NORTHERN ILLINOIS UNIVERSITY

A Mineralogical and Geochemical Analysis of Basaltic Lavas from the Zion National Park Region, Southwestern Utah

A Thesis submitted to the

University Honors Program

In Partial Fulfillment of the

Requirements of the Baccalaureate Degree

With University Honors

Department of Geology

by

Jason R. Price

DeKalb, Illinois

December, 1990

Approved:

Department of: Geology

Date: 1/18/91

HONORS THESIS ABSTRACTS
THESIS SUBMISSION FORM

AUTHOR: Jason R. Price

THESIS TITLE: A Mineralogical and Geochemical Analysis of Basaltic Lavas from the Zion National Park Region, Southwestern Utah

ADVISOR: Dr. James A. Walker ADVISOR'S DEPT: Geology

DISCIPLINE: Geology YEAR: 1990

HONORS PROGRAM: Northern Illinois University Honors Program

NAME OF COLLEGE: Northern Illinois University

PAGE LENGTH: 27 BIBLIOGRAPHY (YES OR NO): Yes ILLUSTRATED (YES OR NO): Yes

PUBLISHED (YES OR NO): ? IF YES, LIST PUBLICATION:

COPIES AVAILABLE (HARD COPY, MICROFILM, DISKETTE): Hard copy and Diskette

SUBJECT HEADINGS: (Choose 5 key words or phrases by which a reader could find your thesis)

Mineralogical
Geochemical
Basaltic
Lavas
Utah

ABSTRACT (100-200 WORDS): In the Transition zone of southwestern Utah, basaltic lavas are geochemically defined as a subduction suite and a plume suite. These predominantly basic lavas are late Cenozoic (<17 Ma) in age, with the two suites related in time and space.

This paper suggests a two layer upper mantle model, an upper metasomatized lithospheric layer underlain by an asthenospheric layer, with both alkali basaltic and olivine tholeiitic magmas being generated by varying degrees of partial melting of spinel lherzolite in each individual layer. Due to the greater depths at which asthenospheric magmas are derived, mixing occurs between the alkali basaltic and the olivine tholeiitic magmas during ascent through the lithosphere. Since lithospher-derived magmas ascend to the crust soon after generation, significantly less mixing occurs, if at all. Time-space relations support such a model.

For Office Use:
THESIS NO:

ABSTRACT

In the Transition zone of southwestern Utah, basaltic lavas are geochemically defined as a subduction suite and a plume suite. These predominantly basic lavas are late Cenozoic (<17 Ma) in age, with the two suites related in time and space.

This paper suggests a two layer upper mantle model, an upper metasomatized lithospheric layer underlain by an asthenospheric layer, with both alkali basaltic and olivine tholeiitic magmas being generated by varying degrees of partial melting of spinel lherzolite in each individual layer. Due to the greater depth at which asthenospheric magmas are derived, mixing occurs between the alkali basaltic and the olivine tholeiitic magmas during ascent through the lithosphere. Since lithosphere-derived magmas ascend to the crust soon after generation, significantly less mixing occurs, if at all. Time-space relations support such a model.

INTRODUCTION

The Transition zone of southwestern Utah (Figure 1), located at the margin of the Colorado Plateau and the Great Basin, contains voluminous late Cenozoic (<17 Ma) basaltic lavas. These rocks are calc-alkalic in composition (Figure 3), though erupted during extensional-block faulting and crustal uplift, as much as 28 Ma following cessation of subduction of the Farallon plate. This subduction chemical characteristic is believed by Fitton et al. (1988) to be the result of metasomatism or hydration of the lithospheric mantle during subduction in the Mesozoic to early Cenozoic.

