF	SF	St. G.	St. G.	SF	T	St. G.	T
Name[4]	Haw	Haw	HAB	Haw	Haw	HAB	HAB	HAB	QT

Table E.1c: Basaltic andesites-rhyolites from the Southwestern Colorado Plateau

	Basaltic Andesites					Andesites, Dacites, Rhyolites			
Sample	A4033	U5016	A4030	A6026	A5014	A6053	A6018	A6054	A6015
Chemical Analyses									
SiO_2	50.26	52.9	56.8	58.77	59.3	58.8	62.82	64.1	72.8
TiO_2	1.72	1.8	.95	1.03	.98	1.4	.62	.66	.04
Al_2O_3	15.81	16.6	14.9	14.79	16.6	16.9	15.42	16.5	13.9
Fe_2O_3	4.77		2.5	3.46	1.8	1.4	.92	2.1	.57
FeO	5.18	8.0	4.1	3.44	4.9	5.6	3.69	2.79	.48
MnO	.20		.13	.12	.10	.14	.10	.13	.04
MgO	5.97	6.3	5.3	5.09	3.9	2.8	2.54	1.3	.12
CaO	8.30	7.3	7.6	6.46	6.4	5.3	4.28	3.1	.87
Na_2O	3.69	4.3	3.7	3.73	3.8	5.1	4.27	5.8	4.4
K_2O	1.27	1.82	2.4	2.06	2.3	2.4	3.27	3.2	4.1
P_2O_5	.48		.48	.51	.21	.4	.27	.29	.05
H_2O^+	.55		.62	.68	.44		.91	.34	2.4
H_2O^-	.46		.42	.44	.25		.29	.12	.22
CO_2			.02		.04	<.05	.04	.0	.01
Total	100.05	99.02	99.92	100.12	100.02	100.24	99.44	100.43	100.00
Barth-Niggli Norms[1]									
Q			3.56	7.26	7.47	3.72	11.52	8.04	27.62
Or	7.60	10.71	14.28	12.30	13.55	13.98	19.61	18.74	24.91
Ab	33.55	38.46	33.47	33.85	34.02	45.54	38.92	51.63	40.63
An	23.13	20.55	17.10	17.73	21.39	16.11	13.46	9.47	4.10
Ne									
Di	12.43	12.43	14.19	9.41	7.12	5.98	5.04	3.12	
Hy	14.01	1.92	13.70	15.67	13.26	10.54	9.02	6.49	1.49
Ol	3.84	11.73							
Mt	2.05	1.70	1.36	1.41	1.39	1.46	.98	.99	.22
Il	2.43	2.50	1.33	1.45	1.36	1.88	.88	.91	.57
Ap	.97		1.01	.93	.44	.79	.57	.60	.11
Plag. An.	40.8	34.8	33.8	34.4	38.6	26.1	25.7	15.5	9.17
Ref.[2]	6	4	4	6	3	3	3	1	3
Ref. No.[3]		SG40	GW17& GW32		NM888	SF017- SF020	MM1081A	SF015	W75P23
Area[4]	WM	St. G.	SF	T	SF	SF	SF	SF	SF

Footnotes for Table E.1

[1] Norms were calculated assuming FeO/FeO + Fe_2O_3 = 0.80, unless the measured value of this parameter exceeded 0.80, in which case the measured value was used.

[2] References: 1 = Moore *et al*. (1975); 2 = McKee and Anderson (1971); 3 = E. Wolfe and R. Moore (written communication); 4 = Leeman (1974); 5 = Best and Brimhall (1974); 6 = this work, A.R. McBirney, analyst.

[3] Area: SF = San Francisco volcanic field; St. G. + St. George area; T = Tonto section of Hayes (1969), an area along the margin of the Colorado Plateau in central Arizona; WM = White Mountains.

[4] Name: Bas = basanite; Ank = ankarimite; AOB = alkali olivine basalt; OT = olivine tholeiite; Haw = hawaiite; HAB = alumina basalt; QT = quartz tholeiite.

