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POST-LARAMIDE VOLCANIC ROCKS OF ARIZONA AND NORTHERN SONORA, MEXICO, AND THEIR INCLUSIONS

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ABSTRACT

Most of the volcanic fields that formed during the past 40 Ma in Arizona can be classified into five petrologic groups: (1) lamprophyre fields, (2) latite fields, (3) basalt-dominated fields, (4) bimodal (basalt-rhyolite) fields, and (5) andesite-rhyolite-dominated fields. Lamprophyres were erupted on the Colorado Plateau over two separate periods of volcanism. During an early period, 42-25 Ma, potassic kimberlitic microbreccias were emplaced in the interior of the Colorado Plateau. At a later period, 8-4 Ma, lamprophyric volcanism produced sodic monchiquites closer to the margin of the plateau. Potassic latites were erupted in the Transition Zone between the Colorado Plateau and Basin and Range provinces coeval with the early period of volcanism on the Colorado Plateau. Following the early episode of lamprophyric and latitic volcanism, andesite-rhyolite-dominated volcanism began in the Basin and Range province and moved into the Transition Zone. Basalt-dominated and bimodal basalt-rhyolite activity followed this style of volcanism.

Basalt-dominant volcanism resulted in the emplacement of predominantly alkalic basalt lavas but also small amounts of tholeiitic basalt, andesite, dacite, trachyte, and rhyolite. Bimodal activity produced basaltic and rhyolitic lavas but few intermediate-composition rocks. Andesite-rhyolite-dominated volcanism resulted in the emplacement of thick sequences of mostly calc-alkalic intermediate- to silicic-composition lavas and ash flows in the Basin and Range province and along the margins of the Transition Zone.

Many of the mafic and some of the intermediate-composition volcanic rocks in Arizona contain ultramafic and mafic xenoliths and a variety of megacrysts. The xenoliths include peridotite, pyroxenite, amphibolite, gabbro, eclogite, garnetite, and granulite of mantle, lower crustal, and cumulate origin. The megacrysts include clinopyroxene, plagioclase, amphibole, orthopyroxene, olivine, and spinel.

The origin of volcanic rocks in Arizona is the subject of many ongoing and recent petrologic studies. Basalts are ultimately derived from upper mantle sources that in many places appear to have been enriched in incompatible elements during upper mantle metasomatism. Most basalts underwent fractional crystallization, and some assimilated small amounts of crustal material on their way to the surface. Intermediate-composition rocks are the products of fractional crystallization and crustal assimilation. Most of the silicic rocks appear to be crustal melts. The large-volume silicic units record open-system magmatic processes involving fractional crystallization, wall-rock assimilation, and magma mixing.

INTRODUCTION

Post-Laramide volcanic rocks are widely exposed in Arizona and form the dominant geomorphic landforms in many areas. The aim of this paper is to present available petrographic, geochemical, and petrological data for volcanic rocks that erupted in Arizona and northern Mexico over the past 40 million years. First, we describe the petrography, chemistry, and field relationships of these volcanic rocks in Arizona to show the diversity of rock types and volcanic associations. We present geochemical plots of more than 3,500 major-element and approximately 500 trace-element whole-rock analyses. These plots are used to characterize the composition of post-Laramide volcanic rocks in Arizona. The data come from our ongoing investigations of volcanic rocks in various parts of Arizona and from published reports and from unpublished data of colleagues. The data are of different quality and abundance. Much of southern Arizona has poor geochemical data, especially trace-element and isotopic data.

Second, we address the origin of the different rock types and the volcanic fields that they form. In attempting to achieve this goal we point out that many of the volcanic rocks in the region have not been studied in sufficient detail yet to allow their source regions to be satisfactorily characterized or for their evolutionary histories to be elucidated.

Finally, we present available geochronologic data in an attempt to define migration patterns of volcanism. The patterns allow us to improve our understanding of the effects of global tectonism on crustal and mantle evolution in this part of North America. Many parts of the region have only limited geochronologic data, and some of the older dates are suspect because of metasomatic alteration.

Post-Laramide volcanic rocks occur in each of the three tectonic provinces that make up Arizona: (1) the Colorado Plateau; (2) Basin and Range province; and (3) Transition Zone (fig. 1). The Colorado Plateau is characterized by relatively flat lying Paleozoic and Mesozoic sedimentary shelf rocks that rest on Precambrian basement. The crust is approximately 40 km thick beneath the plateau (Warren, 1969). The Transition Zone is a mountainous region between the Basin and Range and Colorado Plateau provinces; it has relatively few deep sedimentary basins and is underlain by crust of lesser thickness than that under the plateau. The Basin and Range province is composed of alternating linear mountain ranges and deep sedimentary basins and is underlain by a relatively thin crust about 20 km thick. The major structures in the Basin and Range province include normal faults, detachment faults, metamorphic core complexes, and strike-slip faults (Crittenden and others, 1980; Suneson and Lucchitta, 1983). The pervasive structural disruption of the region makes it difficult to correlate the volcanic units across basins and adjacent ranges.

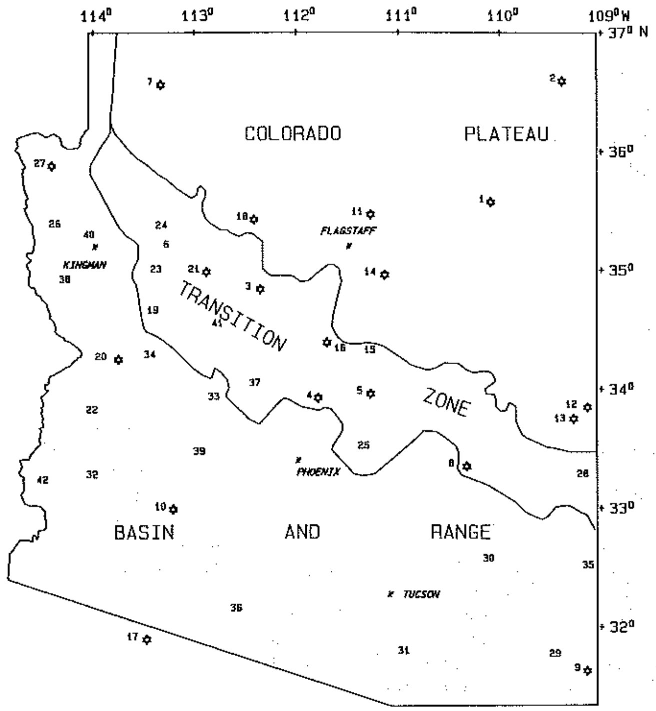


Figure 1. Map showing location of selected post-Laramide volcanic fields of Arizona and of northern Sonora, Mexico. Physiographic boundaries after Peirce (1986). Volcanic fields are: 1. Hopi Buttes; 2. Navajo; 3. Sullivan Buttes; 4. Camp Creek; 5. Reno Pass; 6. Turkey Canyon; 7. Western Grand Canyon; 8. San Carlos; 9. San Bernardino; 10. Sentinel Plains; 11. San Francisco; 12. Springerville; 13. White Mountains; 14. Mormon Mountain; 15. Hackberry Mountain; 16. Black Hills; 17. Pinacate; 18. Mount Floyd; 19. Kaiser Spring; 20. Castaneda Hills; 21. Mount Hope; 22. Plomosa Mountains; 23. Mohon Mountains; 24. Aquarius Mountains; 25. Superstition-Goldfield Mountains; 26. Black Mountains; 27. Hoover Dam; 28. Blue Range; 29. Chiricahua Mountains; 30. Galiuro Mountains; 31. Roskruge Mountains; 32. Castle Dome-Kofa Mountains; 33. Vulture Mountains; 34. McLendon Volcano; 35. Whitlock Mountains; 36. Growler Mountains; 37. Castle Hot Springs; 38. Mohave Mountains; 39. Big Horn Mountains; 40. Cerbat Mountains; 41. Martin Mountain; 42. Trigo Mountains. (Xenolith and megacryst localities indicated by stars.)

Most post-Laramide volcanic fields in Arizona can be assigned to one of five petrologic groups: (1) lamprophyre fields; (2) latite fields; (3) basalt-dominated fields; (4) bimodal (basalt and rhyolite) fields; and (5) andesite-rhyolite-dominated fields. Table 1 lists the volcanic fields that have been characterized on the basis of geologic field work and geochemical data and provides supplementary information relating to volcanic rock associations, post-emplacement metasomatic alteration, and ages of the rocks. The assignments in some cases are preliminary because detailed petrologic work has not been completed. This is especially true for many volcanic fields in southern Arizona. Also, in some areas the styles of volcanism and the resulting rock associations changed through time. For example, we classify the Superstition Mountains as an andesite-rhyolite field, but during a part of its history the volcanism was bimodal (basalt-rhyolite).

Relations between tectonic setting and the composition of volcanic rocks in Arizona are beginning to be unraveled. Large lamprophyre fields occur on the Colorado Plateau; however, lamprophyric dikes also occur in the Basin and Range province (Williams, 1936; Hack, 1942; Cooper, 1973; Haxel and others, 1980; Wright and Haxel, 1982). Latite fields are restricted to the Transition Zone (Tyner, 1984; Esperanca, 1984; Arney and others, 1985). Basalt-dominated fields occur on the Colorado Plateau, in the Transition Zone, and in the southern Basin and Range. Bimodal fields occur in the western part of the state in all three provinces. Andesite-rhyolite-dominated fields occur mostly in the Basin and Range province but overlap into the Transition Zone.

We limit our discussion here to volcanic rocks less than about 40 Ma. Geochronologic data for this paper are based mainly on the compilation of age data recently published by Reynolds and his coworkers at the Arizona Geological Survey (Reynolds and others, 1987). This compilation contains all the high-quality K-Ar analyses published through 1987. Obviously, future geochronologic data may extend the age ranges of individual volcanic fields.

Petrographic and geochemical data used in the assignment of volcanic fields to the five petrologic groups come from a variety of sources (table 2). The interested reader is advised to consult these references for additional discussion of rocks in the different areas and for analytical techniques. The quality of geochemical data from the literature may vary widely, but we consider it important to show all available data for comparative purposes. We have indicated in table 1 those volcanic suites in which metasomatism has been demonstrated. Certain elements, such as Rb, may be especially susceptible to post-emplacement metasomatism and alteration. Additionally, certain mineral phases may concentrate specific elements preferentially to others. For example, Sr is sequestered by plagioclase, and Cr is preferentially concentrated into clinopyroxene and olivine.

Table 1. Volcanic fields of Arizona and northern Sonora, Mexico, according to petrologic type and physiographic province. Metasomatism refers to deuteric alteration of rocks. Numbers are keyed to figure 1. Slash under age indicates age break in the data that may indicate hiatus in volcanic activity.

Field no. and name	Physiographic province	Rock types and comments	Age (Ma)
		Lamprophyre fields	
1. Hopi Buttes	Colorado Plateau	Sodic alkalic series	8-4
2. Navajo	Colorado Plateau	Potassic and sodic alkalic series	42-25
		Latite fields	
3. Sullivan Buttes	Transition Zone	Potassic latite	27-21
4. Camp Creek	Transition Zone	Potassic latite	
5. Reno Pass	Transition Zone	Potassic latite	
6. Turkey Canyon	Transition Zone	Potassic latite	22
		Basalt fields (without differentiated rocks)	
7. Western Grand Canyon	Colorado Plateau	Alkalic series	9-0.01
8. San Carlos	Transition Zone	Alkalic series to mugearite	7-0.5
9. San Bernardino	Basin and Range	Alkalic series	1-0.3
10. Sentinel Plains	Basin and Range		6-1
		Basalt fields (with differentiated rocks)	
11. San Francisco	Colorado Plateau	Subalkalic and alkalic series to rhyolite and trachyte	6-0.05
12. Springerville	Colorado Plateau	Mostly alkalic series, small amount of tholeiitic basalt to benmoreite	9-0.3
13. White Mountains	Colorado Plateau	Alkalic series, basalt to trachyte	9-2
14. Mormon Mountain	Colorado Plateau-Transition Zone	Alkalic and tholeiitic basalt series to rhyolite	14-3
15. Hackberry Mountain	Transition Zone	Alkalic and subalkalic basalt series to rhyolite	14-3
16. Black Hills	Transition Zone	Alkalic and tholeiitic basalt, and small amounts of andesite and rhyolite	15-11
17. Pinacate	Basin and Range	Alkalic series to trachyte; subalkalic series to dacite	18-5/2-0.1
		Bimodal (basalt-rhyolite) fields	
18. Mount Floyd	Colorado Plateau-Transition Zone	Basalt and low- and high- silica rhyolite	10-2
19. Kaiser Spring	Transition Zone	Basalt and low- and high- silica rhyolite	22-8
20. Castaneda Hills	Basin and Range	Basalt and low- and high-silica rhyolite; metasomatism apparent	19-5
21. Mount Hope	Transition Zone	Basalt to andesite and low- and high-silica rhyolite	13-5
22. Plomosa Mountains	Basin and Range	Basalt and rhyolite; metasomatism apparent	25-17
		Andesite-rhyolite-dominated fields	
23. Mohon Mountains	Transition Zone	Alkalic and subalkalic series to dacite	22-21
24. Aquarius Mountains	Transition Zone	Alkalic and subalkalic series to rhyolite	25-18
25. Superstition-Goldfield Mountains	Transition Zone	Basalt to rhyolite; probable metasomatism	30-14
26. Black Mountains	Basin and Range	Basalt to rhyolite	23-15
27. Hoover Dam	Basin and Range	Basalt to dacite	13-3
28. Blue Range	Transition Zone	Basaltic andesite to rhyolite	
29. Chiricahua Mountains	Basin and Range	Basalt to rhyolite; metasomatism apparent	33-17/0.9
30. Galiuro Mountains	Basin and Range	Andesite to rhyolite;	34-23/8
31. Roskruge Mountains	Basin and Range	Basaltic andesite to rhyolite	26-10
32. Castle Dome-Kofa Mountains	Basin and Range	Andesite to rhyolite; metasomatism apparent	25-18
33. Vulture Mountains	Basin and Range	Metasomatism apparent	26-13
34. McLendon volcano	Basin and Range	Basalt to rhyolite	
35. Whitlock Mountains	Basin and Range	Andesite to rhyolite	29-16
36. Growler Mountains	Basin and Range	Basalt to rhyolite	24-14
37. Big Horn Mountains	Basin and Range	Basalt to rhyolite	21-15
		Unclassified fields	
38. Castle Hot Springs	Transition Zone	Basalt to rhyolite	20-16
39. Mohave Mountains	Basin and Range	Basalt to rhyolite; metasomatism apparent	
40. Cerbat Mountains	Basin and Range	Basalt to rhyolite and Peach Springs Tuff	>17
41. Martin Mountain	Transition Zone	Basalt to rhyolite	15
42. Trigo Mountains	Basin and Range	Basalt to rhyolite	39-20

Studies of volcanic rocks of Arizona have been conducted by many workers over the past 85 years. The present authors have conducted field and petrologic studies of volcanic rocks over much of the state. Nealey has done detailed mapping in the Mount Floyd, Mormon Mountain,

Table 2. Selected sources of petrographic, geochemical, and geochronologic data.

Field	Source
	Lamprophyre fields
Hopi Buttes	Nicholls, 1969; Powell and Bell, 1970; Lewis, 1973; Suda and others, 1982; Wenrich and Mascarenas, 1982; Alibert and others, 1986; M. Shafiqullah and P.E. Damon, Univ. of Arizona, unpub. data.
Navajo	Nicholls, 1969; Roden, 1981; Ehrenberg, 1978; Rogers and others, 1982; Thompson and others, 1984; Alibert and others, 1986; Laughlin and others, 1986.
	Latite fields
Sullivan Buttes	Arculus and Smith, 1979; Tyner, 1974 and 1984.
Camp Creek	Esperanca, 1984; Esperanca and Holloway, 1986.
Reno Pass	L.D. Nealey, U.S. Geological Survey, unpub. data.
Turkey Canyon	Arney and others, 1985; L.D. Nealey and B.H. Carlos, U.S. Geological Survey and Los Alamos National Lab., respectively, unpub. data.
	Basalt fields
Western Grand Canyon	Best and Brimhall, 1974; Leeman, 1974; Alibert and others, 1986.
San Carlos	Leeman, 1970; Stueber and Ikramuddin, 1974; Frey and Prinz, 1978; Caporuscio, 1980.
San Bernardino (Geronimo)	Lynch, 1972; Evans and Nash, 1979; Menzies and others, 1983; Arculus and others, 1977.
Sentinel Plains	L.D. Nealey, U.S. Geological Survey, unpub. data.
San Francisco	Alibert and others, 1986; Brookins and Moore, 1975; Moore and Wolfe, 1987; Newhall and others, 1987; Ulrich and Bailey, 1987; Wenrich-Verbeek, 1975 and 1979; Wolfe and others, 1987; M.A. Lanphere, U.S. Geological Survey, unpub. data; Pushkar and Stoeser, 1975; Stueber and Ikramuddin, 1974.
Springerville	Leeman, 1970; Condit, 1984; L.S. Crumpler and J. Aubele, U.S. Geological Survey, unpub. data.
White Mountains	L.D. Nealey U.S. Geological Survey, unpub. data.
Mormon Mountain	Gust, 1978; Gust and Arculus, 1986; L.D. Nealey, U.S. Geological Survey, unpub. data.
Hackberry Mountain	Scott, 1970; Lewis, 1983.
Black Hills	Wittke, 1984; L.D. Nealey, U.S. Geological Survey, unpub. data.
Pinacate	Donnelly, 1974; Gutmann, 1979; Lynch, 1981.
	Bimodal fields
Mount Floyd	Nealey, 1980; Bush, 1986; A. Kisiel, State University of New York at Buffalo, unpub. data; L.D. Nealey, U.S. Geological Survey, unpub. data.
Kaiser Spring	Moyer, 1986; T.C. Moyer and Sonia Esperanca, Vanderbilt Univ. and Carnegie Inst. of Wash., respectively, unpub. data; L.S. Beard, Ivo Lucchitta, and L.D. Nealey, U.S. Geological Survey, unpub. data.
Castaneda Hills	Suneson and Lucchitta, 1983; L.D. Nealey and Ivo Lucchitta, U.S. Geological Survey, unpub. data.
Mount Hope	Simmons, 1986; L.D. Nealey and A.W. Ward, U.S. Geological Survey, unpub. data.
Plomosa Mountains	Miller, 1970; Miller and McKee, 1971; Davis, 1985.
	Andesite-rhyolite fields
Mohon Mountains	Nealey and others, 1986; L.D. Nealey, A.W. Ward, and A.C. Robinson, U.S. Geological Survey, unpub. data.
Aquarius Mountains	Arney and others, 1985; L.S. Beard and L.D. Nealey, U.S. Geological Survey, unpub. data.
Superstition-Goldfield Mts.	Peterson, 1961; Malone, 1962; Fodor, 1969; Stuckless, 1969; Stuckless and O'Neil, 1973; Suneson, 1976; Hillier, 1978; Isagholian, 1983; Rettenmaier, 1984; Prowell, 1984; Kilbey, 1986; M.F. Sheridan, Arizona State University, unpub. data; L.D. Nealey, U.S. Geological Survey, unpub. data.
Black Mountains	Thorson, 1971.
Hoover Dam	Scott and others, 1971; Anderson, 1978; Basu, 1978; Alibert and others, 1986; E.I. Smith, Univ. of Nevada, Las Vegas, unpub. data; Mills, 1985.
Blue Range	Ratté and others, 1969; Wahl, 1980.
Chiricahua Mountains	Latta, 1983; Tsuji, 1984; Bryan, 1988; H. Drewes, W.E. Brooks, U.S. Geological Survey, unpub. data.
Galiuro Mountains	Krieger, 1979.
Roskruge Mountains	Bikerman, 1967; Eastwood, 1970.
Castle Dome-Kofa Mtns.	Gutmann, 1982; Puchalski, 1985; Grubensky, 1987.
Vulture Mountains	Rehrig and others, 1980.
McLendon Volcano	Brooks, 1985a.
Whitlock Mountains	Richter and others, 1981; Walker and Richter, 1988; R.J. Walker, Oregon State University, unpub. data.
Growler Mountains	Gray and others, 1985.
Big Horn Mountains	Capps and others, 1986.
	Other areas
Castle Hot Springs	Ward, 1977; Satkin, 1981.
Mohave Mountains	J.E. Nielson, U.S. Geological Survey, unpub. data.
Cerbat Mountains	Arney and others, 1985; Buesch and Valentine, 1986; L.D. Nealey, U.S. Geological Survey, unpub. data.
Martin Mountain	L.D. Nealey and C.M. Conway, U.S. Geological Survey, unpub. data.
Trigo Mountains	Weaver, 1982; W.E. Brooks, U.S. Geological Survey, unpub. data.

and Mohon Mountains fields and reconnaissance work in the Castaneda Hills, Aquarius Mountains, Black Hills, Cerbat Mountains, Sullivan Buttes, Hopi Buttes, San Francisco, Reno Pass, and Hoover Dam fields. He is also involved in geochemical studies of volcanic rocks from other parts of the state. Sheridan has done considerable field work in the Superstition-Goldfield Mountains, San Francisco, and Pinacate fields and has supervised student research in the Camp Creek, San Carlos, White Mountains, Kaiser Spring, and Castle Hot Springs volcanic fields. He has done reconnaissance work in the Hopi Buttes, Navajo, Western Grand Canyon, Chiricahua, and Big Horn Mountains fields.