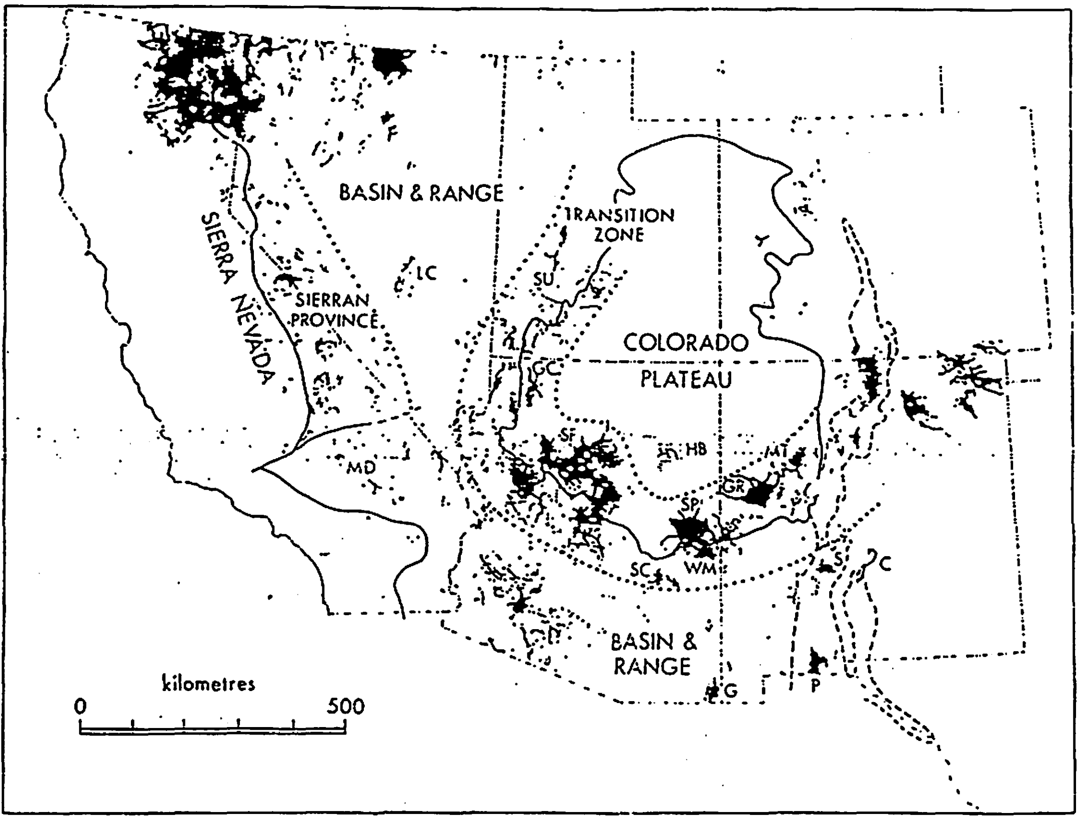

Figure 1. Map of the western United States showing, in black, the distribution of late Cenozoic (<17 Ma) basaltic lavas (from Leudke and Smith, 1984). Solid lines represent the physiographic boundaries of the Basin and Range province and Colorado Plateau.

Gregory (1950) studied and mapped lava flows in and surrounding the Zion National Park region (Figure 2). Lowder (1973) presented a rigorously descriptive paper of basaltic lavas found in southwestern Utah, only briefly discussing petrogenetic mod