Table E.2a: Quaternary basalts from Basin and Range areas (excluding Southern Nevada)

Sample	NM4015	NM4016	N5024	A4005	A4003	NM4044	C4022	C4025	A3008	A3038
Chemical Analyses										
SiO_2	43.23	44.17	44.66	45.36	45.77	46.49	47.24	47.55	48.01	48.22
TiO_2	2.05	2.24	2.33	2.56	2.26	2.01	2.38	2.71	2.36	2.22
Al_2O_3	14.41	15.89	15.35	15.78	15.72	16.92	16.11	16.38	17.00	17.02
Fe_2O_3			3.39	3.00	4.24	6.10	3.07	2.71	2.52	4.76
FeO	10.34	9.95	7.92	7.86	6.38	5.26	7.34	7.84	7.86	6.54
MnO	.19	.18	.21	.20	.19	.25	.19	.20	.17	.19
MgO	9.81	9.26	8.96	8.74	7.16	5.71	7.47	6.40	4.76	4.67
CaO	11.00	10.27	10.40	9.08	8.79	8.16	9.26	8.41	10.31	8.66
Na_2O	2.10	2.69	3.67	3.55	4.44	4.62	4.04	4.46	3.62	3.49
K_2O	1.18	1.43	1.84	1.97	2.30	2.23	1.75	2.11	1.54	1.58
P_2O_5			.65	.55	1.05	.60	.59	.72	.61	.88
H_2O^+			.16	.65	.45	.41		.57	.53	.47
H_2O^-			.04	.32	.63	.53		.11	.76	.81
Total	99.32	96.06	99.89	99.62	99.38	99.29	99.44	100.34	100.05	99.51
Barth-Niggli Cation Norms[1]										
Q										
Or	7.36	8.71	10.83	11.69	13.68	13.30	10.31	12.44	9.26	9.60
Ab	10.55	11.62	8.75	14.82	16.44	19.34	20.85	22.86	26.52	32.25
An	27.77	27.88	19.92	21.41	16.30	19.08	20.61	18.42	26.06	26.88
Ne	5.63	7.93	14.45	10.32	15.23	13.58	9.20	10.27	3.94	
Cpx	23.75	19.66	21.81	16.18	16.57	14.34	17.10	14.83	17.56	9.13
Opx										3.77
Ol	19.61	18.79	17.32	18.58	15.20	13.91	15.24	13.71	9.82	10.91
Mt	2.32	2.18	2.33	2.26	2.19	2.32	3.01	2.19	2.20	2.38
Il	3.01	3.22	3.23	3.58	3.17	2.83	4.55	3.77	3.35	3.18
Ap			1.35	1.16	2.21	1.27	1.43	1.50	1.30	1.89
Plag. An.	72.5	70.6	69.5	59.1	49.8	49.7	49.7	44.6	49.6	45.46
Ref.[2]	2	2	6	1	1	1	4	5	1	1
Ref. No.	DOT-7	DOT-4	LC-9				Avg of 6			
Name[3]	APB	APB	AOB	AOB	TB	Haw	AOB	TB	Haw	Haw

Table E.2a (continued)