The amount of description or discussion given to volcanic fields in this chapter varies. Fields that the authors have studied and those that have been well described in the literature are discussed in the greatest detail. We suggest that interested readers refer to the papers listed in table 2 and the reference list for more detailed descriptions of individual volcanic fields.

Boundaries of several volcanic fields are not well defined. We have followed the prejudices of local workers in distinguishing between contiguous volcanic terranes.

LAMPROPHYRE FIELDS

Lamprophyres are strongly undersaturated to saturated rocks that occur as lava flows, dikes, and pyroclastic deposits. Two chemical varieties of lamprophyre occur in Arizona: sodic lamprophyres in the Hopi Buttes field and potassic-sodic lamprophyres in the Navajo volcanic field (fig. 1). The Hopi Buttes field is one of the world's classic areas for monchiquite lavas and dikes and limburgitic tuff (Hack, 1942; Williams, 1936; Sutton, 1974). The field contains more than 300 funnel-shaped diatremes and maar volcanoes, and associated monchiquite flows. The maars and diatremes resulted from phreatic eruptions through the Pliocene "Hopi Lake" between 8 and 4 Ma and are as much as 2.5 km in diameter and 150-1,200 m deep (Shoemaker and others, 1962; Sutton, 1974). Some of the phreatic eruptions ended with the emplacement of lava domes and flows and the collapse of the walls of the volcanoes. Most vents in the Hopi Buttes are aligned either N. 60° W. or N. 40° E., but a few show north alignment (Sutton, 1974). The monchiquites contain augite and olivine phenocrysts (table 3); they differ from other mafic rocks in Arizona by the absence of feldspar phenocrysts.

The Navajo volcanic field includes Eocene to Miocene (42-19-Ma) undersaturated and quartz-normative, mostly potassic lamprophyre, and minor amounts of sodic lamprophyre. The field is dominated by minette but includes monchiquite, olivine leucitite, vogesite, katungite, and alnoite (Williams, 1936; Ehrenberg, 1978; Laughlin and others, 1986; Roden, 1981; Esperanca and Holloway, 1987). The mineralogy of the rocks is extremely variable but phlogopite, diopside, and alkali feldspar are the major constituents (table 3).

Diatremes in the Navajo field, at Mule Ear, Moses Rock, Cane Valley, Garnet Ridge, Red Mesa, Green Knobs, and Buell Park, are composed of serpentinized ultramafic microbreccia (kimberlitic tuff in older papers). The microbreccias have a fine-grained matrix of olivine, orthopyroxene, clinopyroxene, garnet, apatite, serpentine, and quartzite and contain blocks of Mesozoic and Paleozoic sedimentary rocks and Precambrian gneiss, granite, amphibolite, and granulite.

Middle Tertiary lamprophyric dikes also occur in the Basin and Range province; Cooper (1973) and Haxel and others (1980) mapped numerous lamprophyric dikes in parts of southern Arizona. The chemical composition of these rocks is unknown. Haxel and others (1980) described lamprophyric dikes as being fine-grained to aphanitic rocks composed of hornblende, biotite, and augite phenocrysts.

LATITE FIELDS

Distributed over a large part of the Transition Zone are Oligocene and Miocene phlogopite-hornblende-clinopyroxene-bearing latite flows and plugs and associated pyroclastic deposits (tables 1 and 3). The largest area of latite forms the Sullivan Buttes (27-21 Ma); isolated latite flows occur near Camp Creek, Reno Pass, and Turkey Canyon. These rocks are transitional in chemistry between potassic lamprophyres of the Navajo field and typical basalt and andesite of the basalt-dominated fields.

Transition Zone latites are noted for their mantle and crustal xenolith suites, which are dominated by eclogite and amphibolite but include peridotite, websterite, pyroxenite, granulite, and other crustal lithologies. Eclogite xenoliths in the Sullivan Buttes field are composed of garnet and clinopyroxene, minor amphibole, apatite, rutile, and Fe-Ti oxides, and rare clinozoisite. Amphibolite xenoliths are composed of pargasite and minor clinopyroxene, garnet, phlogopite, apatite, and oxides. Phase layering is common in the mafic and ultramafic xenoliths and is reflected by contrasting layers with different clinopyroxene-garnet ratios.

BASALT FIELDS

Some of the most spectacular volcanic landforms in Arizona are associated with young basalt fields along the margin of the Colorado Plateau and in parts of the Basin and Range. The basalt fields are divided into two groups: basalt fields without highly differentiated rocks and basalt fields with highly differentiated rocks (table 1). Basalt fields without differentiated rocks occur on the Colorado Plateau, in the Basin and Range province, and in the Transition Zone (fig. 1). Basalt fields with differentiated rocks generally are restricted to the Colorado Plateau and Transition Zone, but the Pinacate field is in the Basin and Range province.

In most basalt fields, alkali olivine basalt and basanite are the dominant rock types. Tholeiitic basalt coexists with alkalic basalt in the Black Hills, Springerville, and Mormon Mountain fields. Andesite is the most common differentiated rock in some of these fields (e.g., Mormon Mountain), but dacite and rhyolite are also common (e.g., San Francisco field). Mineral contents of rocks in the basalt fields are presented in table 3.

The basalt fields contain a variety of volcanic landforms: cinder cones, spatter cones, and shields. Many of the cinder cones have associated lava flows, dikes, and pyroclastic deposits. Although rare in most basalt fields, maars and tuff cones occur in the Pinacate, Springerville, San Bernardino (Geronimo), Mormon Mountain, San Carlos, and San

Table 3. Rock-forming minerals composing rocks of post-Laramide volcanic fields of Arizona and of northern Sonora, Mexico. (Rock names are those of the original workers.)

Volcanic fields and rock names	Olivine	Clinopyroxene	Orthopyroxene	Hornblende	Biotite	Phlogopite	Feldspar	Plagioclase	Alkali feldspar	Sanidine	Anorthoclase	Quartz	Tridymite	Apatite	Opaques	Comments
Lamprophyre fields																
Hopi Buttes																
limburgite	ph,gm	ph,gm	—	—	—	—	gm	—	—	—	—	—	—	gm	gm	analcime in gm
Navajo																
minette[1]	ph	ph,gm,xn	—	—	gm	ph,gm	—	—	—	gm	—	gm	—	gm	gm	analcime, nepheline in gm
trachybasalt	ph	ph	—	—	—	ph	—	—	—	gm	—	—	—	—	gm	—
trachyte	—	ph	—	—	—	ph	gm	—	—	—	—	—	—	—	gm	—
Latite fields																
Sullivan Buttes																
latite	—	ph,gm,xn	—	ph	ph	—	ph,gm	xn	—	—	—	xn	—	ph,gm	gm	sphene ph
Camp Creek																
latite	—	ph,xn,gm	—	—	xn,gm	ph	xn	xn,gm	xn	gm	—	—	—	ph	gm	garnet
Reno Pass																
latite	—	ph,gm	—	—	ph,gm	—	—	—	—	—	—	—	—	—	gm	—
Turkey Canyon																
latite	—	ph,gm	—	gm	ph,gm	—	—	ph,gm	—	—	—	xn	—	gm	gm	—
Basalt fields																
Western Grand Canyon																
alk. ol. basalt	—	—	—	—	gm	gm	—	—	—	—	—	—	—	—	—	—
basanite	ph,gm,xn	gm	—	xn	—	—	—	gm	—	—	—	—	—	—	—	—
ankaramite	ph,gm	ph,gm	—	—	—	—	—	gm	—	—	—	—	—	—	—	—
hawaiite	ph	ph	—	—	—	—	—	ph	—	gm	—	—	—	—	—	—
sodic hawaiite	id	id	—	—	—	—	—	—	id	—	—	—	—	—	—	—
anal. hawaiite	ph	gm	—	—	—	—	—	—	—	—	—	—	—	—	gm	analcime in gm
bas. andesite	ph,gm	gm	—	—	—	—	—	ph,gm	—	—	—	—	—	—	gm	—
San Carlos																
basalt	ph	gm	—	—	—	—	—	ph	—	—	—	—	—	—	gm	—
basanite	xn,gm	gm	—	—	—	—	—	gm	—	—	—	—	—	gm	gm	—
mugearite	ph,gm	gm	—	—	—	—	—	gm	—	—	—	—	—	—	gm	—
San Bernardino																
basalt	ph	ph,gm	—	—	—	—	—	rare ph,gm	—	—	—	—	—	gm	gm	spinel ph
Sentinel Plains																
basalt	ph,gm	ph,gm	—	—	—	—	—	ph,gm	—	—	—	xn	—	—	—	—
San Francisco																
basalt	ph	ph	—	—	—	—	—	—	—	—	—	—	—	—	gm	—
hi-al basalt	—	ph	—	—	—	—	—	—	—	—	—	—	—	—	—	Ca-poor pyroxene
bas. andesite	ph	ph	ph (?)	—	—	—	—	ph	—	—	—	ph	—	—	—	Ca-poor pyroxene, cristobalite

Table 3. (Continued)

Volcanic fields and rock names	Olivine	Clinopyroxene	Orthopyroxene	Hornblende	Biotite	Phlogopite	Feldspar	Plagioclase	Alkali feldspar	Sanidine	Anorthoclase	Quartz	Tridymite	Apatite	Opaques	Comments
benmoreite	ph,gm	gm	ph,gm	—	—	—	—	ph,gm	—	—	—	gm	—	ph,gm	gm	—
trachyte	—	—	—	—	ph		gm	ph	—	—	—	—	—	gm	gm	—
andesite	ph,gm	ph,gm	ph,gm	ph,gm	ph,gm	—	—	ph,gm	gm	—	—	—	gm	gm	gm	pigeonite in gm
dacite	gm	ph	ph,gm	ph,gm	ph	—	gm	ph,gm	gm	—	—	gm	gm	gm	gm	—
rhyolite	rare ph,gm	ph,gm	ph	ph	rare ph,gm	—	—	ph,gm	ph,gm	ph	ph	ph,gm	—	—	gm	riebeckite in peralkalines, zircon, aenigmatite
Springerville																
basalt	ph,gm	ph,gm	—	rare ph	—	—	—	ph,gm	—	—	—	—	—	—	gm	—
hawaiite	ph,gm	ph,gm	—	ph	—	—	—	ph,gm	—	—	—	ph	—	—	gm	—
benmoreite	—	—	—	—	—	—	—	ph	—	—	—	—	—	—	—	—
White Mountains																
basalt	ph,gm	ph,gm	—	rare ph	—	—	—	ph,gm	—	—	—	—	—	—	gm	—
trachyandesite	—	—	—	rare ph	—	—	—	ph	ph	—	—	—	—	—	gm	—
tristanite	rare ph	ph	ph	ph	ph	—	gm	ph	—	—	—	—	—	gm	gm	—
trachyte	—	ph	ph	ph	ph	—	—	ph	ph	—	—	rare ph	—	—	gm	—
Mormon Mountain																
basalt	ph,gm	ph,gm	—	rare ph	—	—	—	ph,gm	—	—	—	—	—	—	gm	—
andesite	—	ph,gm	—	ph	—	—	—	gm	—	—	—	—	—	—	gm	—
dacite	—	ph,gm	ph	ph	—	—	—	—	—	—	—	—	—	—	gm	—
rhyolite	—	—	—	ph	—	—	—	ph	—	—	—	—	—	—	gm	—
Hackberry Mountain																
basalt	ph	ph,gm	—	—	—	—	—	rare ph,gm	—	—	—	rare xn	—	gm	gm	—
andesite	ph,gm	ph,gm	—	—	—	—	—	ph,gm	—	—	—	—	—	—	gm	—
dacite	—	rare ph	rare ph	ph	ph	—	gm	ph	—	rare ph	—	rare ph	—	—	gm	—
rhyolite	—	—	—	ph,gm	ph,gm	—	—	ph,gm	—	ph	—	—	—	gm	gm	—
Black Hills																
alkalic basalt	ph,gm	ph,gm	—	—	—	—	—	gm	gm	—	—	—	—	—	gm	—
hawaiite	ph	ph,gm	—	—	—	—	—	gm	—	—	—	—	—	—	gm	—
basanite	ph	gm	—	—	—	—	—	gm	—	—	—	—	—	gm	gm	nepheline in gm
tholeiite	ph	ph,gm	ph,gm	—	—	—	—	ph,gm	—	—	—	—	—	—	gm	acmite in gm
trachybasalt	—	ph	—	ph,gm	—	ph (?)	—	—	gm	—	—	—	—	gm	gm	—
Pinacate																
basalt	ph,gm	ph,gm	—	—	—	—	—	ph,gm	gm	—	—	—	—	gm	gm	rare spinel, kaersutite
hawaiite	ph	ph,gm	—	ph	—	—	—	ph,gm	—	—	—	—	—	gm?	gm	—
mugearite	ph	ph	—	—	—	—	—	ph,gm	—	—	—	—	—	—	gm	—
benmoreite	rare ph	ph	—	—	—	—	—	ph,gm	—	—	—	—	—	—	gm	—
trachyte	—	ph	—	id	—	—	—	ph,gm	ph,gm	—	—	—	—	—	gm	—

Table 3. (Continued)

Volcanic fields and rock names	Olivine	Clinopyroxene	Orthopyroxene	Hornblende	Biotite	Phlogopite	Feldspar	Plagioclase	Alkali feldspar	Sanidine	Anorthoclase	Quartz	Tridymite	Apatite	Opaques	Comments
Bimodal (basalt-rhyolite) fields																
Mount Floyd																
basalt	ph,gm	ph,gm	—	—	—	—	—	ph,gm	—	—	—	xn	—	—	gm	—
rhyolite	—	ph	ph	ph	ph	—	—	ph,gm	ph	—	—	ph	—	—	gm	—
Kaiser Spring																
basalt	ph	ph	—	—	—	—	—	ph	—	—	—	—	—	—	—	—
bas. andesite	—	—	—	—	—	—	—	—	—	—	—	xn	—	—	—	—
rhyolite	—	ph	gm,xn	ph,gm	ph,gm	—	—	ph,xn	—	ph	ph	xn	—	gm	gm	zircon, garnet
Castaneda Hills																
basalt	ph,gm	rare ph,gm	—	—	—	—	—	ph,gm	—	—	—	—	—	—	gm	—
qtz. basalt	rare ph,gm	rare ph,gm	—	—	—	—	—	ph,gm	—	—	—	ph	—	—	gm	—
rhyolite	—	—	—	rare ph	rare ph	—	—	ph	—	ph	—	ph	—	—	gm	zircon in gm
Mount Hope																
basalt	ph,gm	ph,gm	—	—	—	—	—	ph,xn,gm	—	ph	—	xn	—	gm	gm	—
andesite	ph	gm	—	—	—	—	—	ph,gm	—	gm	—	ph	—	gm	gm	—
rhyolite	—	ph	ph,gm	ph	ph,gm	—	—	ph,gm	—	ph	—	ph	—	gm	gm	—
Plomosa Mountains																
basalt	ph	—	—	—	—	—	—	ph,gm	—	—	—	—	—	—	—	—
low-SiO$_2$ rhyolite	—	ph	—	ph	ph	—	—	ph,gm	—	ph,gm	—	—	—	—	ph	—
rhyolite	—	—	—	ph	ph	—	—	—	—	ph	—	—	—	—	—	—
Andesite-rhyolite fields																
Mohon Mountains																
andesite	—	ph	ph	—	—	—	—	ph,gm	ph	ph	—	—	—	gm	—	—
dacite	—	ph,gm	ph,gm	ph,gm	ph,gm	—	—	ph,gm	—	ph,gm	—	rare ph	—	—	gm	—
Aquarius Mountains																
limburgite	ph	ph	—	—	gm	—	gm	gm	—	gm(?)	—	—	—	gm	—	analcite in gm
trachybasalt	ph	ph	—	—	ph	—	—	—	—	id	—	—	—	—	gm	pigeonite in gm
trachyandesite	ph	ph,gm	—	ph	—	—	—	gm	—	gm	—	—	—	gm	—	—
Superstition-Goldfield Mountains																
basalt	ph	ph,gm	—	—	—	—	—	ph,gm	—	ph	—	—	—	—	gm	rare chlorite in gm
latite	—	ph,gm	ph	ph,gm	ph,gm	—	—	ph,gm	—	gm	rare ph	—	—	—	gm	—
rhyodacite	—	—	ph	ph	ph	—	—	ph,gm	—	gm	—	ph,gm	—	—	gm	—
rhyolite	—	—	—	rare ph	ph	—	—	ph,gm	—	ph	rare ph,gm	ph	gm	—	gm	sphene, zircon in gm

Table 3. (Continued)

Volcanic fields and rock names	Olivine	Clinopyroxene	Orthopyroxene	Hornblende	Biotite	Phlogopite	Feldspar	Plagioclase	Alkali feldspar	Sanidine	Anorthoclase	Quartz	Tridymite	Apatite	Opaques	Comments
Black Mountains																
basalt	ph,gm	gm	—	—	—	—	—	gm	—	—	—	—	—	—	—	—
latite	—	ph,gm	ph	—	rare ph	—	—	ph,gm	gm	—	—	gm	—	gm	gm	zircon
trachyte	—	rare ph	—	ph,gm	ph,gm	—	—	ph,gm	rare ph,gm	—	—	ph,gm	—	gm	ph,gm	zircon, sphene
quartz latite	—	ph	rare ph	ph	ph	—	—	ph	—	rare ph	—	rare ph	—	gm	—	zircon, sphene
rhyolite	—	rare ph	rare ph	ph	ph	—	—	ph	gm	—	—	ph,gm	—	gm	gm	zircon, sphene
Hoover Dam																
basalt	ph	ph	—	—	ph	—	—	ph	—	—	—	—	—	—	gm	—
andesite	ph	ph	—	ph	—	—	—	gm	—	—	—	xn	—	—	gm	—
dacite	ph	ph	ph	ph	ph	—	—	ph,gm	—	—	—	ph	—	—	gm	—
rhyolite	—	—	—	ph	ph	—	—	ph	—	—	—	xn	—	—	gm	—
Chiricahua Mountains																
basalt	—	ph,gm	—	—	—	—	—	ph,gm	—	—	—	—	—	—	gm	—
andesite	—	ph	—	ph	ph	—	—	ph	—	ph	—	—	—	gm	gm	—
quartz latite	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
rhyolite	—	ph	—	ph,gm	ph	—	gm (?)	ph	—	ph,gm	—	ph	—	gm	gm	sphene in gm
monzonite	—	ph	—	ph	—	—	—	—	—	—	—	—	—	—	—	—
Galiuro Mountains																
andesite	ph	ph,gm	—	—	—	—	—	—	—	—	—	—	—	—	—	—
trachyte	—	ph	—	—	ph	—	—	—	—	—	—	—	—	—	—	—
quartz latite	—	—	—	—	ph	—	—	ph	—	ph	—	ph	—	—	—	Holy Joe Member
rhyolite	—	ph	—	—	ph	—	—	ph	—	ph	—	ph	—	—	—	Aravaipa and Hells Half Acre
Castle Dome-Kofa Mountains																
latite	—	—	—	ph	ph	—	—	ph	—	—	—	ph,gm	—	—	—	—
dacite	—	—	—	ph	ph	—	—	ph	—	—	—	ph	—	—	—	—
rhyolite	—	ph	—	ph	ph	—	—	ph	—	ph	—	ph	—	—	—	—
Vulture Mountains																
basalt	ph	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
bas. andesite	ph	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
rhyolite	—	—	—	ph	ph	—	—	—	ph	—	—	ph	—	—	—	—
Mclendon Mountain																
basalt	ph	ph	—	—	ph	—	—	ph,gm	—	—	—	—	—	—	gm	—
andesite	ph	ph	—	ph	—	—	—	ph,gm	—	—	—	xn	—	—	gm	—
dacite	ph	ph	ph	ph	ph	—	—	ph,gm	—	—	—	rare ph	—	—	gm	—
rhyolite	—	—	ph	ph	ph	—	—	ph,gm	—	—	—	rare ph	—	—	gm	—

Table 3. (Continued)