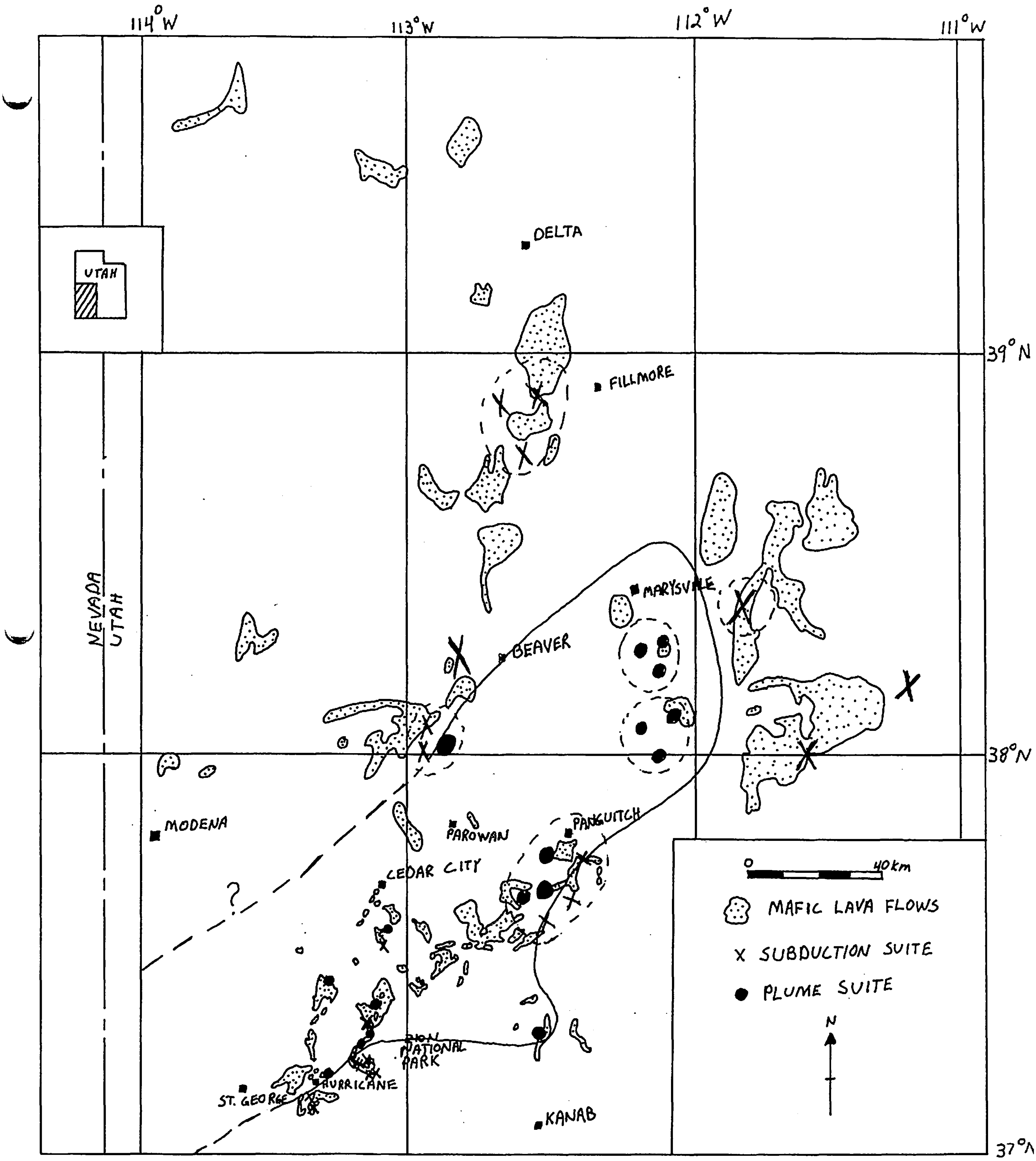

Figure 2. Distribution of mafic lavas in southwestern Utah. Localities of Zion samples shown. Solid line represents approximate boundary of the plume suite surrounded by the subduction suite. Note the parallel between the plume suite and the linear zone of lavas located between St. George and Panguitch.

els. In a paper by Best and Brimhall (1974), lavas of the western Grand Canyon region were analyzed, with all lavas in and near Zion National Park simply being classified as Hawaiites. The geophysical properties of southwestern Utah have been studied by Hausel and Nash (1977) in order to calculate possible source regions of magmas. K-Ar ages for volcanism have been determined by Best et al. (1980) for lavas found in the southwestern quadrant of Utah, southeastern and eastern Nevada, and northwestern Arizona. Smith and Leudke (1984) have speculated on future volcanic hazards in the western United States. However, at this time, few studies have been conducted specifically on the lavas found along the northeast-trending volcanic lineament extending from Hurricane to Panguitch, Utah, particularly those of the Zion National Park region (Figure 2). Mattox and Walker (personal communication) have completed extensive field work, and appropriate geochemical analyses, on lavas found in an approximately 36000 km^2 area located 50 km north and northeast of Zion National Park.

Several authors (e.g. Best and Brimhall, 1974; Fitton et al., 1988) have suggested that a two layer upper mantle exists beneath the Transition zone of southwestern Utah, whereby alkali basaltic magmas are asthenosphere-derived and tholeiitic magmas are lithosphere-derived. Perry et al. (1987) proposed a similar model for the mantle below the Transition zone located on the southeastern margin of the Colorado Plateau. Still others (Lowder, 1973; Hausel and Nash, 1977) suggest a single layer mantle below southwestern Utah, with alkali basalts simply equilibrating at greater depths than the shallow equilibrating tholeiites. Francis and Ludden (1990) envisage a single layered mantle composed of a spinel lherzolite host, which melts to produce transitional alkali basaltic magma, containing amphibole-garnet-clinopyroxene veins, which melt to produce olivine nephelinitic magmas.

The purpose of this paper is to present new geochemical data on young (<3 Ma) (Best et al., 1980) basaltic lavas found in the Zion National Park region, southwestern Utah. This data will be supplemented with unpublished data (Mattox, personal communication) on late Cenozoic lavas found as far as 200 km north and northeast of Zion National Park, in order to establish a new petrogenetic model for the Transition zone of the southwestern margin of the Colorado Plateau.

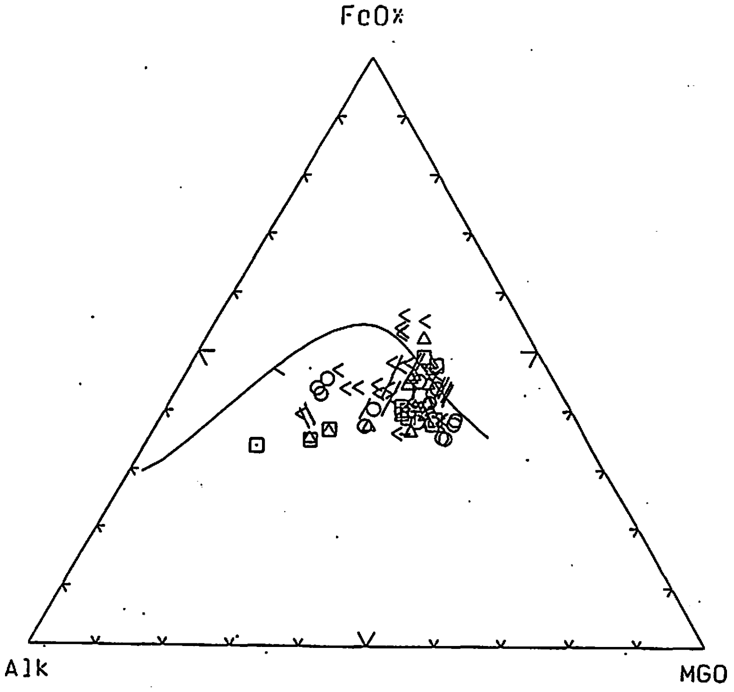

Figure 3. Showing calc-alkaline chemistry of Late Cenozoic lavas from Southwestern Utah.