Sample	C5011	NM7008	NM4010	N3029	NM4007	NM7009	NM7010	C5010	NM7005	C5001
Chemical Analyses										
SiO_2	48.42	48.63	48.80	49.03	49.24	49.24	50.26	50.26	50.46	52.27
TiO_2	2.41	2.03	1.94	1.53	1.79	1.73	1.62	1.66	1.45	2.82
Al_2O_3	16.52	16.03	15.86	15.44	16.09	16.43	16.80	16.74	14.40	14.55
Fe_2O_3	3.10	5.34		2.35	1.82	2.76	2.71	1.45	4.27	2.1
FeO	7.94	6.67	8.68	6.04	8.10	7.75	6.84	6.93	7.11	6.99
MnO	.21	.23	.15	.22	.22	.23	.25	.18	.25	.19
MgO	5.62	5.72	9.48	8.01	7.33	7.06	6.14	5.89	7.33	5.52
CaO	9.06	8.52	9.73	9.96	9.14	9.71	8.19	9.97	9.10	8.54
Na_2O	3.77	4.10	3.10	2.93	3.41	3.70	3.49	3.70	3.09	3.42
K_2O	1.24	1.70	1.58	1.79	1.37	1.95	1.34	1.30	.75	1.10
P_2O_5	.51	.53		.58	.44	.53	.48	.78	.35	.56
H_2O^+	.44	.22		.36	.27	.47	.26	.43	.26	.99
H_2O^-	.36	.34		.43	.34	.82	.35	.54	.41	1.01
Total	99.60	100.06	99.32	98.67	99.56	100.58	98.70	99.83	99.23	100.09
Barth-Niggli Cation Norms[1]										
Q										3,41
Or	7.44	10.13	9.28	10.73	8.14	11.54	8.06	7.73	4.52	6.68
Ab	32.03	28.80	21.57	26.30	30.39	29.60	31.90	33.45	28.31	31.57
An	24.90	20.50	24.47	24.04	24.71	22.52	26.70	25.42	23.69	21.70
Ne	1.42	5.00	3.61	.23	.25	2.21				
Cpx	13.91	14.91	18.71	17.79	14.42	10.71	9.17	15.41	16.04	14.48
Opx							11.19	.73	18.45	14.97
Ol	13.47	14.224	17.84	15.75	16.75	17.72	7.63	11.76	3.79	
Mt	2.33	2.47	1.84	1.76	1.91	2.19	2.02	1.53	2.38	1.95
Il	3.41	2.85	2.67	2.16	2.51	2.41	2.30	2.33	2.06	4.04
Ap	1.08	1.12		1.23	.93	1.11	1.02	1.64	.75	1.20
Plag. An.	43.7	41.58	53.1	47.8	44.9	43.2	45.6	43.2	45.6	40.7
Ref.[2]	1	1	2	1	1	1	1	1	1	1
Ref. No.			POT-24							
Name[3]	Haw	Haw	AOB	AOB	Haw	AOB	HAB	Haw	HAB	HAB

Table E2.b: Pliocene and older volcanic rocks from Basin and Range areas (excluding Southern Nevada)

Sample	N3027	C7001	N3016	C6002	A6004	N5026	C4020	A3041	A3C09	N3023	A6005
Chemical Analyses											
SiO_2	47.8	49.31	49.85	51.27	51.68	52.71	53.16	53.53	56.21	56.62	59.83
TiO_2	1.03	2.28	1.80	1.46	1.10	1.28	1.51	1.14	1.23	1.32	1.08
Al_2O_3	16.7	15.66	16.29	15.43	16.57	16.67	18.18	16.52	16.98	14.41	17.24
Fe_2O_3	2.0	5.30	8.92	4.70	3.16	3.87	3.14	4.61	2.88	2.45	2.51
FeO	7.35	5.55	1.49	3.79	5.15	4.28	5.05	5.05	4.74	6.86	3.44
MnO	.18	.24	.21	.21	.16	.20	.12	.17	.16	.22	.12
MgO	9.1	5.76	5.11	6.26	6.02	3.42	2.38	4.90	3.07	4.16	2.34
CaO	11.7	9.38	10.30	8.13	9.90	8.06	8.47	8.33	6.61	8.58	4.90
Na_2O	2.1	3.86	2.99	3.32	3.12	3.63	3.49	3.47	3.91	2.99	4.80
K_2O	.26	1.34	1.09	2.53	1.32	1.87	1.85	2.01	2.98	1.66	2.17
P_2O_5	.37	.47	.64	.55	.38	.55	.40	.43	.68	.45	.76
H_2O^+	.45	.42	.31	.82	.61	1.48	1.49	.53	.55	.23	.53
H_2O^-	.24	.78	.47	.85	.89	.64	.40	.87	.71	.41	.55
Total	99.29	100.35	99.47	99.32	100.06	98.66	99.67	101.56	100.71	100.36	100.27
Barth-Niggli Cation Norms											
Q						2.37	3.70	.07	3.17	8.39	8.46
Or	1.55	8.02	6.63	15.28	7.91	11.51	11.30	11.92	17.76	9.98	12.90
Ab	19.07	32.00	27.63	30.48	28.40	33.97	32.40	31.27	35.42	27.33	43.37
An	35.79	21.75	28.63	20.18	27.70	24.68	29.29	23.66	20.17	21.39	19.22
Ne		1.88									
Di	17.07	17.85	15.73	13.91	15.67	10.61	9.17	12.00	6.75	15.17	.20
Hy	12.10		15.16	6.08	14.50	12.08	9.37	16.61	12.00	12.94	11.51
Ol	10.49	12.07	.18	9.07	1.74						
Mt	1.97	2.23	2.09	1.75	1.73	1.73	1.74	1.97	1.57	1.97	1.22
Il	1.45	3.22	2.58	2.08	1.55	1.86	2.17	1.59	1.73	1.87	1.51
Ap	.51	1.00	1.39	1.18	.81	1.20	.86	.90	1.43	.96	1.60
Plag. An.	65.2	40.5	50.9	39.8	49.3	42.08	47.5	43.1	36.3	43.9	30.7
Ref.	7	1	1	1	1	1	3	1	1	1	1
Ref. No.	Avg of 2						J-1				
Name	OT	Haw	HAB	HAB	HAB	And	And	An	And	And	And