Volcanic fields and rock names	Olivine	Clinopyroxene	Orthopyroxene	Hornblende	Biotite	Phlogopite	Feldspar	Plagioclase	Alkali feldspar	Sanidine	Anorthoclase	Quartz	Tridymite	Apatite	Opaques	Comments
Whitlock Mountains																
basalt	gm	gm	—	—	—	—	—	ph,gm	—	—	—	—	—	gm	gm	—
bas. andesite	ph	ph	ph	—	—	—	—	—	—	—	—	—	—	—	—	—
andesite	—	ph,gm	—	ph	—	—	—	ph,gm	—	—	—	ph	—	—	gm	turkey-track
dacite	—	ph	—	ph	ph	—	gm	ph,gm	ph	ph	—	—ph	—	—	gm	—
quartz latite	—	ph	—	—	—	—	gm	ph	—	—	—	rare ph	—	gm	gm	rare fluorite ph
rhyolite	—	ph	—	ph	ph	—	gm	ph	rare ph,gm	ph	—	ph,gm	gm	—	gm	—
Growler Mountains																
basalt .	ph,gm	ph,gm	—	—	—	—	—	ph,gm	—	—	—	—	—	—	gm	—
bas. andesite	ph	ph,gm	rare ph	—	—	—	—	ph,gm	—	—	—	—	—	—	gm	—
andesite	ph	ph	ph	rare ph,gm	ph	—	—	ph	—	—	—	—	—	—	gm	—
latite	ph,gm	ph,gm	rare gm	—	—	—	—	ph,gm	—	—	—	—	—	gm	gm	Childs Latite
rhyolite	—	—	—	—	—	—	ph	—	—	—	—	—	—	—	—	—
Unclassified fields																
Castle Hot Springs																
basalt	ph,gm	ph,gm	—	—	—	—	—	gm	—	—	—	—	—	—	gm	—
latite	—	—	rare ph	ph	ph	—	—	ph,gm	—	ph	—	—	rare ph	gm	gm	zircon
rhyolite	—	—	—	—	ph	—	—	ph	—	ph	—	—	—	—	—	—
Mohave Mountains																
mafic	ph	ph	—	—	—	—	—	—	—	—	—	—	—	—	—	—
silicic	—	id	—	id	id	—	—	—	—	—	—	—	—	—	—	—
Cerbat Mountains																
basalt	ph	ph	—	ph	—	—	—	—	—	—	—	xn	—	—	—	—
rhyolite	rare ph,xn	ph	—	ph	rare ph	—	—	ph	—	ph	—	ph	—	—	gm	rare sphene in Peach Springs Tuff

explanation of symbols:
ph = phenocrysts
gm = groundmass
xn = xenocrysts
id = identified but not recorded as either phenocrysts or groundmass
alk. ol. basalt = alkali olivine basalt
hi-al basalt = high-alumina basalt
qtz. basalt = quartz basalt
bas. andesite = basaltic andesite

— = not identified or absent
[1] minette of Navajo field also contains accessory melilite, perovskite, wollastonite, pectolite, thomsonite, and tobermorite (Laughlin and others, in press)

Francisco volcanic fields. Basaltic centers in the fields formed over relatively short periods of time compared to the larger silicic volcanic centers. Many basaltic vents probably formed over a period of a few months, but others probably developed over a few hundred years. Evidence of multiple eruptions from the same vent is indicated by petrographically and chemically distinct lithologies on the same structure, for example, in the Springerville, San Francisco, and Mormon Mountain volcanic fields.

The number of vents in individual basalt fields is highly variable (Lynch, this volume). The two largest fields, San Francisco and Springerville, each contain between 400 and 600 volcanic centers. Approximately 300 vents occur in the Pinacate field and 100-200 in the Mormon Mountain, San Bernardino, and western Grand Canyon fields. Relatively few vents are exposed in the Sentinel Plains field where low shield volcanoes dominate the topography.

Volcanic rocks of most of the basalt-dominated volcanic fields in Arizona yield ages less than about 15 Ma. The oldest volcanic rocks associated with these fields occur in the central part of the Transition Zone in the Mormon Mountain (15-3-Ma), Hackberry Mountain (13-3-Ma), and Black Hills (14-9-Ma) volcanic fields. Slightly younger, mostly basaltic rocks occur along the margin of the Colorado Plateau in the White Mountains (9-2-Ma), Western Grand Canyon (9-Ma), and Springerville (9-Ma) fields. The most recent basalt-dominated volcanism occurred in several parts of the southern Basin and Range (table 1).

Basaltic vents in several fields show strong preferred alignments, as indicated by chains of cones, elongate cones, and dikes. Northwesterly alignments are common in the San Francisco volcanic field, especially in the eastern part of the field (Moore and Wolfe, 1976). Most vents in the San Bernardino field show north-northeast alignment apparently controlled by preexisting structures and the regional state of stress (Lynch, 1978; Menges and others, 1981).

Volcanic centers are commonly referred to as monogenetic and polygenetic volcanoes. Monogenetic volcanoes are emplaced over a relatively short period of time, erupting only once (Nakamura, 1977). Monogenetic volcanoes in Arizona include some basalt cinder cones and basalt shield volcanoes and andesite and dacite lava domes in the Mormon Mountain, San Francisco, Springerville, and Black Hills fields. Polygenetic volcanoes evolve over a relatively long period of time and erupt numerous times from the same vent or vents. They commonly show a wide range in composition and style of volcanic activity. Examples of polygenetic volcanoes include San Francisco Mountain in the San Francisco field, Mormon Mountain in the Mormon Mountain field, and Mount Baldy in the White Mountains.

The largest shield volcano in Arizona, Mount Baldy, is a polygenetic center in the White Mountains volcanic field; it is composed of at least 20 trachyandesitic to trachytic, extrusive and pyroclastic units derived from the summit of Mount Baldy. Flow units are easily distinguished on the basis of their petrography. They vary from aphyric to coarsely porphyritic.

BIMODAL (BASALT-RHYOLITE) FIELDS

Several volcanic fields in western Arizona contain little or no andesite to dacite. Bimodal associations occur in the Castaneda Hills, Kaiser Spring, Mount Hope, and Mount Floyd volcanic fields (fig. 1). A bimodal association may also occur in the Plomosa Mountains, but sufficient geochemical data are unavailable for this area. Well-characterized bimodal associations show large silica gaps and similar chemical compositions. Silica gaps in the bimodal fields range from 58-72 weight percent SiO_2 in the Castaneda Hills, 56-69 weight percent silica in the Kaiser Spring field, and 52-70 weight percent SiO_2 in the Mount Floyd field. Rhyolite lavas in the fields can also be divided into low- and high-silica varieties.

Rhyolite volcanism in bimodal fields, and perhaps bimodal volcanism in general, shows a northeastward migration from the Basin and Range province, across the Transition Zone, and onto the Colorado Plateau over the past 19 m.y. Rhyolites erupted 19-15 Ma in the Castaneda Hills, 13-8 Ma in the Kaiser Spring area, 8 Ma in the Mount Hope field, and 10-2.5 Ma in the Mount Floyd field. Based on limited age data for the bimodal fields, basaltic volcanism preceded rhyolitic activity in all of them.

The alignment of the bimodal fields may be structurally controlled. The fields are situated along the southern extension of the Bright Angel fault system, a major structural feature in northern Arizona that dates from the Precambrian (Shoemaker and others, 1978).

ANDESITE-RHYOLITE-DOMINATED FIELDS

Large volcanic fields composed of large amounts of intermediate to silicic rocks, and relatively small amounts of basalt, occur in various parts of Arizona from the southeast to the northwest corner of the State. Two types of andesite-rhyolite-dominated fields are described: ash-flow fields and lava fields. Ash-flow fields are associated with the development and subsequent collapse of large silicic volcanoes. These fields formed in the Basin and Range province and along the margin of the Transition Zone. Andesite-rhyolite volcanism appears to have begun about 34 Ma and ceased about 10 Ma (table 1). Younger volcanic rocks in the andesite-rhyolite fields are generally basaltic or bimodal in composition and are not considered by us to be associated with any older andesite-rhyolite activity. The ash-flow fields include the Chiricahua Mountains, Black Mountains, Superstition-Goldfield Mountains, Castle Dome and Kofa Mountains, and the Blue Range. No caldera-related volcanism occurred on the Colorado Plateau.

In central Arizona, ash-flow tuffs form one of the largest and most complex volcanic centers in the State, the

Superstition-Goldfield Mountains volcanic field. The field covers at least 5,000 km^2 of the Transition Zone and includes calc-alkaline latitic and rhyolitic ash-fall and air-fall tuffs, lavas, and breccias. Minor amounts of nepheline-normative alkalic basalt were extruded at various times during the development of the volcanic sequence. Sheridan (1978) suggested that the volcanic sequence resulted from the emplacement of three overlapping cauldrons: the Superstition cauldron (25 Ma), the Goldfield cauldron (15-16 Ma), and the Tortilla cauldron (<15 Ma).

The Chiricahua Mountains in southeastern Arizona is a well-characterized andesite-rhyolite ash-flow field composed of rocks ranging in composition from basalt to rhyolite. The source of many of the lavas was the Turkey Creek caldera, a feature that is now occupied by a resurgent monzonitic intrusion. The caldera erupted high-silica rhyolite ash-flow tuff that locally attains a thickness of 430 m (Latta, 1983). The remainder of the ash-flow tuffs originated from a vent area southeast of the Turkey Canyon caldera. Most dated rocks from the Chiricahua Mountains yield ages between 32 and 22 Ma.

Northwest of the Chiricahua Mountains in the Galiuro Mountains is a sequence of andesitic to rhyolitic flows and tuffs, the Oligocene and Miocene Galiuro Volcanics, that includes two major and two minor ash-flow tuffs (Creasey and Krieger, 1978; Krieger, 1979).

Widespread ash-flow sheets in the Castle Dome and Kofa Mountains were derived from at least two late Oligocene and Miocene calderas (Grubensky and others, 1986; Grubensky, 1987). The ash flows are associated with lahars, pyroclastic tuffs, and silicic to intermediate lava flows and domes. Inferred calderas are situated above a 25-mGal negative gravity anomaly.

The 19-Ma Peach Springs Tuff is a key stratigraphic horizon in west-central Arizona and parts of southern California. The unit covers more than 35,000 km^2; it attains a maximum thickness of 90 m in the southern part of the Cerbat Mountains. The source of the Peach Springs Tuff is unknown, but it is thought to have erupted from the nearby Black Mountains or a buried caldera in the area.

The second type of andesite-rhyolite-dominated field is characterized by voluminous andesite-rhyolite flows and pyroclastic rocks. These fields differ from the ash-flow fields by the absence of voluminous ash-flow sheets. Examples of andesite-rhyolite lava fields include the Growler Mountains in the Basin and Range province and the Mohon and Aquarius Mountains in the western part of the Transition Zone. Vent areas for andesite and dacite rocks in the Mohon and Aquarius Mountains are Miocene (22-20-Ma) stratovolcanoes. Volcanic products include lava flows, breccias, and minor pyroclastic deposits.

UNCLASSIFIED FIELDS AND OTHER VOLCANIC ROCKS

Because of limited geologic and geochemical information, we are presently unable to classify the volcanic rocks of the Castle Hot Springs, Mohave Mountains, Cerbat Mountains, Trigo Mountains, and Martin Mountain volcanic fields. The volcanic section in Castle Hot Springs area does not fit any of our five volcanic associations. Ward (1977) estimated that the area contains 10 km^3 of basalt, 13 km^3 of rhyolite, and about 6 km^3 of intermediate (latite) lavas and pyroclastic rocks. We are uncertain whether this package should constitute a sixth volcanic association or just reflects the limited scope of Ward's study.

The volcanic section in the southern Cerbat Mountains includes a thick (<100-m) lower basalt section, which is overlain by the informally named <55-m-thick Cook Canyon tuff, which is in turn overlain by the <90-m-thick Peach Springs Tuff (Buesch and Valentine, 1986). Numerous K-Ar dates indicate that the Peach Springs Tuff is about 19.2 Ma. Basalts of the Cerbat Mountains were derived from local vents; the Cook Canyon and Peach Springs ignimbrites were derived from an unknown source(s). Based on the descriptions of Buesch and Valentine (1986), the two ignimbrites can be distinguished on the basis of their modal compositions. The older Cook Canyon tuff contains phenocrysts of biotite and plagioclase and has trace amounts of quartz, olivine, clinopyroxene, and hornblende. The Peach Springs Tuff is composed of sanidine, quartz, plagioclase, and sphene phenocrysts. Hornblende, olivine, and clinopyroxene also occur in the Peach Springs Tuff and, according to Buesch and Valentine (1986), may be xenocrystic in origin. These workers also suggested that the Peach Springs is a simple cooling unit in the southern Cerbat Mountains.

The volcanic geology of the Trigo Mountains is poorly known because much of it lies within the restricted part of the Yuma Proving Grounds. Based on the geology of the surrounding mountain ranges, we would guess that this is an andesite-rhyolite field. We also do not presently have sufficient information to classify the Mohave Mountains field. Volcanic rocks of this area have been dated between 39 and 19 Ma.

Two distinctive rock types occur in southern and eastern Arizona. The first is a "turkey-track" andesite that is composed of abundant (as much as 90 per cent of the mode), large plagioclase phenocrysts (as much as 4 cm in length) and sparse clinopyroxene, orthopyroxene, and olivine phenocrysts and corroded quartz xenocrysts (Cooper, 1961; Percious, 1968). The unit receives its name from its characteristically large "turkey-track" glomerocrysts (as much as 5 cm in diameter; Richter and others, 1983). It is distributed across a large part of southern Arizona where it has been dated between 36 and 27 Ma. Turkey-track andesites also occur in the Peloncillo Mountains, in the east-central part of the state, where one unit there has been dated at 20.4 Ma (Richter and others, 1983).

The second distinctive unit in southern Arizona is the Miocene Childs Latite. This rock is composed of plagioclase phenocrysts (as much as 2.5 cm in length), augite, and sparse olivine phenocrysts in a groundmass of magnetite, olivine, plagioclase, augite, rare orthopyroxene, and minor glass (Gilluly, 1946; Gray and others, 1985). The unit has been dated at about 18 Ma.

XENOLITHS AND MEGACRYSTS

Xenolith- and megacryst-bearing volcanic rocks are common in Arizona (fig. 1). Mantle-derived xenoliths represent fertile and refractory upper mantle material. Cumulate xenoliths are interpreted to be high-pressure products of fractional crystallization and may represent fragments of layered basic intrusions, pieces of deep-seated plutonic bodies, or feeder dikes for high-level intrusions or eruptive rocks. These rocks provide direct evidence of the composition of the upper mantle and deep crust.

Mantle and cumulate xenoliths in basaltic rocks are distinguished from one another on the basis of petrography and chemical composition. Mantle-derived xenoliths usually are lherzolites and harzburgites. These rocks are dominated by olivine, orthopyroxene, clinopyroxene, and spinel, in decreasing order of abundance. Minor amounts of phlogopite and pargasite also occur in some mantle xenoliths. Cumulate xenoliths have highly variable modes, but the proportion of clinopyroxene usually exceeds that of orthopyroxene. Plagioclase is primary in cumulate gabbros. Cumulate xenoliths contain accessory titanomagnetite, apatite, and ilmenite. Eclogites in the latite fields are garnet-clinopyroxene rocks containing small amounts of amphibole, apatite, rutile, iron-titanium oxides, and altered clinozoisite (Arculus and Smith, 1979; Helmstaedt and Schulze, 1979; Tyner, 1984; Esperanca and Holloway, 1984). Mantle xenoliths are depleted in iron (Mg/Mg+Fe = 0.86 to 0.91) and light rare-earth elements (chondrite-normalized La <20) compared with cumulate xenoliths (Mg/Mg+Fe = 0.62 to 0.78; chondrite-normalized La = 8-120).

Host rocks for xenoliths and megacrysts include a wide range of mafic and intermediate rocks. Garnet-bearing xenoliths (garnet peridotites, garnet clinopyroxenites, and eclogites) are virtually limited to the lamprophyres in the Navajo field and to latites in the Transition Zone (table 4). Best (1975) described pyropic garnet-bearing xenoliths from the western Grand Canyon volcanic field. No other garnet-bearing xenoliths have been described from alkalic basalts in Arizona. Spinel-bearing xenoliths occur in alkalic basalts, latites, and lamprophyres of the Navajo field. Mica clinopyroxenites occur in lamprophyres in the Hopi Buttes and Navajo fields and in latites of the Sullivan Buttes (Arculus and Smith, 1979). Gabbros are locally present in alkalic basalts.

The size and shape of xenoliths in volcanic rocks are highly variable (table 4). Most xenoliths are 2-3 cm in diameter, but some are as large as 55 cm. They range in shape from well rounded to angular. Round ones are thought to have been abraded during ascent to the surface.

The most petrographically distinctive cumulate xenoliths are comb-layered mafic and ultramafic rocks from the Mount Floyd and San Francisco volcanic fields (Nealey, 1980). Most of them consist of alternating bands (0.1-1.0 cm thick) of clinopyroxene, olivine, and plagioclase in a matrix of opaque oxides and glass. The crystals are strongly oriented, generally perpendicular to the banding. These rocks are thought to represent quenched basaltic melts formed at shallow depths along the walls of dikes and other magma reservoirs.

Volcanic rocks that contain ultramafic and mafic xenoliths usually also contain large single-crystal fragments (table 4). Megacrysts (as large as 14 cm) of clinopyroxene, amphibole, and plagioclase are common; those of olivine, spinel, magnetite, orthopyroxene, anorthoclase, and biotite are rare. Clinopyroxene and amphibole generally are the largest megacrysts, and clinopyroxene is invariably the dominant megacrystal phase. Megacrysts have been interpreted as cognate crystals and as accidental inclusions incorporated into ascending mafic and intermediate magmas.

In addition to ultramafic and mafic xenoliths and megacrysts, some mafic and intermediate volcanic rocks also contain lower crustal, granulite-facies inclusions. Granulite-facies and gneissic xenoliths have been reported from the Navajo, Sullivan Buttes, Camp Creek, San Carlos, San Bernardino, San Francisco, Castaneda Hills, and Mount Hope volcanic fields (table 4). The compositions of these rocks are variable, ranging from two-pyroxene granulite to charnockite to amphibolite to eclogite (Kempton and others, 1984; Stoeser, 1973; Esperanca and others, 1988).

Lower crustal xenoliths from the Colorado Plateau and Transition Zone show a wide range in Sr-isotope ratio. Granulite xenoliths in basalts of the San Francisco volcanic field have low measured ^{87}Sr/^{86}Sr values (0.7026-0.7037; Gust and Arculus, 1986; M. A. Lanphere, U.S. Geological Survey, written commun. 1987; Unruh and Nealey, U.S. Geological Survey, unpub. data). These values are similar to those assumed for the sources of basalts in Arizona. Measured ^{87}Sr/^{86}Sr values of eclogites and amphibolites from the Sullivan Buttes and Camp Creek are generally higher than those for San Francisco field granulites (Sullivan Buttes: 0.7040-0.7074, Arculus and others, in press; Camp Creek: 0.7047-0.7081, Esperanca and others, 1988). Sr isotopic compositions of Sullivan Buttes and Camp Creek eclogites are similar to those of some samples of the Jurassic Point Sal ophiolite in California (Menzies and others, 1977). These data allow that the xenoliths were derived from subducted oceanic lithosphere, as suggested by Helmstaedt and Doig (1975) for similar xenoliths from the Navajo volcanic field.

Most Type I ultramafic xenoliths from the Transition Zone and Basin and Range have low measured Sr isotopic ratios. Of five Sr isotopic analyses that have recently been reported, four are between 0.7031 and 0.7040 (Zindler and Jagoutz, 1988; Menzies and others, 1985). One of the most petrologically fertile mantle samples analyzed from San Carlos yielded a value of 0.70555. The high Sr-isotope ratio of this sample is in part due to secondary contamination by caliche.

The isotopic compositions of mantle and crustal xenoliths are important for characterizing mantle and lower crustal sources of silicate melts. Available strontium isotopic data for mantle and crustal xenoliths indicate that the upper mantle and lower crust beneath some parts of Arizona have similar Sr isotopic ratios (Menzies and others, 1985; Roden and Jagoutz, 1988; Gust and Arculus, 1986; D. M. Unruh and L. D. Nealey, U.S. Geological Survey, unpub. data). These data emphasize that certain magmatic processes, such as crustal contamination, may be difficult to discern solely on the basis of isotope geochemistry. To illustrate this, it is usually assumed that crustal contamination results in enrichment in radiogenic Sr. Sr isotopic ratios greater than 0.706 in basalts are commonly taken as evidence of crustal contamination; however, assimilation of some lower crustal material can actually lower the Sr isotopic ratios of rising magmas. At this time we know very little about the composition of the lower crust, but it has to be considered in our models of magma genesis.