GEOLOGICAL SETTING

Geochronology

Mesozoic and early Cenozoic subduction of the Farallon plate beneath the western United States was responsible for a broad belt of calc-alkaline volcanism which extended as far inland as the western margin of the Great Plains (Fitton et al., 1988). Though low angle (<15°) (Fitton et al., 1988) subduction appears to be a reasonable theory for the magmatism, it is not entirely accepted among geologists. At approximately 29 Ma (Fitton et al., 1988), the westward drifting North American plate overrode the East Pacific Rise, which separated the Farallon and Pacific plates (Fitton et al., 1988; Best and Brimhall, 1974). Fitton et al. (1988) state that "This event led to the propagation of the San Andreas transform system...." With migration of the Mendocino triple junction northward along the California coast (Best et al., 1980), calc-alkaline magmatism progressively became confined to the Cascades (Fitton et al., 1988).

The cessation of Farallon plate subduction was followed by a hiatus in magmatic activity approximately 18 Ma which marked the transition from the intermediate to silicic calc-alkaline suite (Hausel and Nash, 1977), to basaltic volcanism (Best and Brimhall, 1974). Best et al. (1980) state that along latitude 38° N in the Transition zone between the Colorado Plateau and Basin and Range Province, structural differentiation began as early as 26 Ma, with main block faulting not beginning before 22 Ma.

The focus of this study is a suite of late Cenozoic (<17 Ma) basalts found in the Transition zone. The Transition zone is from the relatively undeformed, flat-lying Paleozoic and Mesozoic sedimentary rocks of the Colorado Plateau, to the extensively block faulted mountain ranges of the Basin and Range province. This zone contains north-striking, normal fault systems, such as the Hurricane fault system found in the study area of this paper, which have displacements of up to 5000 m with the west block down (Best and Brimhall, 1974). Late Cenozoic basaltic volcanism is closely related to the lithospheric extension in and around the Basin and Range Province (Fitton et al., 1988). Crustal thickness of the Transition zone ranges from approximately 30 km to 40 km (Hausel and Nash, 1977).

The Transition zone of this study has been shown to be analogous to the Sierran province found on the western margin of the Basin and Range province, and the Transition zone found between the Colorado Plateau and the Rio Grande rift (Fitton et al., 1988; Perry et al., 1987, respectively). These three regions are "transitional" in upper crustal structure and lithospheric properties, the similarities of which are easily recognizable geochemically and geophysically.

Field Relations

Of the late Cenozoic basaltic regions found in the western United States, the Transition zone (for this paper any use of the term "Transition zone" will refer to the southwestern margin of the Colorado Plateau) contains the most voluminous lava fields (Fitton et al., 1988), which cover several hundred square miles (Best and Brimhall, 1974). The flows unconformably overlie the older flat-lying sedimentary rocks, with some flows forming mesa cappings, while others can be found in drainage systems. Occasionally flows are cut by faults, such as the Hurricane fault scarp.

In the Zion National Park region flows are typically 20 feet-thick. However, in and near Zion National Park flows can be observed which are over a hundred feet in thickness. These thick flows are found amidst an extensive lava field and are presumed to be a combination of flows. Columnar jointing, too, is common, but pillow lavas (location 14) also crop out. Cinder cones are widespread and youthful in appearance. Scoria appears not only on the flanks of the cinder cones, but also among many of the flows. Sills and dikes are extremely rare, the only dike ever being found in the Zion National Park region is the Divide dike, found approximately eight miles south of Hurricane, Utah (Gregory, 1950). The study area is devoid of any Phanerozoic igneous rocks, except the basaltic lavas described in this study. The southernmost limit of silicic volcanism occurs approximately 20 km north of Hurricane, Utah (Best and Brimhall, 1974).

TABLE 1.

MODAL MINERALOGY

Sample #	Z-1	Z-2	Z-5	Z-6	Z-7	Z-9	Z-12	Z-14	Z-15
PHENOCRYST									
Olivine	17	17	9	7	2	15	8	4	3
Plagioclase						1		<1	4
Augite	3	3	1	2		10	2	<1	
GROUNDMASS									
Plagioclase	32	32	54	38	49	45	36	48	65
Fe-Ti Oxides	20	20	13	29	25	2	18	5	
Olivine	4	5	5	1	5	27	9	4	
Augite	24	23	18	23	18		27	38	28

Sample #	Z-16	Z-17	Z-18	Z-19	Z-25	Z-29	Z-30	Z-31
PHENOCRYST								
Olivine	3	13	9	2	2	10	12	9
Plagioclase	2							
Augite		2	1	1		5	3	<1
GROUNDMASS								
Plagioclase	57	65	45	34	49	38	37	39
Fe-Ti Oxides	2	6	18	29	20	43	20	21
Olivine				5				
Augite	46	14	27	29	29	4	28	30

PETROGRAPHY AND MINERALOGY

Petrographic data of the Zion National Park region samples is summarized in Table 1. The entire suite (17 samples) is basic, and composed of porphyritic olivine basalts containing phenocrysts of olivine (Fo_{80-85}), and sometimes plagioclase and/or augite. 6 of the 17 samples have iddingsitized olivine phenocrysts. In several of the samples the augite shows oscillatory or sector zoning.