Table E.2c: Basalts from Southern Nevada and neighboring regions in California

Sample	N5024	C4025	C5009	C3013	N6040	C3014	N5023	N6036	N6034
Chemical Analyses									
SiO_2	44.66	47.55	47.81	48.83	50.87	52.30	53.94	54.19	55.39
TiO_2	2.33	2.71	2.17	1.27	2.22	1.26	1.78	1.34	1.51
Al_2O_3	15.35	16.38	16.68	14.52	16.87	14.84	15.04	16.60	16.26
Fe_2O_3	3.39	2.71	6.92	3.87	1.35	4.51	2.92	2.49	2.47
FeO	7.92	7.84	4.68	5.17	7.86	3.33	6.44	4.34	6.47
MnO	.21	.20	.22	.19	.22	.21	.21	.18	.24
MgO	8.96	6.40	5.33	9.29	5.25	5.60	5.27	4.72	4.69
CaO	10.40	8.41	8.01	11.10	8.31	7.75	8.29	7.04	7.74
Na_2O	3.67	4.46	3.62	2.57	3.58	2.85	3.52	3.51	3.07
K_2O	1.84	2.11	1.89	1.46	1.95	4.24	1.31	4.13	1.56
P_2O_5	.65	.72	.61	.60	1.27	1.13	.58	.68	.41
H_2O^+	.16	.57	1.18	.45	.43	.62	.21	.31	.23
H_2O^-	.04	.11	.72	.44	.68	.67	.36	.39	.35
Total	99.89	100.34	99.84	99.76	100.36	99.31	99.87	99.92	100.39
Barth-Niggli Cation Norms									
qtz							3.36		6.47
orth	10.83	12.44	11.49	8.67	11.578	25.60	7.85	24.47	9.32
alb	8.75	22.86	30.66	23.20	32.31	26.16	32.05	31.61	27.88
an	19.92	18.42	24.39	23.91	24.34	15.52	21.68	17.41	26.29
neph	14.45	10.27	1.68						
diop	21.81	14.83	9.93	22.02	7.01	13.00	12.95	10.54	7.88
hyp				.03	12.58	6.67	16.41	4.21	17.28
ol	17.32	13.71	15.02	17.27	4.46	7.24		7.06	
mgt	2.33	2.19	2.40	1.86	1.95	1.61	1.96	1.41	1.88
ilm	3.23	3.77	3.11	1.78	3.11	1.79	2.51	1.87	2.18
apa	1.35	1.50	1.31	1.26	2.67	2.41	1.23	1.43	.87
Plag. An.	69.5	44.6	44.3	50.8	43.0	37.2	40.4	35.5	48.5
Ref.	6	5	1	1	1	1	1	1	1

Footnotes for Table E.2

[1] Norms were calculated assuming FeO/Fe_2O_3+FeO = .80, unless the measured value of this parameter exceeded .80, in which case the measured value was used.

[2] References: 1 = this work, A.R. McBirney, analyst; 2 = Renault (1970); 3 = Hawkins (1970); 4 = Smith and Carmichael (1969); 5 = Wise (1969); 6 = Scott and Trask (1971); 7 = McKee and Mark (1971).

[3] Rock names: APB = alkaline picrite basalt; AOB = alkaline olivine basalt; TB = trachybasalt; Haw = hawaiite; HAB = high alumina basalt; OT = olivine tholeiite; And = andesite.