GEOCHEMISTRY

Volcanic rocks in Arizona show a large range in composition, from strongly undersaturated lamprophyres to strongly oversaturated high-silica rhyolites. The silica content of these rocks ranges from 36 weight percent in some lamprophyres to more than 77 percent in high-silica rhyolites. Trace-element abundances also show considerable ranges, from high incompatible-element abundances in some lamprophyres to low incompatible-element abundances in some tholeiitic basalts. In the following sections, we present geochemical data for the five petrologic groups described above. These data clearly show the spectrum of major- and trace-element compositions and isotopic ratios that characterize the volcanic rocks in Arizona.

Major-, trace-, and rare-earth-element whole-rock analyses that we have obtained were performed by X-ray fluorescence and instrumental neutron activation analysis in the laboratories of the U.S. Geological Survey in Menlo Park, California, and Denver, Colorado. Analytical techniques for the U.S. Geological Survey data were described by Baedecker and McKown, (1987), Taggart and others (1987), and Johnson and King (1987).

Major-element geochemistry

The nomenclature of volcanic rocks is based mainly on major-element chemistry. Whereas plutonic rocks can be classified on the basis of their petrography, the abundance of matrix material (e.g., glass) in volcanic rocks makes geochemical data essential for their classification. In this section we discuss the volcanic rocks of Arizona on the basis of more than 3,000 major-element analyses. The object is to classify the rocks according to the recommendations of the International Union of Geological Sciences Subcommission on the Systematics of Igneous Rocks (LeBas and others, 1986, fig. 2). This nongenetic classification scheme uses total alkalies and silica. Analyses were normalized volatile free before plotting.

Lamprophyres on the Colorado Plateau range chemically from foidite to trachyandesite. Hopi Buttes and Navajo lamprophyres contain 40-59 weight percent SiO_2 (fig. 2). Most of the analyzed Hopi Buttes rocks are basanites, but most of the analyzed Navajo rocks are shoshonites and latites. Both lamprophyre suites plot above the line that separates alkalic from subalkalic rocks in Hawaii (Macdonald and Katsura, 1964).

Latites in the Transition Zone are also potassic rocks with shoshonitic affinities. They plot in the shoshonite, latite, and K-trachyte fields on alkali-silica diagrams. Latites straddle the alkalic-subalkalic line and have K_2O/Na_2O greater than unity.

Volcanic rocks in basalt-dominated fields range in composition from basalt to rhyolite (figs. 2 and 3). Most mafic rocks are alkalic basalt; a few are tholeiitic. Many basalt-dominated suites straddle the alkalic-subalkalic line, and they commonly trend from the alkalic field to the subalkalic field with increased silica content.

Two distinct chemical trends are present in the Pinacate volcanic field. Older Pinacate rocks (18-5 Ma) are subalkalic with calc-alkalic affinities. Younger lavas (<2 Ma) are alkalic and range in composition from basalt to trachyte. This pattern shows that relatively similar parent magmas can evolve along different paths.

The bimodality of the bimodal (basalt-rhyolite) volcanic fields is apparent on alkali-silica diagrams and silica histograms (figs. 2 and 3). Whereas the basalt-dominated fields with differentiated rocks contain substantial amounts of andesite and dacite (e.g., Mormon Mountain), the bimodal fields contain no dacite and usually no andesite (e.g., Mount Floyd, Kaiser Spring). Rhyolites in the bimodal fields plot below the extension of the alkalic-subalkalic line and can be distinguished into a high-silica group and a low-silica group. Low-silica rhyolite in the Mount Floyd field averages about 70 weight percent SiO_2 and high-silica rhyolite 76 weight percent SiO_2.

Andesite-rhyolite-dominated fields contain rocks ranging in composition from basalt to rhyolite (fig. 2). Analyzed basic rocks in the fields are typically alkalic basalts that plot above the alkalic-subalkalic line.

Although unaltered volcanic rocks are analysed if available, many of the late Cenozoic volcanic rocks in southern and central Arizona have undergone pervasive alteration. Identification of these rocks is extremely important for geochronologic studies in the region. Alteration of late Oligocene and Miocene andesite-rhyolite suites is indicated by either abnormally high or abnormally low total alkali contents, by high K_2O/Na_2O, and by the presence of secondary potassium feldspar (Or_{95}-Or_{99}; S. J. Reynolds, written commun., 1987), epidote, calcite, and silica (W. E. Brooks, oral commun., 1987). Altered volcanic rocks occur in the Mohave Mountains ($K_2O/Na_2O < 54$), Vulture Mountains ($K_2O/Na_2O < 42$), Chiricahua Mountains ($K_2O/Na_2O < 44$), at Hoover Dam ($K_2O/Na_2O < 10$), and in the Castle Dome Mountains ($K_2O/Na_2O < 7$).

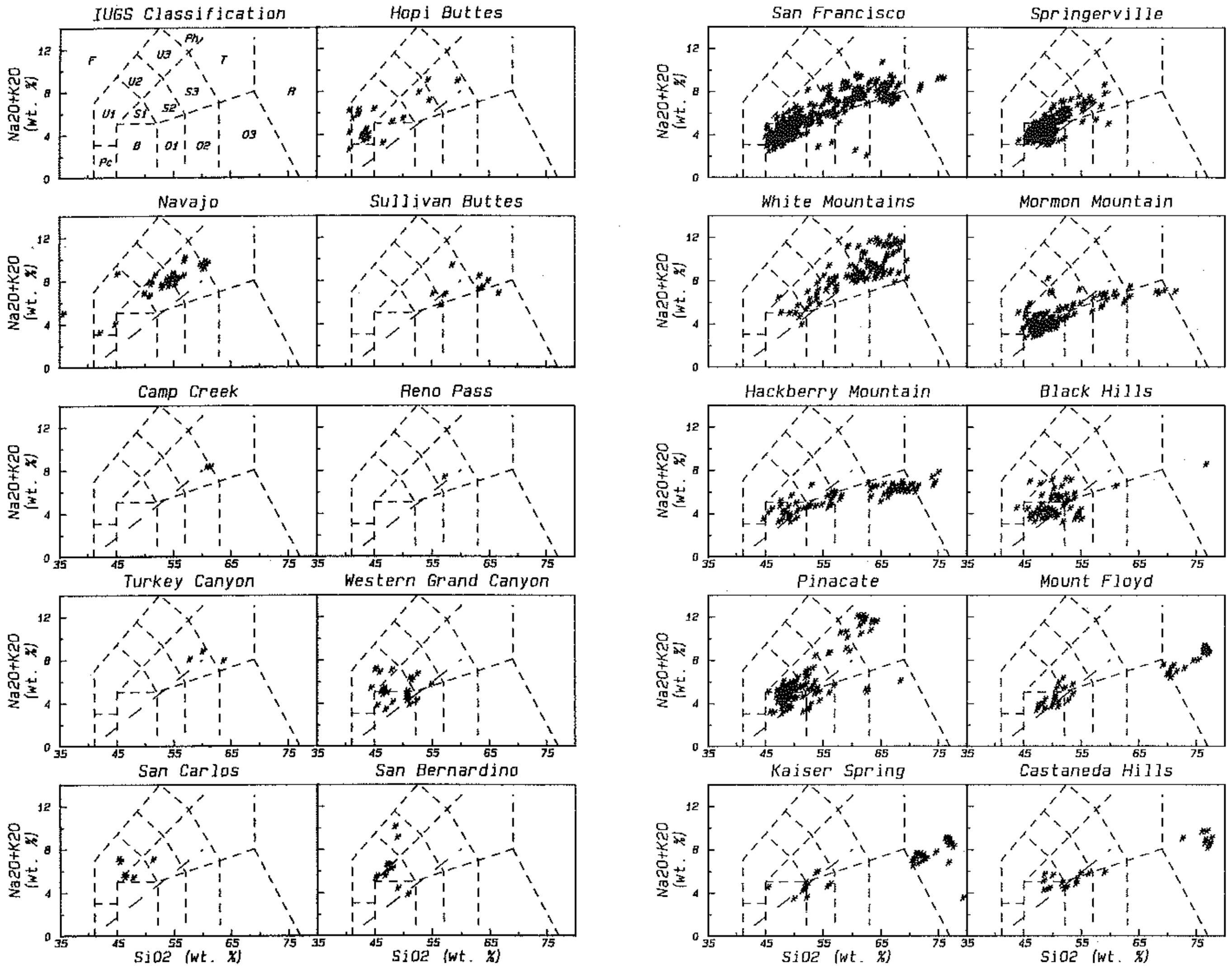


Figure 2. Alkali versus SiO_2 diagrams for selected post-Laramide volcanic rocks in Arizona and in northern Sonora, Mexico. Classification scheme from LeBas and others (1986). Pc = picrobasalt; B = basalt; O1 = basaltic andesite; O2 = andesite; O3 = dacite; R = rhyolite; S1 = trachybasalt; S2 = basaltic trachyandesite; S3 = trachyandesite; T = trachyte; U1 = basanite; U2 = phonotephrite; U3 = tephriphonolite; Ph = phonolite; and F = foidite. Long-dashed line is alkalic-subalkalic line of Macdonald and Katsura (1964). All values in weight percent (adjusted volatile-free). Sources of data given in table 2. (Continued on next page.)

Trace-element Geochemistry

Although they amount to less than one percent of a rock, trace elements are extremely valuable for understanding the origin and evolution of volcanic rocks. Based on more than 300 trace-element analyses, abundances of Rb, Ta, Th, Cr, and Sr were used to distinguish the five petrologic groups. The selection of the elements was made on the basis of the availability of data, but more importantly to show the behavior of specific elemental groups. Rb was selected as an index of differentiation and as a good indicator of crustal interaction. Ta usually behaves as an incompatible trace element that is little affected by post-emplacement alteration and is commonly highly correlated with other incompatible elements. Cr is a compatible element that is sensitive to the fractionation of mafic mineral phases. Sr is highly compatible with feldspars and is essential to Rb-Sr isotopic systematics. And finally, Th was selected as an index of differentiation because of its highly incompatible behavior in magmatic systems.

Rb and Cr show considerable variability in Arizona volcanic rocks. Rb ranges from 5 ppm in sodic lamprophyres to 300 ppm in potassic lamprophyres, trachytes, and high-silica rhyolites. Rb generally increases in abundance with increasing differentiation. Cr is usually high in mafic rocks

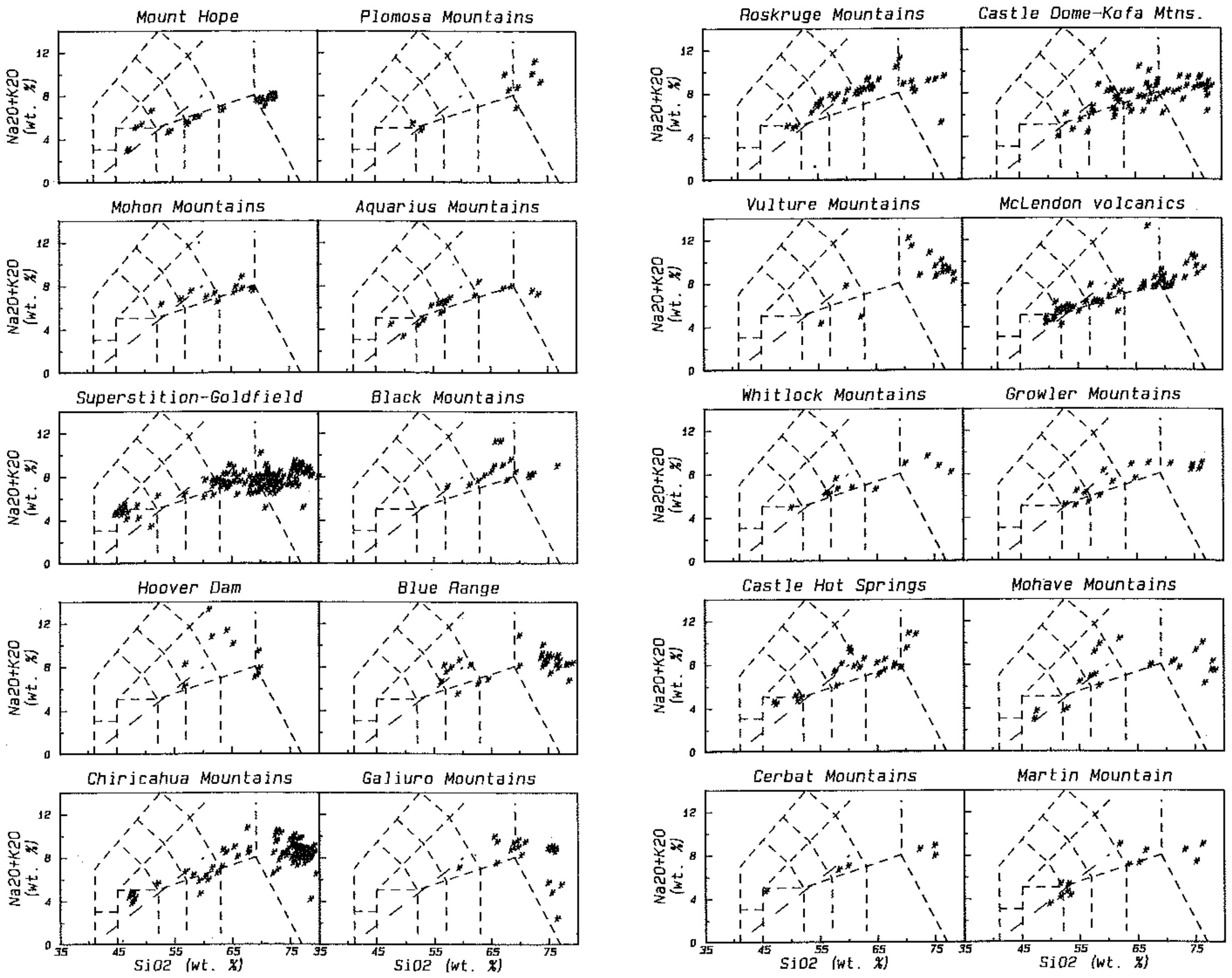


Figure 2, continued.

(as much as 575 ppm in K-lamprophyres; as much as 700 ppm in basalts of basalt fields), low in intermediate and acid rocks (as little as <1 ppm, the instrument detection limit for neutron activation analysis). The decrease in Cr content with increasing differentiation is in part related to its preferential incorporation into clinopyroxene and olivine during fractional crystallization.

Cr versus Rb diagrams (fig. 4) demonstrate that (1) the late Oligocene and Miocene volcanic rocks of the Transition Zone and Colorado Plateau have high Cr and Rb concentrations, (2) the late Miocene to Holocene basalt-dominated suites generally show a rapid decrease in Cr with increasing Rb content, and (3) the late Miocene and Pliocene rocks of bimodal basalt-rhyolite suites are characterized by intermediate rates of decrease of Cr with increase of Rb. In general, Cr decreases with increasing Rb content, but these two elements show considerable scatter in suites from the Springerville, Black Hills, and the Hopi Buttes areas. Two samples from the Springerville field have high Rb and low Cr contents compared with the rest of the suite; they were derived from lava flows erupted from Mount Baldy (White Mountains field). Cr and Rb are highly correlated in the bimodal suites of the Mount Floyd, Castaneda Hills, and Kaiser Spring volcanic fields and in lamprophyres of the Navajo field. One the most interesting characteristics of these rocks, and of latites from Sullivan Buttes and Turkey Canyon latites, is their high Cr contents at high Rb concentrations. Two samples from the Mohon Mountains also have high Cr contents at intermediate to high Rb concentrations.

Trends in some basaltic volcanic fields that show little change in Rb with change in Cr (e.g., Springerville) are difficult to explain solely by olivine and clinopyroxene fractionation. To explain the trace-element variations in the western part of the Springerville volcanic field, Condit (1984) suggested that the basalts evolved from different

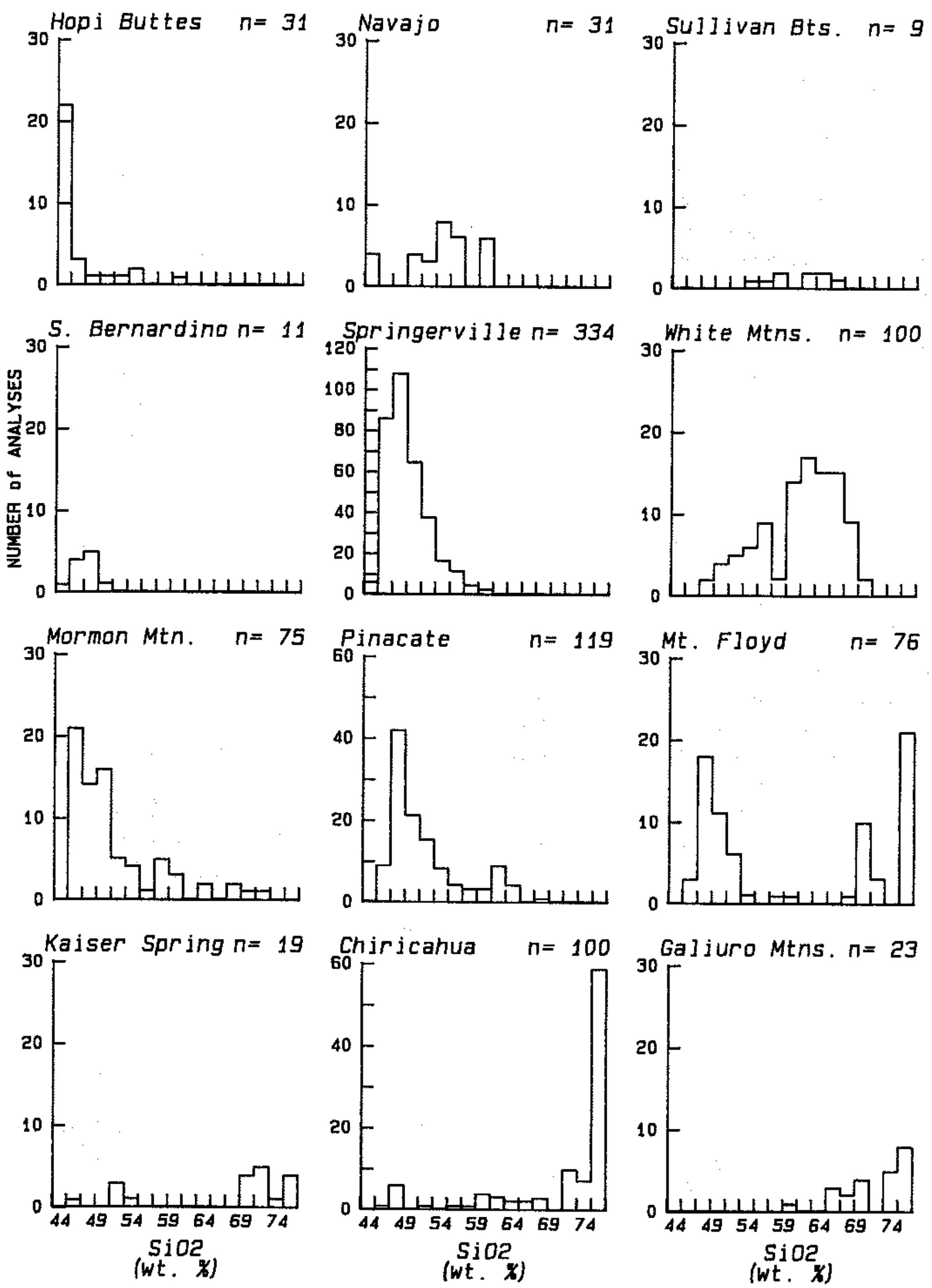


Figure 3. Histograms showing the distribution of silica in rocks from selected post-Laramide volcanic fields of Arizona and of northern Sonora, Mexico. Data sources are given in table 2. All analyses plotted volatile-free. Analyses less than 42 weight percent silica normalized to 42 percent silica. Analyses greater than 77 weight percent silica normalized to 77 percent silica. Normalization affects the lamprophyre fields and altered rocks and was done in order to allow better comparison between fields.

batches of parental magma. Based on preliminary analysis of available data, Condit's model may be true for other basalt-dominated fields such as the San Francisco and Mormon Mountain fields. Strong negative correlations between Cr and Rb in the bimodal suites are probably related to the basalts having a mantle source and the rhyolites having a crustal origin. Intermediate members of these suites may be the products of magma mixing. The high Cr and Rb contents of the late Oligocene and Miocene lavas are enigmatic.