The groundmass is composed of olivine, Fe-Ti oxides, olivine, augite, glass, and plagioclase in any combination. Where distinguishable, the groundmass plagioclase has compositions in the range An_{63-30}.

Orientation of the groundmass plagioclase laths around the phenocrysts in a trachytic texture is very common. Though a small number of samples display a seriate texture, this difference may be attributed to the plane in which the rock was cut for thin section.

Many of the samples contain vesicles. Only those samples devoid of calcium carbonate infillings were chosen for geochemical analyses and petrography. Sample Z-2 was found to have small olivine crystals surrounding one of the vesicles.

In general, only the olivine tholeiites contain any plagioclase phenocrysts, though not all of them do. Petrographically, the subduction suite and the plume suite are indistinguishable.

PETROGENESIS

Data Of This Study

Analytical Methods

Analytical methods for whole-rock major and trace elements were determined by X-ray fluorescence (XRF) at Northern Illinois University. The XRF used is a completely automated Siemens 300 sequential wavelength-dispersive system. Whole-rock analyses for the Zion National Park region are given in Table 2. Supplemental data of flows north and northeast of Zion were given by Mattox (personal communication).

Results

The rocks of the Zion National Park region can be subdivided into two groups: one with a subduction signature, and one with a plume signature (Figures 5 and 6). Of the 17 samples, 6 were found in the subduction suite, 9 were found in the plume suite, and 2 were found to be flyers which appear to be more subduction than plume, but will be ignored when modeling petrogenesis (Figure 6). The subduction suite is generally higher in K, Sr, and Zr, and lower in Rb, than the plume suite. Both suites contain significant numbers of both alkali basalts and olivine tholeiites (subduction suite: 4 alkali basalts and 2 olivine tholeiite; plume suite: 4 alkali basalts and 5 olivine tholeiites) (Figure 4). None of the samples were found to be either

Table 2.

	PM	PM	PM	PM	SB	PM	PM	?	SB	?	SB	SB	PM	SB	PM	PM	SB
Sample	Z-1	Z-2	Z-5	Z-6	Z-7	Z-9	Z-12	Z-14	Z-15	Z-16	Z-17	Z-18	Z-19	Z-25	Z-29	Z-30	Z-31
	AB	AB	OT	OT	AB	AB	OT	OT	OT	OT	AB	AB	AB	AB	OT	OT	OT
SIO_2	48.43	48.15	51.13	50.55	52.61	45.90	50.63	50.69	52.57	51.94	50.32	50.08	48.86	50.93	51.28	49.81	53.13
TIO_2	2.04	2.05	1.48	1.50	1.66	2.44	1.69	1.47	1.65	1.52	2.00	1.84	1.61	1.94	1.46	1.68	1.49
AL_2O_3	13.37	13.39	14.84	14.29	15.57	13.32	15.16	15.52	16.74	16.77	16.91	16.37	16.47	16.16	14.80	14.06	16.14
FEO	10.94	11.10	10.35	10.63	8.50	11.88	10.15	10.88	8.89	9.64	9.62	9.58	10.31	9.24	10.32	10.57	8.77
MNO	0.17	0.17	0.16	0.16	0.14	0.18	0.17	0.17	0.15	0.15	0.15	0.16	0.18	0.15	0.16	0.16	0.15
MGO	10.36	10.43	8.45	9.28	6.11	10.54	7.10	7.58	6.17	6.12	7.13	8.06	7.03	7.25	8.45	9.72	6.78
CAO	9.75	9.78	9.08	8.98	8.31	10.41	10.27	9.13	8.27	8.96	7.84	8.05	10.86	7.53	8.97	9.42	7.30
NA_2O	2.99	3.01	3.13	3.18	3.85	2.95	3.38	3.15	3.60	3.39	3.91	3.79	3.21	4.29	3.09	3.00	3.95
K_2O	1.40	1.38	1.03	1.04	2.53	1.65	1.00	1.09	1.50	1.08	1.54	1.49	0.88	1.75	1.11	1.15	1.67
P_2O_5	0.55	0.54	0.34	0.39	0.72	0.73	0.47	0.32	0.46	0.43	0.59	0.58	0.59	0.76	0.36	0.43	0.62
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
V	194.5	201.7	181.8	158.2	143.1	227.0	180.7	184.4	166.0	180.9	167.4	167.0	236.9	144.0	170.4	182.0	142.5
SC	20.1	19.2	24.9	20.0	17.0	22.5	23.6	25.3	27.0	22.3	24.7	22.0	32.0	15.8	23.4	23.0	18.1
BA	721.3	702.3	598.5	649.1	1596.9	1003.5	726.2	677.5	661.0	823.2	540.8	630.6	927.8	860.0	613.2	699.0	953.4
LA	49.5	47.1	30.8	34.7	64.2	46.4	45.0	32.6	36.0	27.6	35.1	38.6	41.3	54.6	39.6	30.4	48.0
CE	85.0	76.2	64.9	64.3	129.0	96.1	78.2	76.1	70.8	55.9	73.8	82.5	89.8	102.1	53.7	68.1	87.2
CR	388.8	398.4	331.8	376.5	151.0	371.3	245.8	269.7	189.0	156.4	202.1	260.5	197.3	203.1	327.0	378.5	192.2
CO	66.5	67.0	54.0	59.3	40.0	67.1	48.2	56.2	44.2	40.5	44.9	49.1	47.1	44.9	61.8	64.1	48.5
NI	235.6	244.4	151.3	196.4	93.0	192.3	94.8	122.7	91.9	52.0	119.4	147.0	61.4	124.1	148.0	211.4	133.0
CU	65.5	54.5	59.7	42.7	37.8	72.0	45.5	61.0	37.6	41.6	40.7	40.2	51.5	43.7	57.5	65.2	37.9
ZN	92.6	97.5	100.2	90.9	82.2	203.0	96.5	106.0	81.2	87.2	84.0	80.7	91.3	73.4	100.1	130.1	88.5
GA	17.8	18.1	23.4	19.4	19.3	21.3	21.8	22.2	20.9	21.6	18.3	20.5	19.8	19.4	19.8	18.2	19.2
PB	4.1	7.6	8.2	6.2	13.2	7.3	5.6	7.4	14.3	6.3	9.2	7.1	6.9	11.0	8.4	6.6	10.8
TH	5.2	8.3	3.8	6.0	5.3	6.2	5.8	3.0	0.6	0.4	1.2	1.8	3.7	1.2	7.9	3.8	2.2
RB	20.0	19.4	16.2	15.6	26.0	15.5	12.7	14.8	17.7	15.3	13.6	14.6	8.8	17.2	16.7	15.9	21.4
SR	703.2	706.9	549.0	568.7	1364.7	1087.3	689.2	692.3	615.6	584.7	849.5	841.7	764.2	1136.6	538.4	605.1	885.4
Y	25.6	25.1	23.2	22.0	27.2	24.2	25.2	23.9	31.0	32.2	29.5	28.9	29.3	29.9	24.7	22.3	29.4
ZR	202.0	204.9	153.2	153.3	257.1	237.6	156.3	134.4	259.8	221.1	292.7	272.8	187.9	310.1	155.1	166.0	274.9
NB	45.8	46.7	25.3	30.7	29.4	64:0	36.7	15.6	24.7	12.2	28.9	28.9	41.4	32.3	26.3	35.2	30.4

PM=Plume suite SB=Subduction suite ?=Suite uncertain AB=Alkali basalt OT=Olivine tholeiite