Strontium concentrations in Arizona volcanic rocks are even more variable than Rb concentrations. Strontium ranges from 4,150 ppm in limburgitic tuffs of the Hopi Buttes to less than 10 ppm in some high-silica rhyolites. Strontium abundances in latites are 700-1,300 ppm and in the basalts of basalt and bimodal fields are 300-3,000 ppm (e.g., Black Hills 400-3,000 ppm; Mohon Mountains 300-800 ppm; Castaneda Hills, 350-900 ppm; Mormon Mountain, 400-800 ppm). In basalt fields with differentiated rocks the concentration of Sr generally decreases with increasing silica content, but in several suites in central Arizona Sr increases in the basalt-andesite range and decreases in the dacites and rhyolites (e.g., Mormon Mountain and Mohon Mountains). In the bimodal basalt-rhyolite fields, the concentration of Sr is either higher in the basaltic rocks than it is in the rhyolites (e.g., Kaiser Spring), or completely uncorrelated with silica content (e.g., Mount Floyd). High-silica rhyolites in the Kaiser Spring and Mount Floyd fields are depleted in Sr relative to the low-silica rhyolites. Of five analyzed high-silica rhyolites from the Mount Floyd field, four contain less than 10 ppm Sr, compared to 210-750 ppm Sr in the low-silica rhyolites.

Arizona volcanic rocks define two distinct patterns on Sr versus Rb diagrams: one a curvilinear pattern and the other a linear pattern (fig. 5B). Bimodal and andesite-rhyolite suites show curvilinear patterns that trend from high Sr contents at low Rb to low Sr at high Rb. Pinacate and White Mountains volcanic rocks (fig. 5A) also closely follow the same overall trends. Pinacate rocks, however, show a much more rapid decrease in Sr with increasing Rb than the bimodal and andesite-rhyolite suites. Lamprophyres of the Hopi Buttes and Navajo volcanic fields have high Sr contents at nearly constant Rb levels, but the rocks in the latter field have higher Rb concentrations than Hopi Buttes lamprophyres, consistent with their potassic affinities. Latites of the Sullivan Buttes and Camp Creek volcanic fields contain similar amounts of Sr at nearly constant Rb levels. Sr abundances in the latites, however, are slightly lower than they are in Navajo lamprophyres.

We attribute the two distinct patterns of Sr versus Rb to a combination of crystal fractionation and crustal contamination. Removal of olivine and clinopyroxene will increase Sr and Rb in the residual liquids; however, the fractionation of plagioclase will decrease Sr and increase Rb in the residual magma. Suites such as those from the White Mountains show plagioclase-controlled fractionation. Other suites that are enriched in Rb relative to Sr apparently originated by mixing of mantle-derived melts and middle-upper crustal material. High Sr concentrations in some Colorado Plateau and Transition Zone rocks are considered by us to be related to interaction with high-Sr lower crust, as indicated by the presence of high-Sr lower crustal xenoliths.

The second index of differentiation that we use for interelement comparison is tantalum. Tantalum is highly incompatible in magmatic systems, being partitioned preferentially into the melt during crystal fractionation. It occurs in trace abundances (0.4-15 ppm) in volcanic rocks in Arizona. Binary plots of Th versus Ta for rocks from various volcanic fields show two basic patterns (fig. 6A). The first pattern is characterized by strong positive correlations between Ta and Th. Rocks from the Mount Floyd, Springerville, White Mountains, San Francisco, Mormon Mountain, Chiricahua Mountains, and Kaiser Spring fields typify this trend. The second pattern is a shotgun array and typifies the Castaneda Hills and Mohon Mountains suites. Sullivan Buttes and Turkey Canyon latites show features of this pattern and are notable for their high Th abundances at low Ta contents (0.6-2 ppm Ta). Ash-flow tuffs of the Chiricahua Mountains also have high Th contents but are enriched in Ta (2-7 ppm Ta) compared with the latites. Navajo lamprophyres also have high Th contents (18-70 ppm); however, the concentration of Ta in these rocks is poorly known. A single Ta analysis of a Navajo lamprophyre gave a value of 4.15 ppm (Thompson and others, 1984). If the data for the late Oligocene and early Miocene lavas are representative, then these rocks can be distinguished from younger volcanic rocks by their generally low Ta and high Th abundances.

Strong correlations between Ta and Th are commonly used to test whether volcanic rocks are related by crystal fractionation or by some other magmatic process. This test involves the assumption that mineral phases on the liquidus of silicate melts are solely responsible for magmatic differentiation. In continental volcanic fields, this assumption may not be valid because of the likelihood of crustal contamination and anatexis. Assuming that the crust beneath Arizona has Ta and Th abundances similar to the average upper crust and lower crust estimated by Taylor and McClennan (1985), then patterns for several of the volcanic suites in Arizona (e.g., Castaneda Hills, San Francisco, Mormon Mountain) have minimum Ta contents similar to the composition of average lower crust (0.6 ppm Ta; 1.06 ppm Th), and many have maximum Ta contents near the composition of average upper crust (2.2 ppm Ta; 10.7 ppm Th; Taylor and McClennan, 1985). These similarities may be indicative of substantial crustal involvement in the evolution of these rocks.

Rare-earth Element Geochemistry

Lanthanide-group elements are important trace elements for studying magmatic processes in igneous rocks. Their abundances relative to chondrites, mid-ocean ridge basalt, and primitive mantle are a common means of comparing volcanic rocks within individual volcanic fields and between volcanic fields from different tectonic environments. In this section we use chondrite-normalized rare-earth-element (REE) diagrams to characterize post-Laramide volcanic rocks in Arizona. Chondrite-normalized REE patterns for selected volcanic rocks from several post-Laramide fields are shown in figure 7. We do not show REE spectra for tuffaceous rocks from the Navajo and Hopi Buttes fields because of possible effects of crustal contamination and post-emplacement alteration.

Table 4. Types of xenoliths and megacrysts in volcanic rocks of Arizona and of northern Sonora, Mexico. (Rock and mineral names are those of original workers. Maximum dimension of inclusions shown in parentheses.)

Field no.	Field name	Xenoliths	Megacrysts	Reference
			Lamprophyre fields	
1.	Hopi Buttes	mica clinopyroxenite, hornblendite (12.5 cm)	clinopyroxene, mica, amphibole (5 cm)	Lewis (1973); L.D. Nealey, unpub. data
2.	Navajo	spinel peridotite, garnet peridotite, lherzolite, harzburgite, dunite, websterite, garnet granulite, eclogite, clinopyroxenite (30 cm)	clinopyroxene (9 cm)	McGetchin and Silver, 1972; Ehrenberg, 1978; Hunter and Smith, 1981; O'Brien, 1983
			Latite fields	
3.	Sullivan Buttes	eclogite, hornblendite, garnet clinopyroxenite, amphibole garnet websterite, granulite, spinel peridotite (55 cm)	orthopyroxene,	Arculus and Smith, 1979; Tyner and Smith, 1986; Tyner, 1984; Arculus and others, in press
4.	Camp Creek	eclogite, amphibolite, garnet websterite (15 cm)		Esperanca and Holloway, 1984
5.	Reno Pass	eclogite (7.5 cm)		M.F. Sheridan, unpub. data
			Basalt fields	
7.	Western Grand Canyon	amphibole peridotite, spinel peridotite, gabbro, garnet-spinel peridotite (30 cm)	kaersutite, clinopyroxene, orthopyroxene, olivine (6 cm)	Best, 1970, 1974a,b, 1975
8.	San Carlos	spinel lherzolite, harzburgite, websterite, clinopyroxenite, orthopyroxenite, gabbro, granulite (21.5 cm)	kaersutite, plagioclase, spinel, olivine, clinopyroxene, biotite, anorthoclase (6 cm)	Frey and Prinz, 1978; Basu, 1978; Caporuscio, 1980; Garcia and others, 1980; Irving and Frey, 1984; Zindler and Jagoutz, 1988; Joaquin Ruiz, oral commun., 1988
9.	San Bernardino	alkali gabbro, kaersutite peridotite, two-pyroxene granulite, spinel lherzolite, clinopyroxenite, websterite, wehrlite, harzburgite, granulite (30 cm)	clinopyroxene, plagioclase, olivine, spinel, amphibole, anorthoclase (6 mm)	Lynch, 1972; Arculus and others, 1977; Evans and Nash, 1979; Kempton and others, 1984; Menzies and others, 1985
10.	Sentinel Plains	olivine clinopyroxenite (1 cm)		L.D. Nealey, USGS, unpub. data
11.	San Francisco	granulite, dunite, spinel pyroxenite, wehrlite, gabbro, websterite, granulite, anorthosite, clinopyroxenite (50 cm)	clinopyroxene, olivine (6 cm)	Cummings, 1972; Stoeser, 1973; R.B. Moore, USGS, unpub. data
12.	Springerville	olivine-clinopyroxenite, gabbro (30 cm)	clinopyroxene, plagioclase, amphibole (2.5)	Condit, 1984; L.S. Crumpler and J.C. Aubele, USGS, unpub. data
13.	White Mountains	olivine-clinopyroxenite (3 cm)	clinopyroxene (1.5 cm)	L.D. Nealey, unpub. data
14.	Mormon Mountain	gabbro, spinel wehrlite, olivine websterite, spinel websterite (8 cm)	clinopyroxene, olivine (9 cm)	Gust and Arculus, 1986; L.D. Nealey, unpub. data
19.	Pinacate	gabbro, dunite, spinel peridotite, clinopyroxenite, websterite, wehrlite (35 cm)	plagioclase, clinopyroxene, spinel, olivine, amphibole (10 cm)	Lynch, 1981; Gutmann, 1986
			Bimodal (basalt-rhyolite) fields	
20.	Mount Floyd	spinel peridotite, gabbro, dunite (12 cm)	plagioclase, clinopyroxene, amphibole (3 cm)	Nealey, 1980
22.	Castaneda Hills	peridotite, gabbro, websterite, wehrlite, granulite (28 cm)	plagioclase, clinopyroxene, olivine, spinel, magnetite, amphibole (11 cm)	Suneson and Lucchitta, 1983; Wilshire and others, 1985
21.	Mount Hope	spinel peridotite, gabbro, gneiss (18 cm)	plagioclase, amphibole, clinopyroxene, magnetite (14 cm)	Nealey and Ward, USGS, unpub. data; A.M. Simmons, SUNY at Buffalo, unpub. data
			Andesite-rhyolite fields	
37.	Hoover Dam	dunite, wehrlite, websterite, spinel lherzolite (15 cm)	amphibole, olivine, plagioclase, clinopyroxene, alkali feldspar (15 cm)	Campbell and Schenk, 1950; Basu, 1978; Garcia and others, 1980

All volcanic rocks in Arizona are enriched in REE relative to average chondritic values. Minettes in the Navajo field show the most enrichment (total REE abundances = 286-942 ppm), followed by Hopi Buttes lamprophyres (total REE = 418-572 ppm). Rocks showing the least REE enrichment are tholeiites in the Black Hills (total REE = 46 ppm) and Martin Mountain volcanic fields (total REE = 42 ppm). Ultramafic microbreccias of the Navajo field also

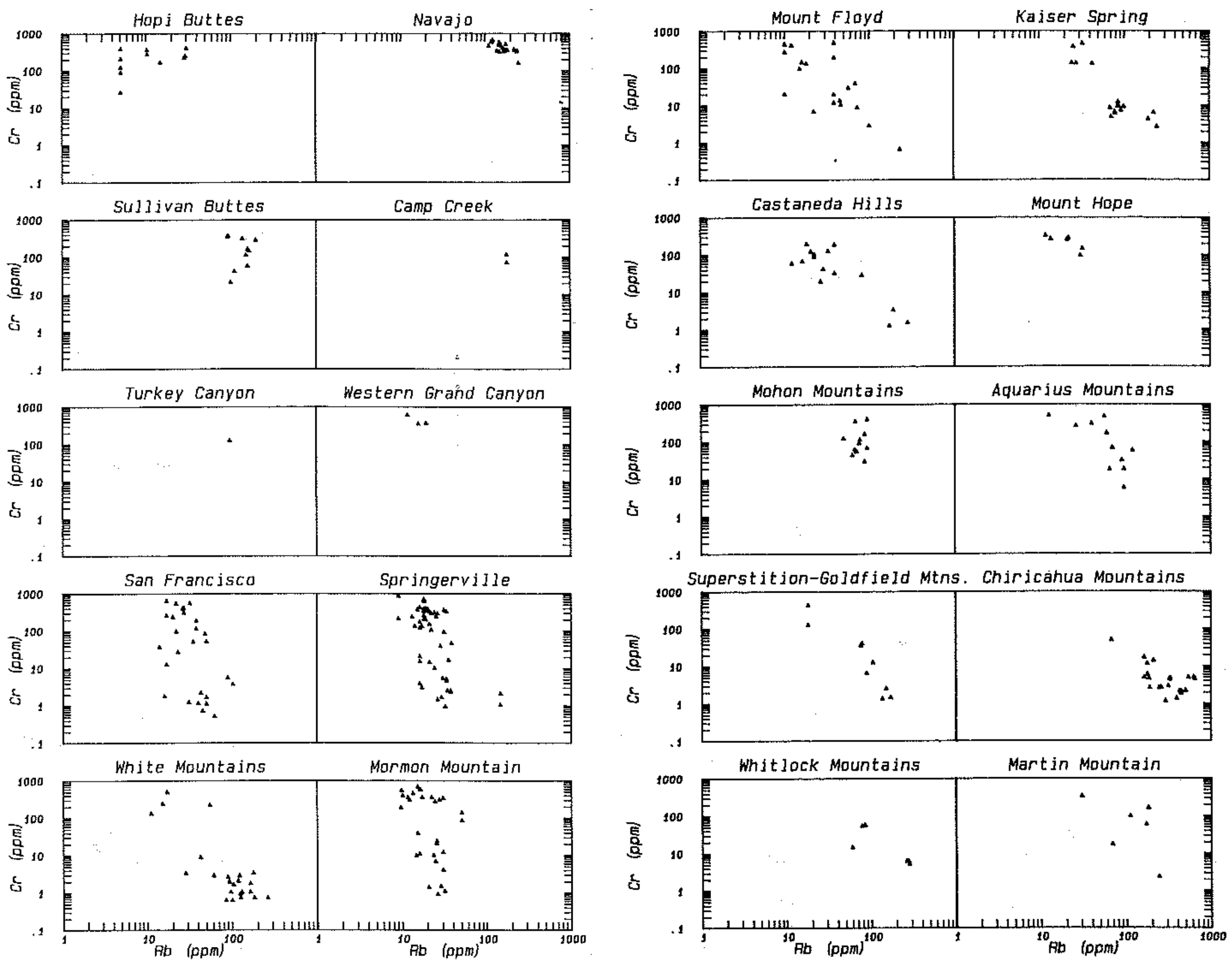


Figure 4A. Chromium versus rubidium plots for rocks in selected post-Laramide volcanic fields, Arizona.

have low REE concentrations (Roden, 1981). The high REE enrichment of most basalts indicates that their source(s) was enriched in REE relative to chondritic values. This is supported by REE enrichments in mantle xenoliths from this region (Frey and Prinz, 1978; Menzies and others, 1985).

Except for high-silica rhyolites in the Kaiser Spring, Mount Floyd, and Castaneda Hills fields, volcanic rocks in Arizona are also enriched in light REE compared to heavy REE. Chondrite-normalized La/Yb values range from 87 in the most fractionated Navajo lamprophyre to 2 in basalt from Martin Mountain. Significant fractionation of light from heavy REE can result from either partial melting of the source region or crystal fractionation of parental magmas.

Arizona volcanic rocks also show a wide range in europium anomalies, although many rocks show no Eu anomaly. Small positive anomalies occur in basalts from the Aquarius Mountains and Black Hills fields. Large negative anomalies occur in some rhyolites, especially high-silica rhyolites in bimodal and andesite-rhyolite fields (e.g., Mount Floyd, Castaneda Hills, Kaiser Spring). Mild positive europium anomalies can be related to either Eu anomalies in the source region or to feldspar accumulation. Negative Eu anomalies in silicic lavas are attributed either to the removal of feldspar by crystal fractionation, especially under reducing conditions, or to partial melting of a feldspathic source in which the feldspar remains as a refractory mineral phase in the source region.

Strontium and Neodymium Isotopes

Another geochemical tool used by petrologists for unraveling the evolution of volcanic rocks is isotopic ratios. Isotopic ratios of volcanic rocks are important petrologic tools because they can provide information about the source material, magma mixing, and crustal contamination. Some volcanic fields in Arizona, especially those on the Colorado Plateau, have received considerable attention by geochemists,

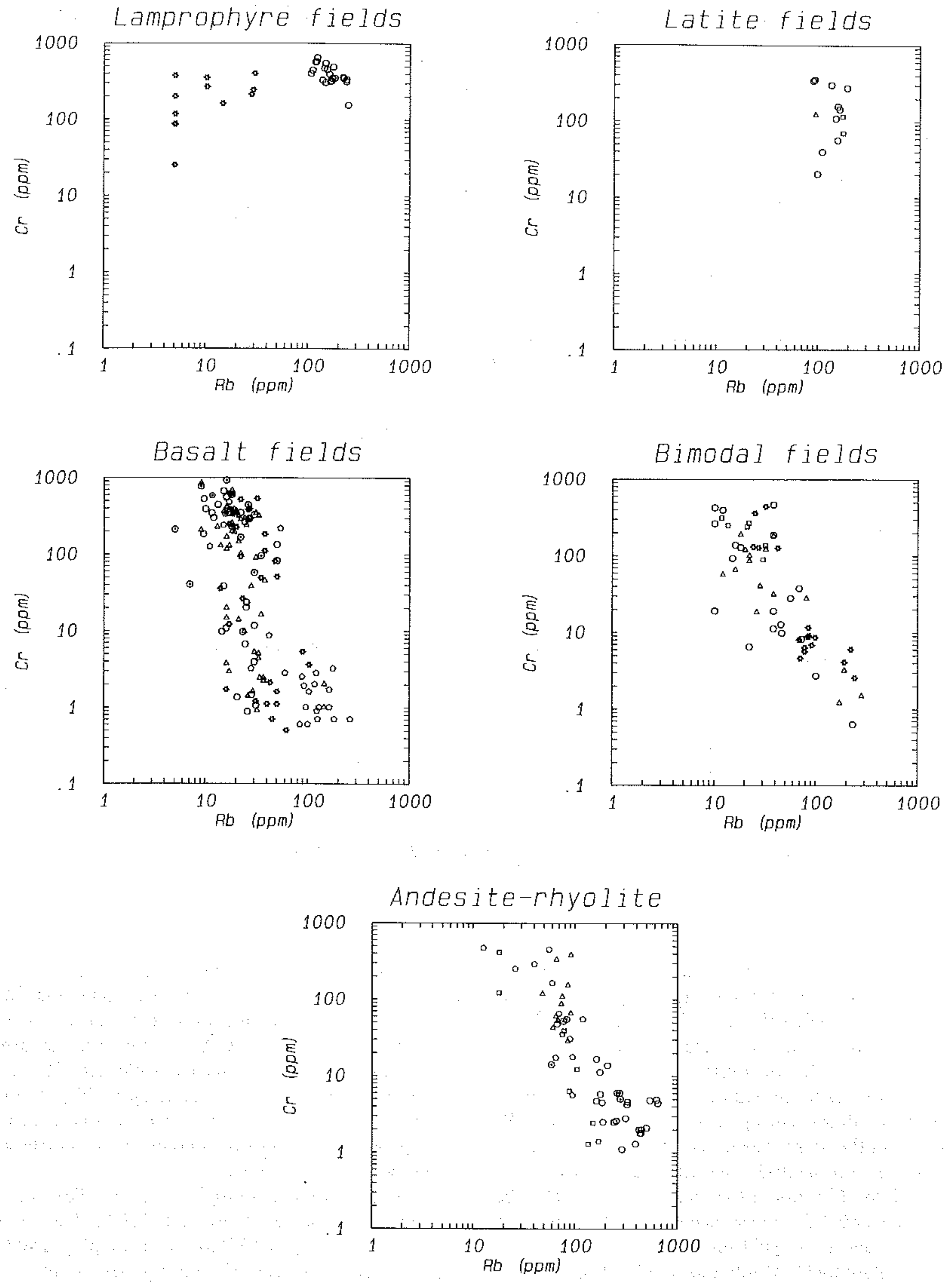


Figure 4B. Chromium versus rubidium plots for the five petrologic groups of rocks from representative volcanic fields, Arizona. Explanation of symbols: Lamprophyre fields: star = Hopi Buttes; circle = Navajo. Latite fields: circle = Sullivan Buttes, square = Camp Creek, triangle = Turkey Canyon. Basalt fields: dotted pentagon = Western Grand Canyon; star = San Francisco; triangle = Springerville; pentagon = White Mountains; circle = Mormon Mountain. Bimodal fields: circle = Mount Floyd; star = Kaiser Spring; square = Mount Hope; triangle = Castaneda Hills. Andesite-rhyolite fields: triangle = Mohon Mountains; pentagon = Aquarius Mountains; square = Superstition Mountains; circle = Chiricahua Mountains; dotted square = Castle Dome-Kofa Mountains; dotted circle = Whitlock Mountains.