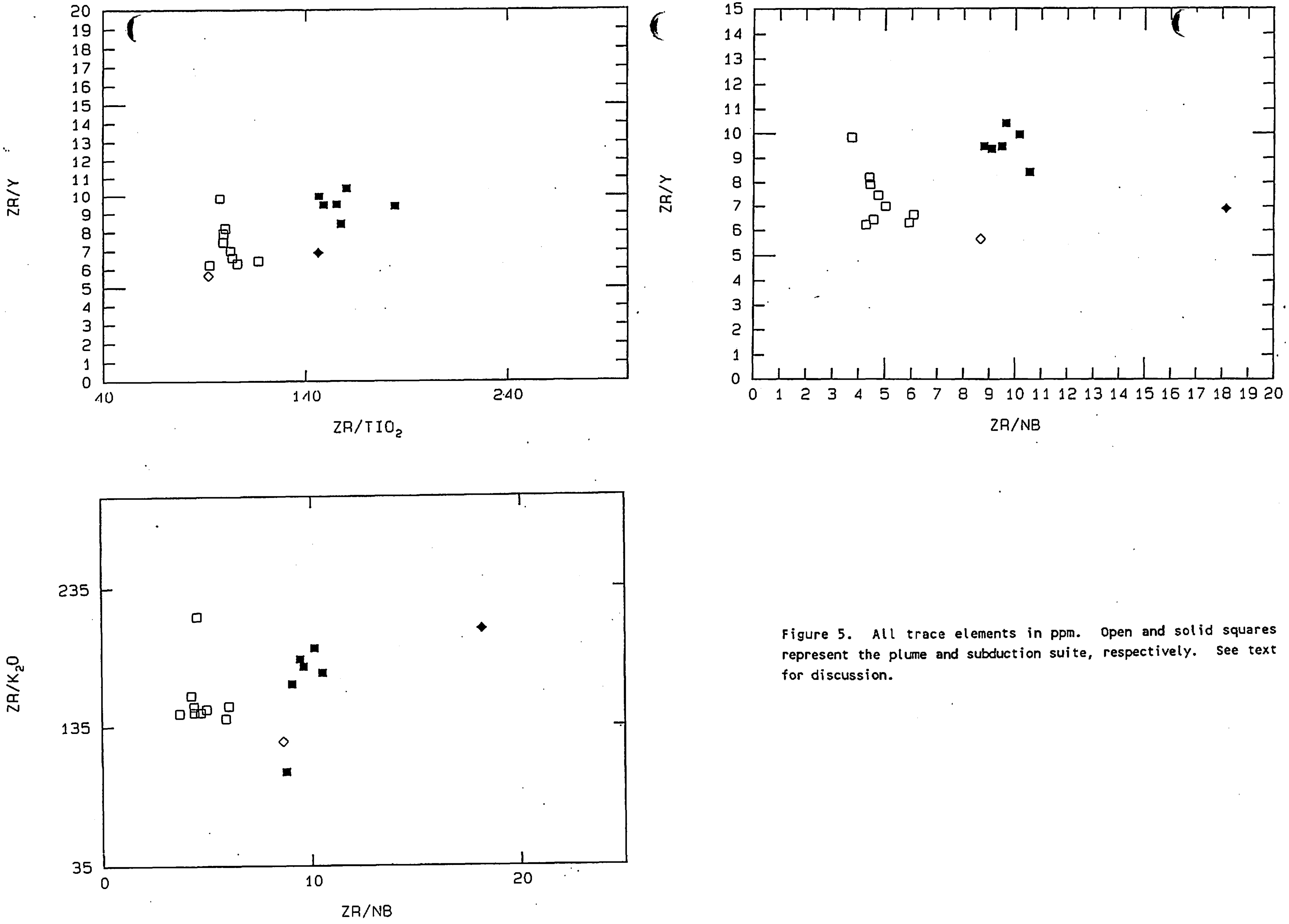

Figure 5. All trace elements in ppm. Open and solid squares represent the plume and subduction suite, respectively. See text for discussion.