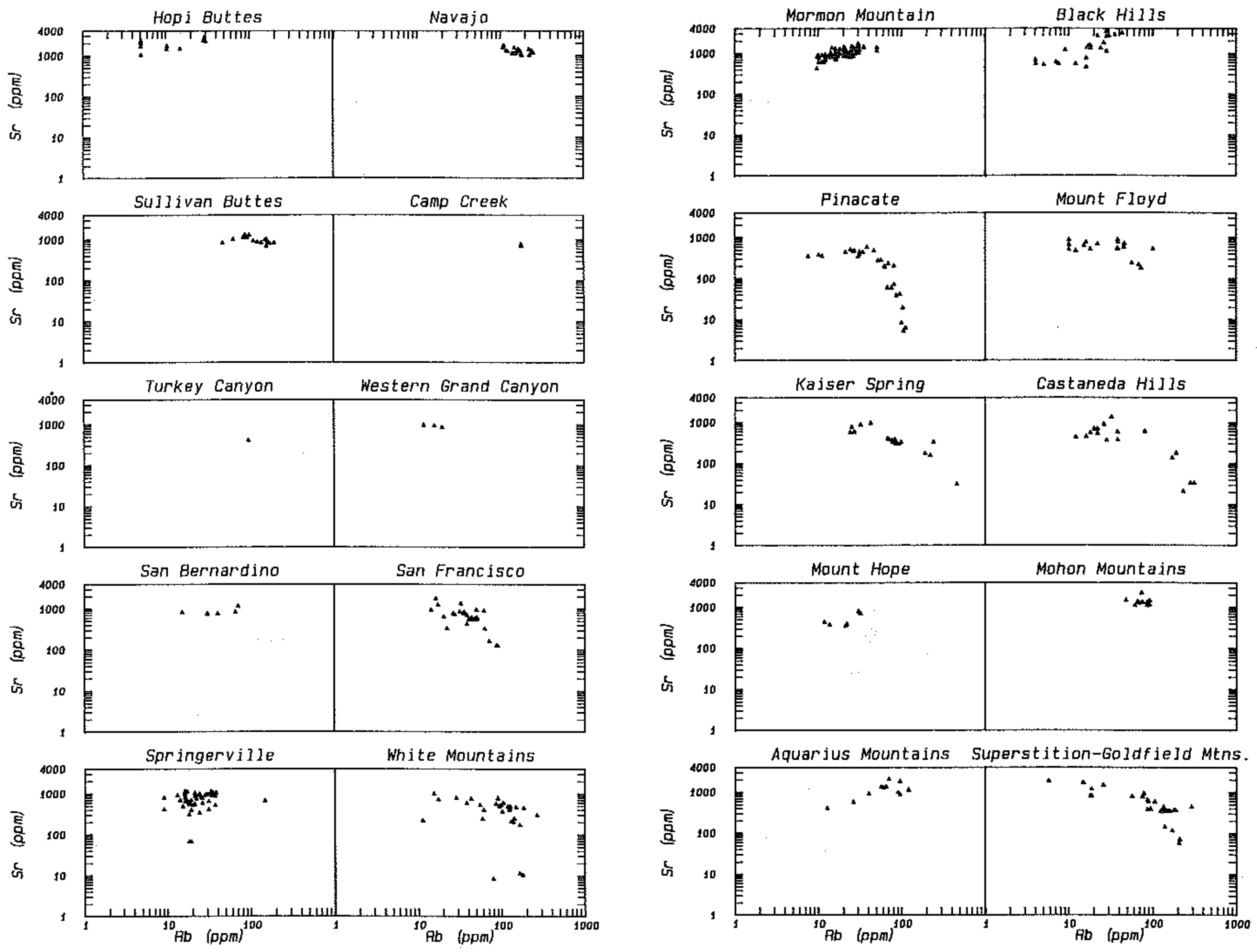


Figure 5A. Strontium versus rubidium plots for rocks in selected post-Laramide volcanic fields of Arizona and of northern Sonora, Mexico.

but many fields have not been studied at all. Below we briefly review available strontium and neodymium isotopic data for post-Laramide volcanic rocks in Arizona.

Strontium isotopic ratios of Arizona volcanic rocks (fig. 8) are highly variable and overlap considerably for the different rock types in this study. Initial Sr isotopic ratios are also highly dependent upon the ages and Rb and Sr abundances of the rocks. The lowest ratios (<0.704) occur in young (<8-Ma) basalt-dominated volcanic fields (e.g., San Francisco, Mormon Mountain, San Carlos). The highest ratios (>0.713) are associated with the Oligocene and Miocene andesite-rhyolite-dominated Chiricahua and Superstition-Goldfield Mountains fields. The potassic lamprophyres of the Navajo field are enriched in radiogenic strontium compared with the sodic lamprophyres of the Hopi Buttes field. Latites from Camp Creek and Sullivan Buttes and lamprophyres of the Navajo field have similar strontium isotopic compositions.

Strontium isotopic compositions of young basalts on the Colorado Plateau (e.g., San Francisco and White Mountains fields) overlap with those of basalts in the Basin and Range and Transition Zone (e.g., San Carlos, San Bernardino, and Hackberry Mountain fields). Colorado Plateau basalts generally tend to show a wider range in $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ than Basin and Range basalts, and this suggests that plateau basalts experienced more crustal contamination than those erupted in the Basin and Range.

Initial strontium isotopic ratios of silicic rocks on the Colorado Plateau are lower (<0.705) than those in the Basin and Range (>0.705). For example, rhyolites in the San Francisco and Hackberry Mountain fields have $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ values of 0.703-0.7055 compared with values of 0.7055-0.714 in the Superstition-Goldfield and Chiricahua Mountains. This difference may be because silicic rocks in these two regions have different sources or because the silicic magmas erupted in the Basin and Range had greater

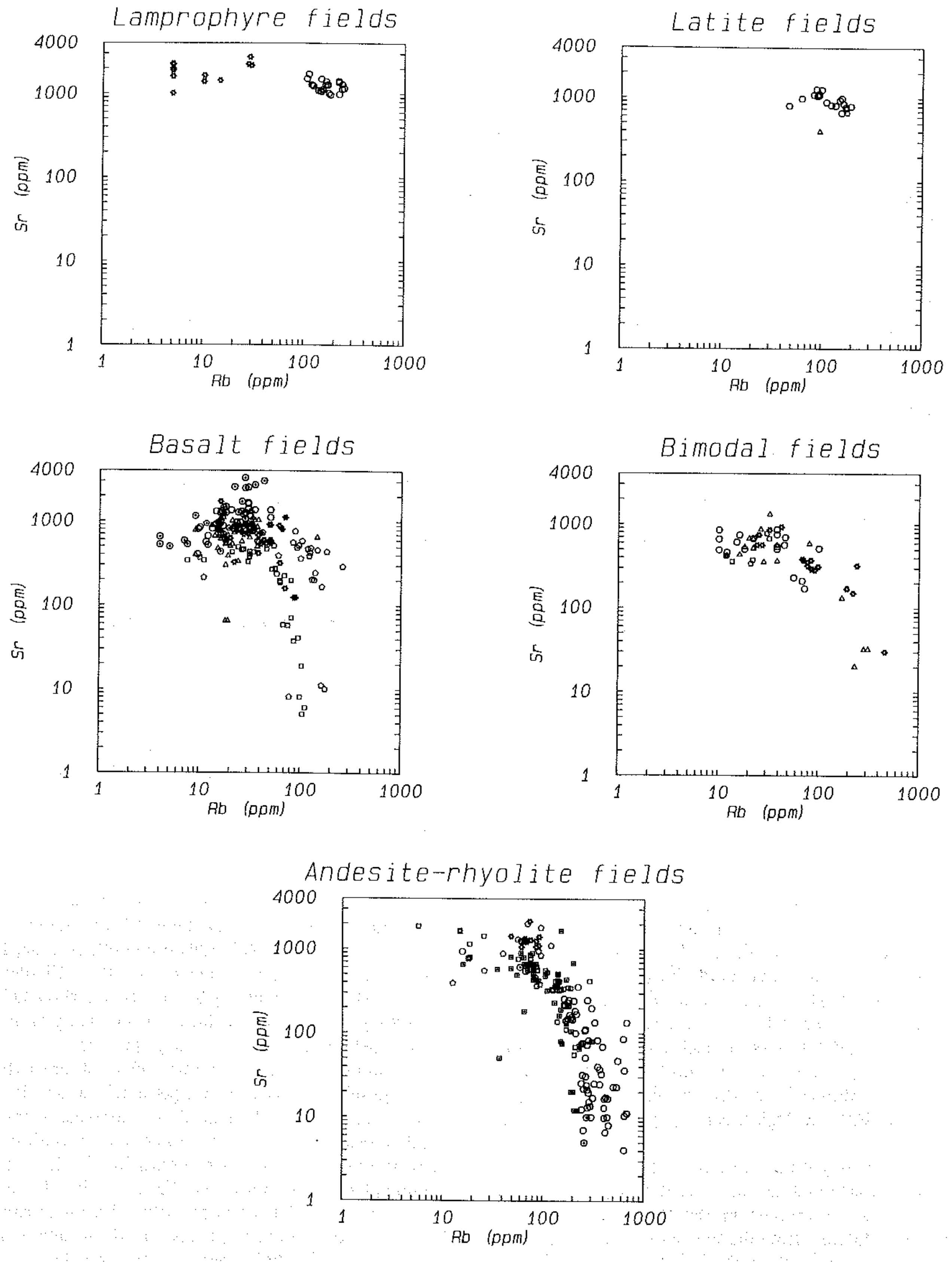


Figure 5B. Strontium versus rubidium plots for the five petrologic groups of rocks from representative volcanic fields of Arizona and of northern Sonora, Mexico. Explanation of most symbols on figure 4B. Additional symbols for basalt fields: dotted star = San Bernardino; dotted circle = Black Hills; square = Pinacate. Sources of data given in table 2.

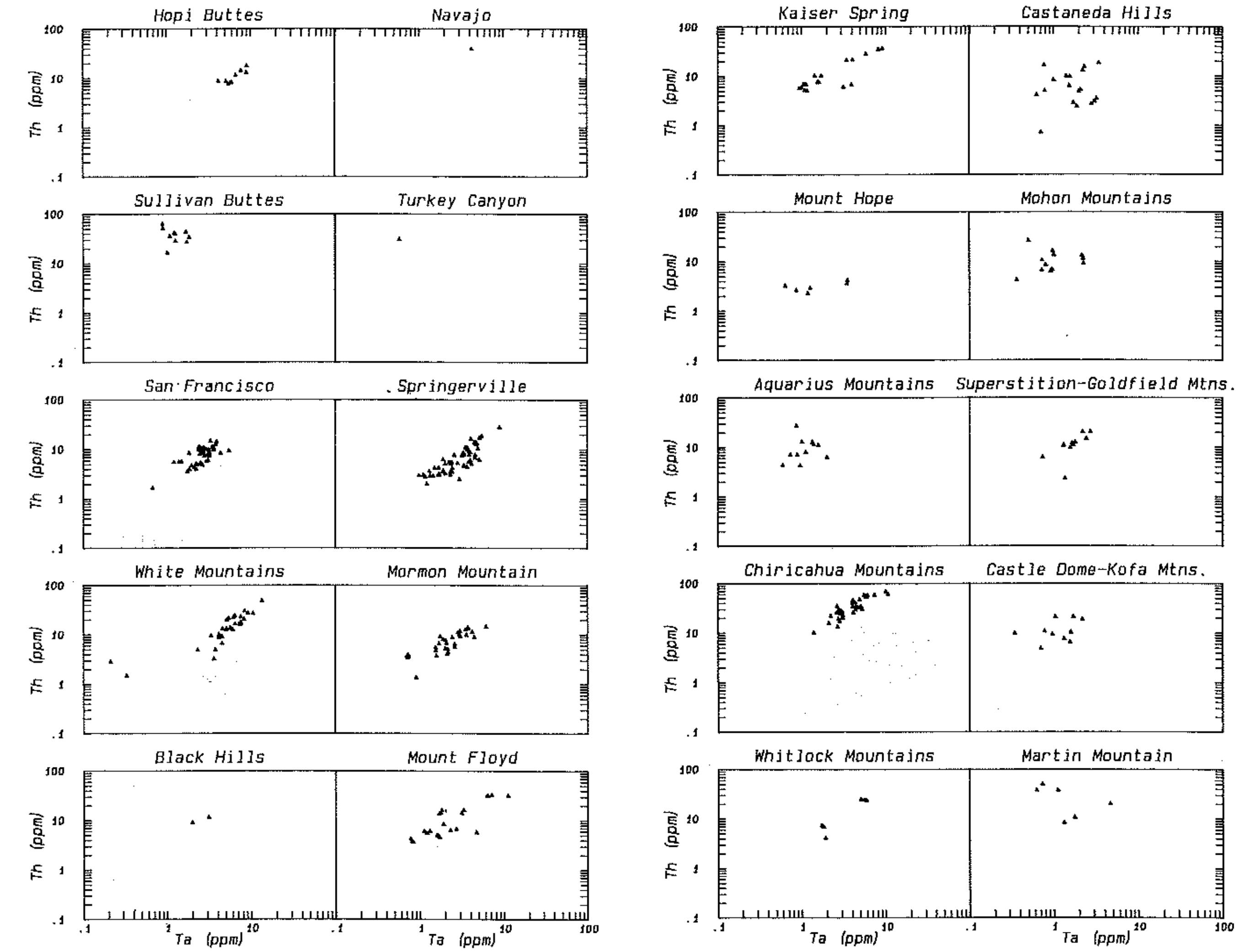


Figure 6A. Thorium versus tantalum plots for rocks in selected post-Laramide volcanic fields, Arizona.

amounts of upper crustal contamination. Young (<5-Ma) Colorado Plateau dacites and rhyolites have strontium isotopic ratios that overlap those of lower crustal granulite-facies xenoliths of the Colorado Plateau (Gust and Arculus, 1986; M. A. Lanphere, U.S. Geological Survey, unpub. data; D. M. Unruh and L. D. Nealey, U.S. Geological Survey, unpub. data). Miocene dacites and rhyolites in the Basin and Range, in contrast, typically have $^{87}Sr/^{86}Sr$ values that approach those of some Proterozoic granitic rocks (R. W. Kistler, U.S. Geological Survey, personal commun., 1986).

Limited neodymium isotopic data exist for post-Laramide basalts in Arizona. These data suggest that the source of basalts erupted in the Basin and Range is isotopically different from the source of basalts erupted in the Transition Zone and on the Colorado Plateau (fig. 9). Basalts from the Basin and Range and Rio Grande Rift have higher $^{143}Nd/^{144}Nd$ than those from the Transition Zone and Colorado Plateau, with the exception of basalts in the San Carlos field, whose Nd isotopic signature resembles that of Basin and Range basalts (Wittke, 1984; Menzies and others, 1985; Alibert and others, 1986; Perry and others, 1987; Unruh and others, 1988; Zindler and others, 1988). This similarity between San Carlos and Basin and Range basalts may be due to the proximity of the San Carlos field to the Basin and Range province.

In summary, it appears that trace elements are useful for distinguishing between the five petrologic groups: lamprophyre, latite, basalt-dominated, bimodal basalt-rhyolite, and andesite-rhyolite. Abundances of rubidium and chromium are useful for separating latites and K-lamprophyres from other volcanic associations because of the high Cr contents of these rocks. These data can also distinguish the Na-lamprophyres from the K-lamprophyres and help to distinguish basalt suites from bimodal and andesite-rhyolite suites. REE abundances serve to separate K-lamprophyres from K-latites and are useful for distinguishing tholeiitic basalts from alkalic basalts in basalt-dominated

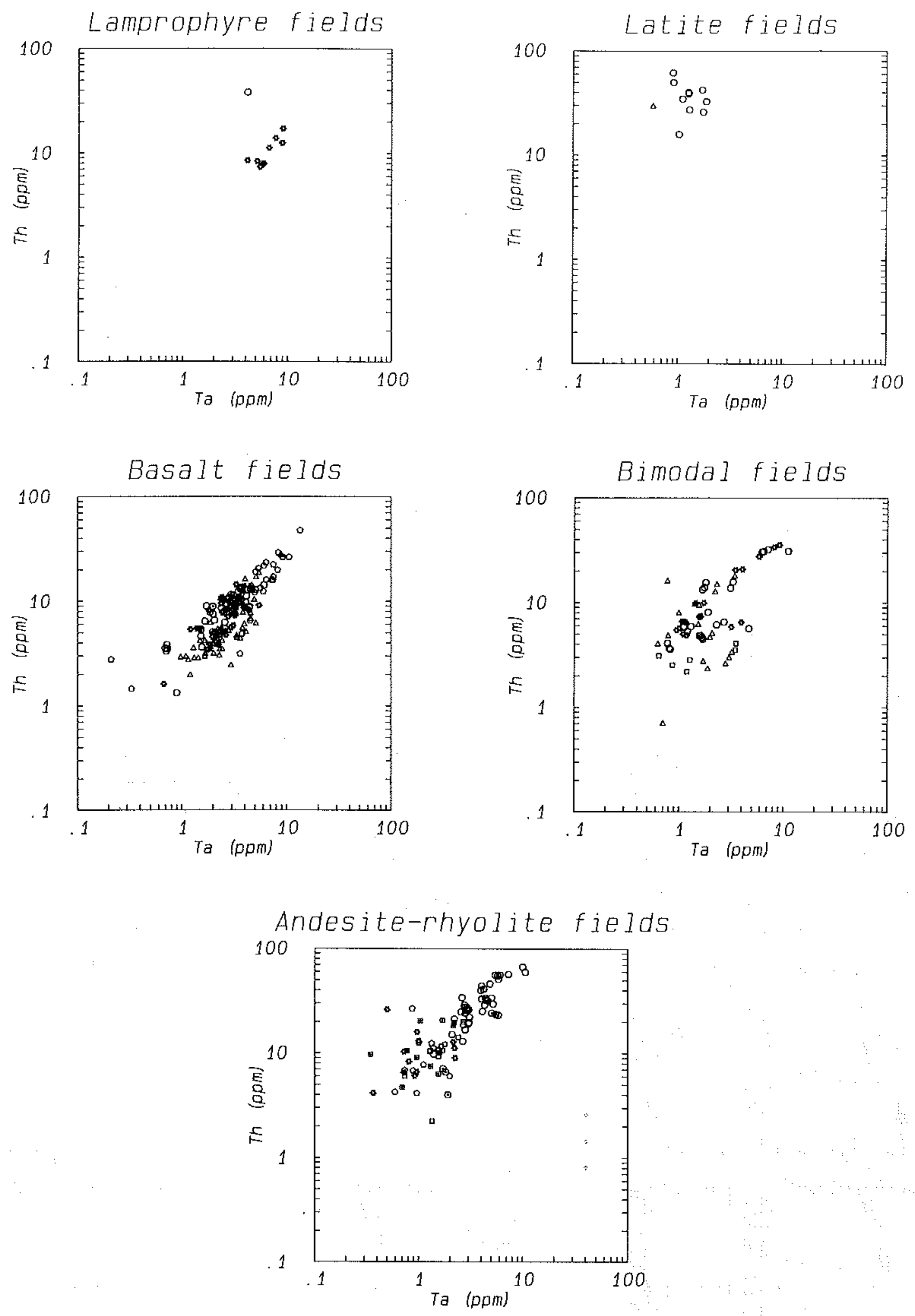


Figure 6B. Thorium versus tantalum plots for the five petrologic groups of rocks from representative volcanic fields, Arizona. Explanation of most symbols on figures 4B and 5B. Additional symbols for andesite-rhyolite fields: circle = Chiricahua Mountains; dotted square = Castle Dome-Kofa Mountains; dotted circle = Whitlock Mountains. Sources of data given in table 2.

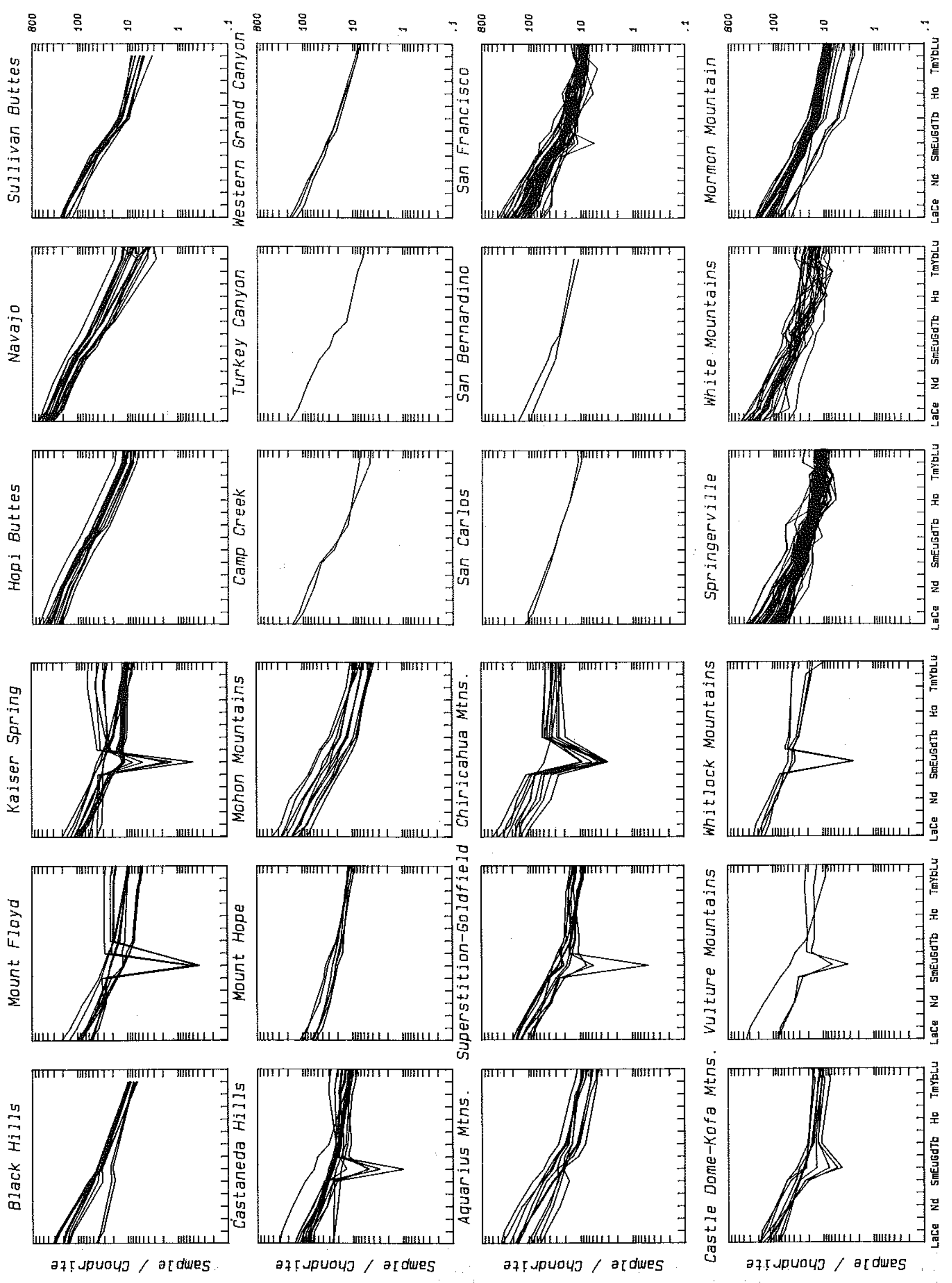


Figure 7. Chondrite-normalized rare-earth element plots of selected rocks from selected post-Laramide volcanic fields, Arizona. All spectra are for individual samples except those for the Whitlock Mountains suite, which are for averaged data. Growler Mountains sample is the Childs Latite. Normalizing factors (Hanson, 1980) are La = 0.315, Ce = 0.813, Nd = 0.597, Sm = 0.192, Eu = 0.722, Gd = 0.259, Tb = 0.047, Ho = 0.070, Tm = 0.030, Yb = 0.208, Lu = 0.0323. Sources of data given in table 2.

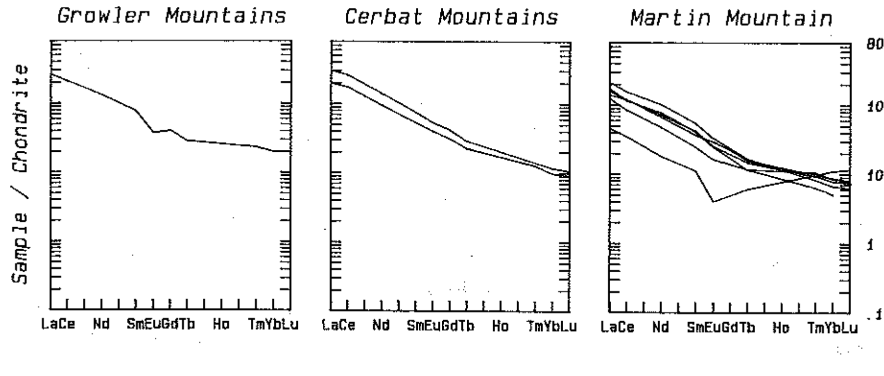


Figure 7, continued.

fields. Combined with isotopic data, trace-element geochemistry may also be useful to distinguish between volcanic rocks emplaced in different structural provinces in Arizona and other parts of the Southwest.

ORIGIN OF MAGMAS

The great diversity in rock type and tectonic association of the Arizona and northern Sonora volcanic fields demands diverse explanations. In this section we present some often-cited models for the generation of magmas and attempt to relate these models to magma genesis in Arizona. Because of the paucity of detailed petrologic studies of volcanic rocks in the state, we depart from our previous format of discussing volcanic rocks by their petrologic association and a take more general approach of grouping them according to rock type: mafic rocks (basalts); intermediate rocks (andesite and dacite); and silicic rocks (rhyolite). Most studies to date have considered only the origin of specific rocks; for example, Alibert and others (1986) studied only basalts on the Colorado Plateau. Moreover, different rock types in some of the fields are not genetically related by crystal fractionation. We have divided the rocks into mafic (<52 wt. percent SiO_2), intermediate (52-64 wt. percent SiO_2), and silicic groups (> 64 wt. percent SiO_2). Basaltic andesites are classified as mafic rocks, and latites as intermediate.

Mafic rocks

Published trace-element and isotopic studies (Menzies and others, 1985; Alibert and others, 1986; Perry and others, 1987; Zindler and Jagoutz, 1988; Unruh and others, 1988) indicate that at least four distinct source regions contributed to the composition of basaltic magmas in Arizona: (1) depleted mantle, similar in composition to the source of mid-ocean ridge basalts; (2) mantle enriched in radiogenic Sr, Pb, and Nd; (3) lower continental crust; and (4) upper continental crust. Table 5 presents a summary of mantle sources that have been proposed for the parental magmas of basalt, lamprophyre, and latite in several volcanic fields in Arizona and northern Sonora. Mantle source regions for primary basaltic melts are considered to be either spinel peridotite or garnet peridotite (Kay and Gast, 1973; Condit, 1984; Alibert and others, 1986).

Many basalts in Arizona were apparently derived from metasomatised mantle that was enriched in incompatible elements during or prior to magma genesis (Menzies and others, 1985). Mantle metasomatism, not to be confused with post-eruptive potassic metasomatism, is indicated by the presence of mantle-derived ultramafic xenoliths composed of hydrous and incompatible-element-enriched mineral phases, such as amphibole, phlogopite, and apatite (Best, 1970, 1974a,b, 1975; Nealey, 1980; Menzies and others, 1985; Roden and Murthy, 1985). Metasomatism presumably resulted from the migration of fluids and melts through the mantle. Incompatible elements are usually immobile, but under mantle pressures their distribution coefficients are much higher (Mysen, 1979).

Few basalts in Arizona represent primary magmas. Based on their compositions, most basalts underwent polybaric fractional crystallization on their way to the surface. Cumulate xenoliths and phenocryst assemblages indicate that fractionation involved removal of olivine, clinopyroxene, orthopyroxene, plagioclase, and spinel (Best and Brimhall, 1974; Stoeser, 1973; Nealey, 1980; Lynch, 1981; Condit, 1984; Menzies and others, 1985).

In many of the volcanic fields in Arizona and northern Sonora both alkalic and tholeiitic basalts coexist. For example, in the Springerville, Mormon Mountain, Pinacate, and Black Hills fields tholeiitic basalts coexist with more voluminous amounts of alkalic basalt. In the Black Hills the earliest eruptive products were alkalic basalts, beginning about a million years before the onset of tholeiitic volcanism, which lasted 3-4 million years (Wittke, 1984). Wittke interpreted the change from alkalic to tholeiitic magmatism as representing either progressive melting of the same source material or melting of a similar source at different depths (i.e., diapiric melting). Other volcanic fields, such as Springerville and the Western Grand Canyon, show trends toward increasing degree of undersaturation with time (C. D. Condit, oral commun., 1987; J. G. Fitton, written commun., 1988).

Quartz-bearing basalts occur in many, if not all, of the late Cenozoic volcanic fields in Arizona. These rocks are

Table 5. Characterization of mantle sources of some post-Laramide basalts, lamprophyres, and latites of Arizona and northern Sonora, Mexico.

Field name	Mantle source characteristics	References
	Lamprophyre fields	
Navajo	Phlogopite- and apatite-bearing garnet peridotite subcontinental mantle	Roden and Smith, 1979; Roden, 1981; Laughlin and others, 1986; Alibert and others, 1986; Esperanca and Holloway, 1987
	Latite fields	
Sullivan Buttes	Metasomatised subcontinental mantle	Tyner, 1984; Tyner and Smith, 1986
Camp Creek	Phlogopite-bearing spinel or garnet peridotite mantle	Esperanca and Holloway, 1986
	Basalt fields	
Western Grand Canyon	Ancient subcontinental mantle	Leeman, 1974; Alibert and others, 1986
San Carlos	Metasomatised suboceanic-type mantle	Frey and Prinz, 1978; Zindler and Jagoutz, 1988; Menzies, 1987
San Bernardino	Metasomatised suboceanic-type mantle	Menzies and others, 1985
San Francisco	Subcontinental mantle, possible crustal contamination	Leeman, 1982; Everson, 1979; Alibert and others, 1986
Springerville	Metasomatised mantle	C.D. Condit, written commun., 1987
White Mountains	Metasomatised spinel or garnet peridotite subcontinental mantle	L.D. Nealey, USGS, unpub. data
Mormon Mountain	Metasomatised mantle	Gust and Arculus, 1986
Black Hills	Metasomatised subcontinental mantle	Wittke, 1984; Everson, 1979
Pinacate	Metasomatised mantle	D.J. Lynch, oral commun., 1987

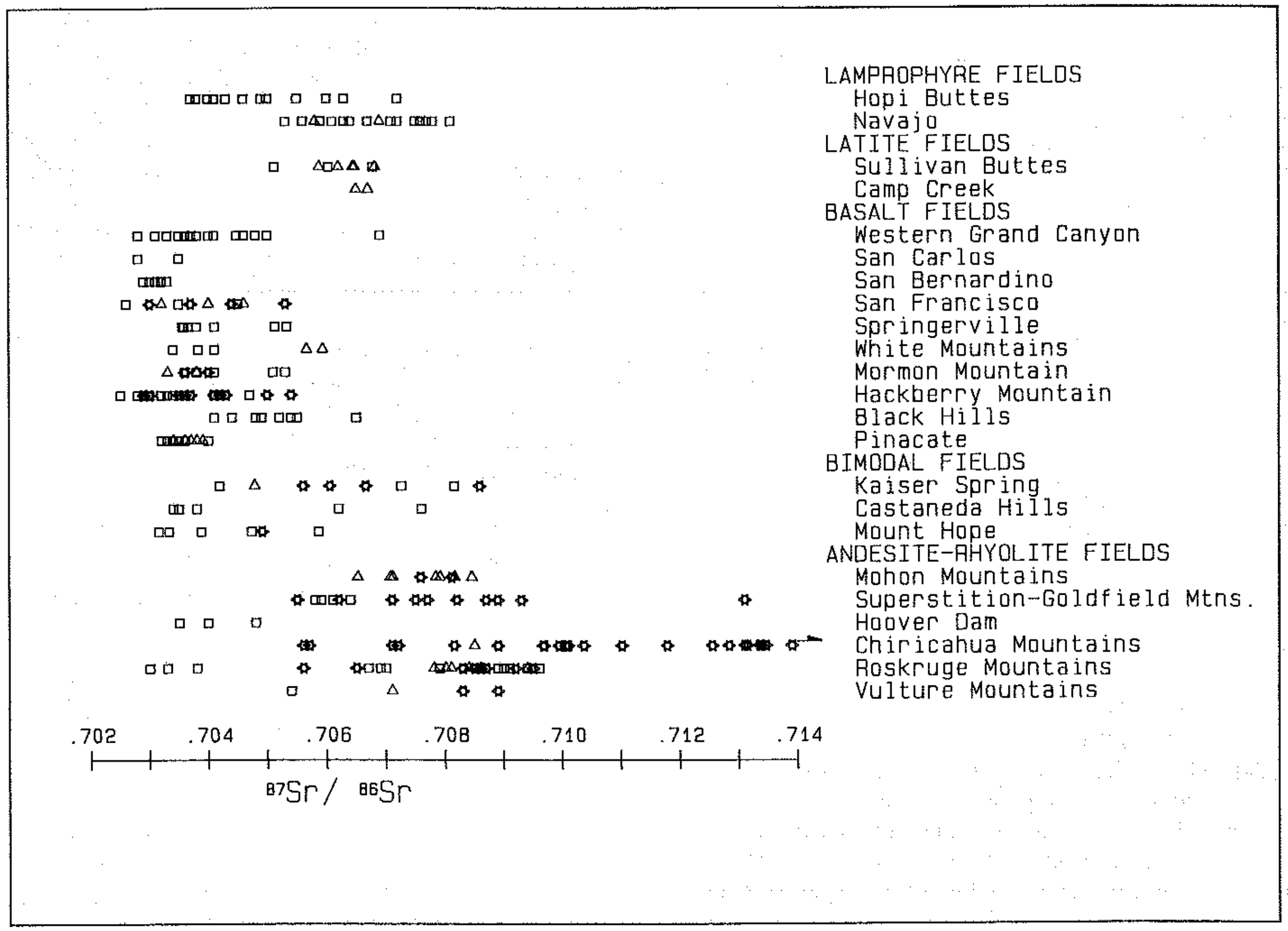


Figure 8. Strontium isotope plot for rocks from selected post-Laramide volcanic fields of Arizona and of northern Sonora, Mexico. Symbols: squares = mafic rocks, triangles = intermediate rocks, stars = silicic rocks. Arrow indicates value greater than 0.714. Sources of data given in table 2.

interpreted to have evolved by decompressive resorption of primary magmas that fractionated at high pressures (15 to 25 Kb; Suneson and Lucchitta, 1983); by crustal contamination of primary and differentiated magmas (Nealey, 1980); and by partial melting of the lower crust (Otton, 1982).

The source of the latites in the Transition Zone has been attributed to melting of phlogopite-bearing garnet peridotite (Esperanca, 1984; Tyner, 1984). Evolved latites of the Camp Creek field were suggested to be related to primitive latites by fractional crystallization (Esperanca and Holloway, 1986). Tyner (1984) stated that she was not able to demonstrate a simple genetic relationship between different types of latite from the Sullivan Buttes field. She suggested that evolved latites of the Sullivan Buttes could be related to mafic latite magmas by contamination by xenolithic material similar in composition to the associated eclogite-amphibolite suite, combined with crystal fractionation.

Intermediate rocks

Petrologic studies of andesites and dacites in Arizona (Wenrich-Verbeek, 1975, 1979; Eichelberger, 1978; Gust and Arculus, 1986; Simmons, 1986; Unruh and others, 1988) suggest that they originated by a variety of processes, including crystallization of primary basaltic material, assimilation of crustal material by parental basaltic magma, and mixing of basalt and melted sialic crust. Crystal fractionation of basalt is indicated by major- and trace-element modeling of phenocrystic phases. Magma mixing and crustal assimilation are substantiated by disequilibrium phenocryst textures, the presence of crustal xenoliths and xenocrysts, and by linear trace-element and isotopic patterns.

Open-system magmatic processes have been shown to be effective in producing intermediate rocks in the San Francisco and White Mountains volcanic fields (Wenrich-Verbeek, 1975, 1979; Nealey, 1987). Temporal variations in

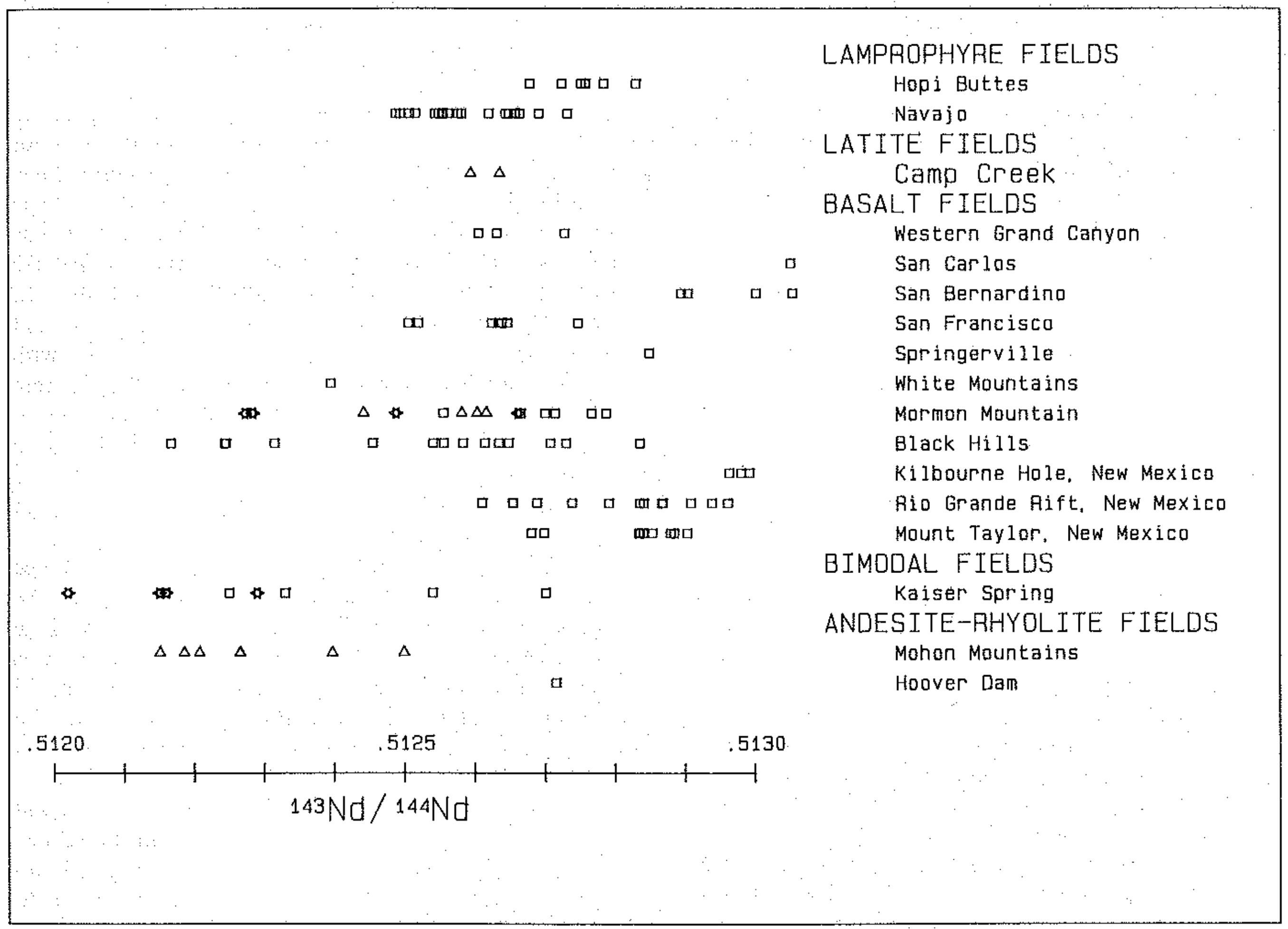


Figure 9. Neodymium isotope plot for selected post-Laramide volcanic fields, Arizona. Analyses of late Cenozoic volcanic rocks from New Mexico are shown for comparison. Symbols: squares = mafic rocks, triangles = intermediate rocks, stars = silicic rocks. Sources of data given in table 2. New Mexico data from Perry and others, 1987.

major- and trace-element geochemistry of the San Francisco Peaks (San Francisco volcanic field) and Mount Baldy (White Mountains) lavas indicate that they formed by repeated injections of primitive magma into differentiating magmatic systems. Differentiation resulted from fractional crystallization and crustal assimilation. The ultimate source of some intermediate lavas in the San Francisco Peaks and at Mount Baldy may be the lower crust.

Silicic Rocks

Most rhyolites in Arizona were probably derived by anatexis of the crust, but crystal fractionation is theorized as the origin of some rhyolite magmas (Gust and Arculus, 1986). Based on trace-element modeling, Gust and Arculus (1986) concluded that rhyolites in the Mormon Mountain field could have formed by either partial melting of lower crustal amphibolite or fractionation of associated andesite.

Rhyolite lavas of bimodal (basalt-rhyolite) fields probably originated by crustal melting. High-silica rhyolites (>75 wt. percent SiO_2) in bimodal fields of western Arizona have strong negative europium anomalies and high Sr isotopic ratios (Suneson and Lucchitta, 1983; Moyer, 1986; Moyer and Nealey, 1987). They plot in the low-pressure field of the Ab-Or-Qtz system and in the same field as central Arizona Proterozoic granitic rocks on Th-Ta-Hf diagrams. The high Sr isotopic ratios of the high-silica rhyolites (0.709-0.714) also overlap those of Proterozoic granitic rocks from western Arizona (Suneson and Lucchitta, 1983; T. C. Moyer, Vanderbilt Univ., oral commun., 1987; Sonia Esperanca, Northwestern Univ., written commun., 1987; R. W. Kistler, U.S. Geological Survey, unpub. data). These data are consistent with an upper crustal origin for the high-silica rhyolites, although derivation from less evolved magmas may also have been involved.

Low-silica rhyolites (69-75 wt. percent SiO_2) of bimodal fields have small or no Eu anomalies and high Sr contents. Their Sr isotopic ratios are similar to those of lower crustal xenoliths in Colorado Plateau basalts (Gust and Arculus, 1986; M. A. Lanphere, U.S. Geological Survey, unpub. data). Generally they have lower relative proportions of normative quartz than high-silica rhyolites. They probably originated either by lower crustal melting or by assimilation and fractionation of mantle-derived magmas.

No detailed petrologic studies have been published for silicic rocks associated with ash-flow fields in Arizona, and the origin of such rocks is, therefore, poorly understood. Latta (1983) suggested that ash flows of the Turkey Creek caldera (Chiricahua Mountains) erupted from a compositionally zoned magma chamber in which crystal-liquid fractionation was probably the dominant differentiation process. Latta also suggested that the chemical variability of the Turkey Canyon ash flows is consistent with the thermogravitational double-diffusive process of Hildreth (1979, 1981). Bryan (1988) modeled trace-element and Sr isotope ratios, and concluded that the latites and rhyolites in the Chiricahua Mountains are related by the fractionation of a parent magma produced by crustal melting. In any case, the origin of these rocks probably is complicated.

TIME-SPACE-COMPOSITION PATTERNS OF POST-LARAMIDE VOLCANIC ROCKS

Volcanic activity occurred repeatedly in Arizona and northern Mexico over the past 40 Ma. In figure 10 we use available geochronologic data to show the distribution of late Cenozoic volcanic rocks in the state. Most of these data were compiled by Reynolds and others (1987). With but a few exceptions, we ignored data that Reynolds and others (1987) considered to be of questionable quality. We supplemented those data with unpublished data obtained by the U.S. Geological Survey (E. H. McKee, U.S. Geological Survey, written commun., 1982; R. J. Miller, U.S. Geological Survey, written commun., 1988) and the University of Arizona (M. Shafiqullah, oral commun., 1988). In total, more than 735 K-Ar and fission-track ages were used in the construction of the plots. Data are inadequate for several areas, especially the San Carlos volcanic field and the surrounding area, and the Mohave Mountains field.

The composition of volcanic rocks is essential to establishing migratory trends. Because of the lack of detailed mapping in some areas, we show geochronologic data for the region based on rock type rather petrologic association. The rock names are those listed by Reynolds and others (1987) or based on our chemical data. Alkalic rocks were plotted as their subalkalic equivalents, i.e., mugearite = basaltic andesite, benmoreite = andesite, and trachyte = dacite. Quartz latite and latite associated with caldera complexes were plotted as dacite. All tuffs were plotted as rhyolites. These data are displayed on a series of maps representing 5- and 10-Ma intervals beginning at 40 Ma (figs. 10A-G).

Volcanic rocks 40-30 Ma (fig. 10A) occur in the Navajo field, in the Blue Range, Chiricahua Mountains, Roskruge Mountains, and a few other places in the Basin and Range province. Volcanism began in the Navajo field with the explosive emplacement of potassic mafic to intermediate rocks. Most of the activity in the Basin and Range was intermediate to silicic in composition. Between 30 and 25 Ma (fig. 10B) intense volcanic activity began in the southeastern part of the State. Intermediate to silicic tuffs and lavas were emplaced in the Chiricahua Mountains, Roskruge Mountains, Kofa-Castle Dome Mountains, and in other parts of the Basin and Range and Transition Zone. Large basaltic shield volcanoes formed in the Superstition-Goldfield Mountains in central Arizona, and mafic to intermediate volcanism continued in the Navajo field (northeast corner of the state) and began in the Sullivan Buttes and probably in the Camp Creek area.

Silicic volcanism reached its maximum intensity in southern Arizona by 25-20 Ma (fig. 10C). Caldera-related volcanism occurred in the Superstition-Goldfield, Galiuro, Chiricahua, Trigo, and Castle Dome-Kofa Mountains and in the Blue Range field during this period, as large ash-flow sheets were extruded. Late Oligocene to early Miocene "turkey-track" latites erupted over a large area of south-central Arizona from the Buckskins Mountains to the Tucson Mountains (S. J. Reynolds, oral commun., 1988). In northwestern Arizona, voluminous basaltic, andesitic, and dacitic rocks were emplaced in the Mohon and Aquarius Mountains.

Between 20 and 15 Ma (fig. 10D) calc-alkalic andesite-rhyolite volcanism associated with calderas and central vents began to change to bimodal volcanism (basalt-rhyolite; e.g., Superstition-Goldfield Mountains). A major silicic ash-flow sheet, the Peach Springs Tuff, was emplaced in west-central Arizona and adjacent parts of southern California and Nevada at about 18 Ma. Widespread basaltic and andesitic activity together with smaller volumes of silicic volcanism occurred in central and western Arizona.

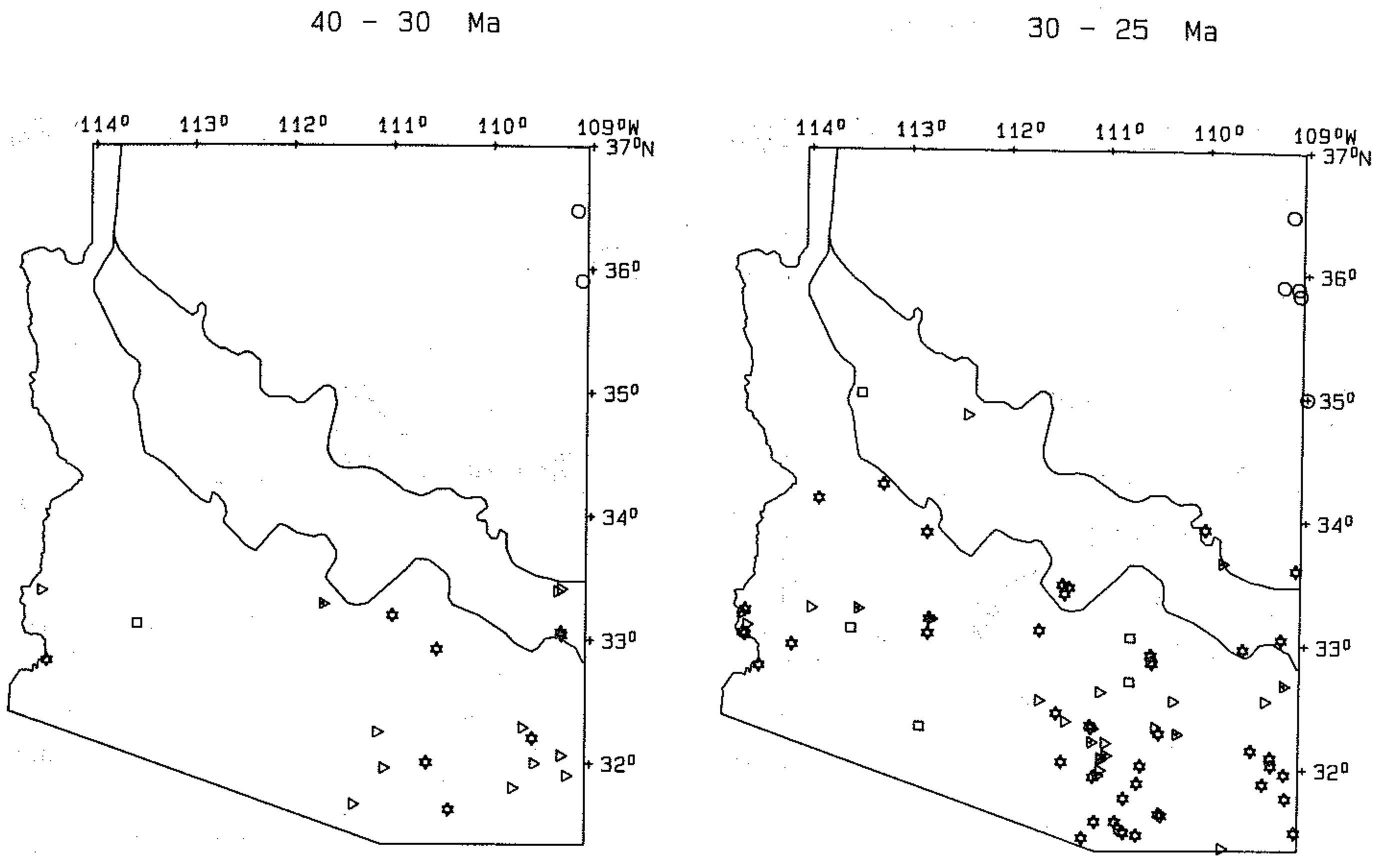
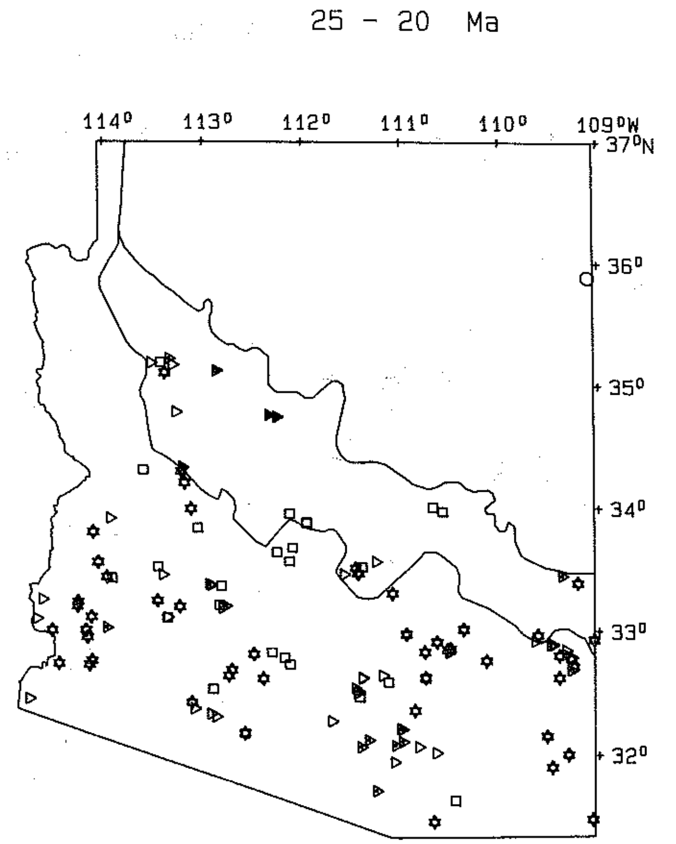


Figure 10. Maps showing the distribution of volcanic rocks in Arizona and in northern Sonora, Mexico, for various time intervals. A. 40-30 Ma; B. 30-25 Ma; C. 25-20 Ma; D. 20-15 Ma; E. 15-10 Ma; F. 10-5 Ma; G. 5-0 Ma. Symbols: open circles = lamprophyres; squares = basalts; dotted triangles = basaltic andesites; open triangles = andesites; closed triangles = potassic latites; stars = dacites and rhyolites. Data compiled from Reynolds and others (1986) and unpublished data of the U.S. Geological Survey and from the University of Arizona Geochronology Laboratory. (Continued on next page.)



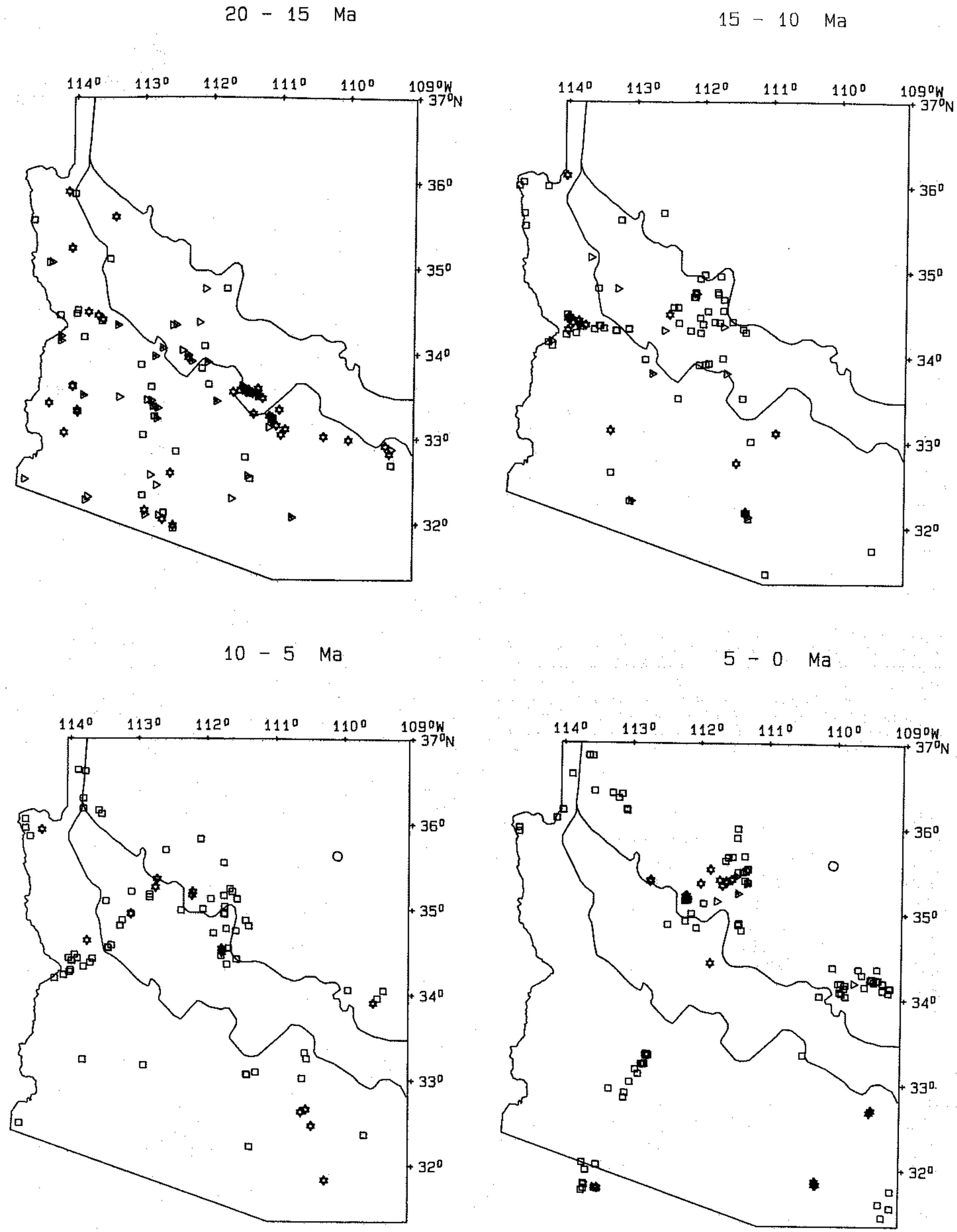


Figure 10, continued.

A drastic change in the distribution, style, and composition of volcanic activity occurred between 15 and 10 Ma, as mafic volcanism became dominant in the region (fig. 10E). Silicic activity, which until this time had mainly been associated with caldera-forming events, decreased in volume and was restricted to a few small- to intermediate-size stratovolcanoes and lava domes in the western part of the state. Intense activity appears to have taken place in the Castaneda and Black Hills fields.

The main episode of bimodal basalt-rhyolite volcanism occurred in western Arizona between 10 and 5 Ma (fig. 10F). Bimodal activity took place in the Castaneda Hills, Kaiser Spring, Mount Hope, and Mount Floyd fields. Earlier basalt-dominated volcanism in the Black Hills migrated onto the margin of the Colorado Plateau to produce the first activity in the Mormon Mountain and San Francisco fields. Sodic lamprophyric volcanism began during this period in the Hopi Buttes, as less alkaline activity took place in the White Mountains. The Hoover Dam area was also a hot spot during the period 10-5 Ma.

The main belt of basaltic activity in northern Arizona continued to migrate onto the Colorado Plateau over the past 5 m.y. Large areas along the margin of the plateau were covered by basalts of the San Francisco, Springerville, and western Grand Canyon fields. Mafic alkalic volcanism also continued in the Hopi Buttes. Basaltic volcanism in the San Francisco and Springerville fields was accompanied by the emplacement of relatively small volumes of intermediate rock, and in the case of the San Francisco field, by silicic rock (fig. 10G). Relatively short-lived basaltic volcanism also took place during this period in the Sentinel Plains, San Carlos, San Bernardino, and Pinacate fields. Basalt vents in the San Bernardino field show several alignments that suggest that they formed along fractures that were controlled by the regional stress regime, and that it changed through time. Silicic activity in the Basin and Range during the past 5 m.y. appears to have been limited to a few small areas in the Whitlock Mountains, Pinacate field, and the San Pedro Valley, south of Benson.

Geochronologic and paleomagnetic data for fields along the margin of the Colorado Plateau indicate that volcanism migrated at similar rates in all the fields. Tanaka and others (1986) have shown that basaltic volcanism in the San Francisco field initially migrated northeastward then eastward from about 5 Ma to the present. They calculated a mean migration rate for the period prior to the Matuyama Reversed-Polarity Chronozone (2.48 Ma) of 1.2 cm/yr. Since the Matuyama reversal the rate has been approximately 9 cm/yr.

Migration rates have also been calculated for the Western Grand Canyon and the Springerville fields. Best and Brimhall (1974) calculated that volcanism migrated eastward across the Western Grand Canyon field at a rate of approximately 1 cm/yr. Chris Condit (written commun., 1987) calculated that volcanism migrated eastward at a rate of 1.5-2 cm/year in the Springerville field over the last 3 m.y.

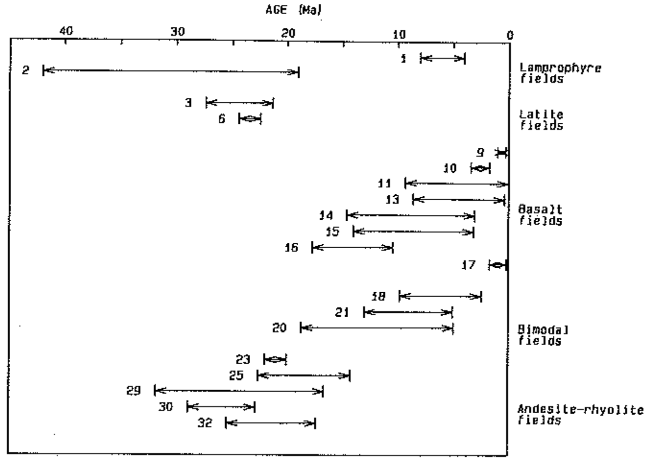


Figure 11. Geochronological data for the five petrologic groups for selected post-Laramide fields in Arizona and in northern Sonora, Mexico. Data compiled from Reynolds and others (1986). Numbers designate fields listed in table 1.

The consistent eastward migration of late Cenozoic volcanism near the edge of the Colorado Plateau is thought to be related to westward motion of the North American plate (Tanaka and others, 1986).

In conclusion, post-Laramide volcanism in Arizona produced rocks with a wide range in composition. Early activity resulted mainly in lamprophyric activity in the interior of the Colorado Plateau, latitic volcanism in the Transition Zone, and andesite-rhyolite-dominated volcanism in the Basin and Range province and along the edge of the Transition Zone (fig. 11). Lamprophyric volcanism on the Colorado Plateau ended about 19 Ma but later recurred between 8 and 4 Ma. Latite volcanism may have began as early as 28 Ma and ended about 19 Ma, and was limited to the Transition Zone. Andesite-rhyolite-dominated volcanism became intense about 30 Ma and ceased about 15 Ma. It resulted in widespread ash-flow sheets in southern, central, and northwestern Arizona and adjacent parts of southeastern California and southern Nevada. Bimodal (basalt-rhyolite) volcanism began in the Basin and Range province (western Arizona) about 20 Ma and migrated onto the Colorado Plateau and ceased about 2 Ma. In the younger basalt terranes, basalt-dominated volcanism began at least by 14 Ma and continued on the Colorado Plateau and in the Basin and Range province almost to the present.

Note added in final proof: Silicic lava domes have recently been observed in the San Carlos volcanic field. The San Carlos field is now considered to be a bimodal basalt-rhyolite field.

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