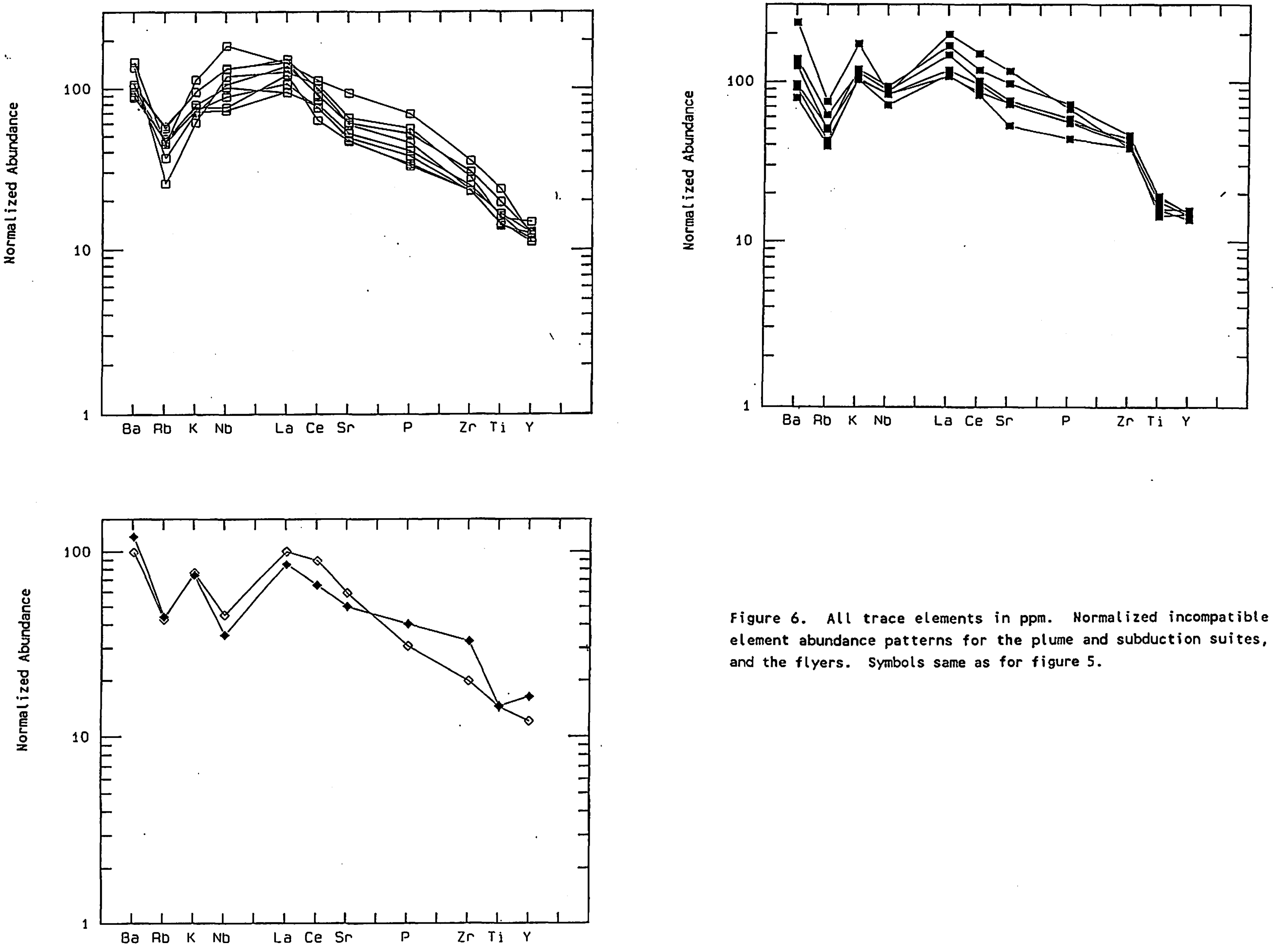

Figure 6. All trace elements in ppm. Normalized incompatible element abundance patterns for the plume and subduction suites, and the flyers. Symbols same as for figure 5.

highly potassic nor sodic, with Na_2O/K_2O in the range of 1.52 to 3.65.

Subtle provinciality occurs in the Zion National Park region for the two suites (Figure 2). Generally, the subduction suite lies to the southeast of the plume suite, separated by a very narrow zone of overlap. Whether or not true provinciality is present will only be resolved with additional sampling and analyses.

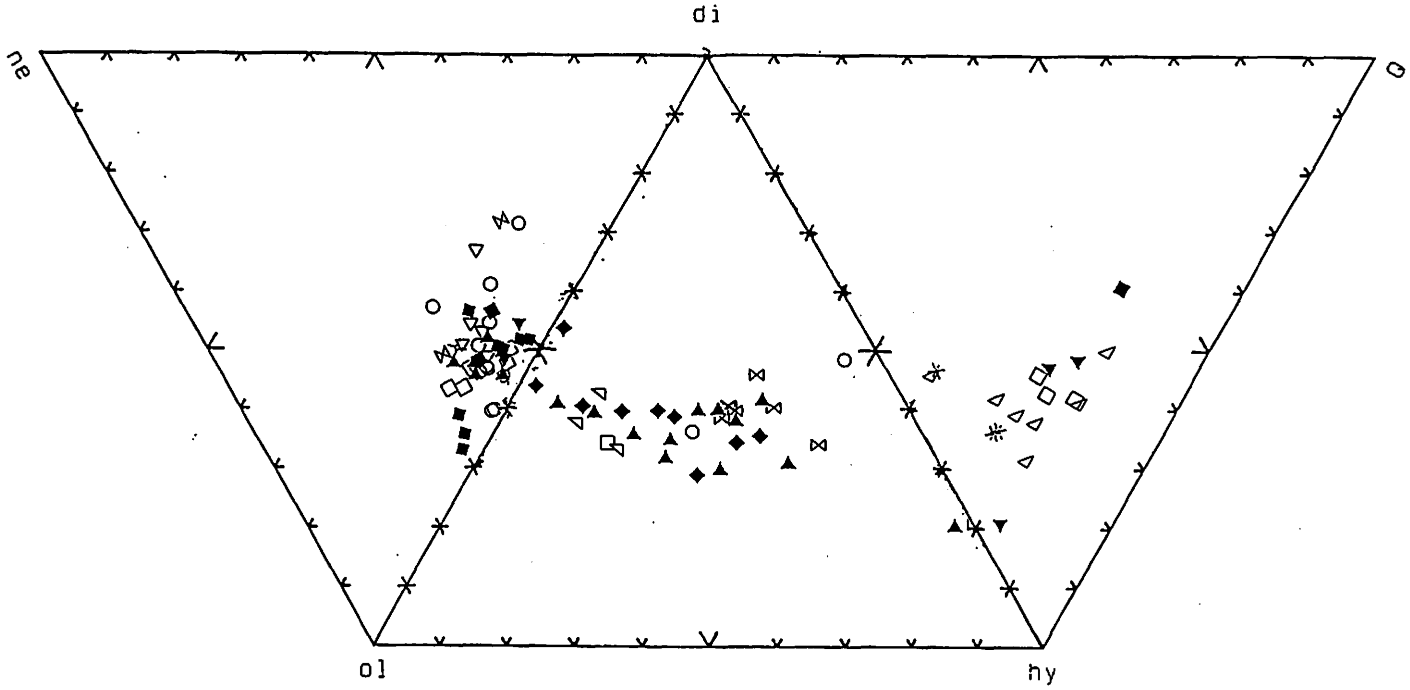

Figure 4. Normative compositions of late Cenozoic lavas from southwestern Utah. Solid diamonds represent samples from the Zion National Park region.

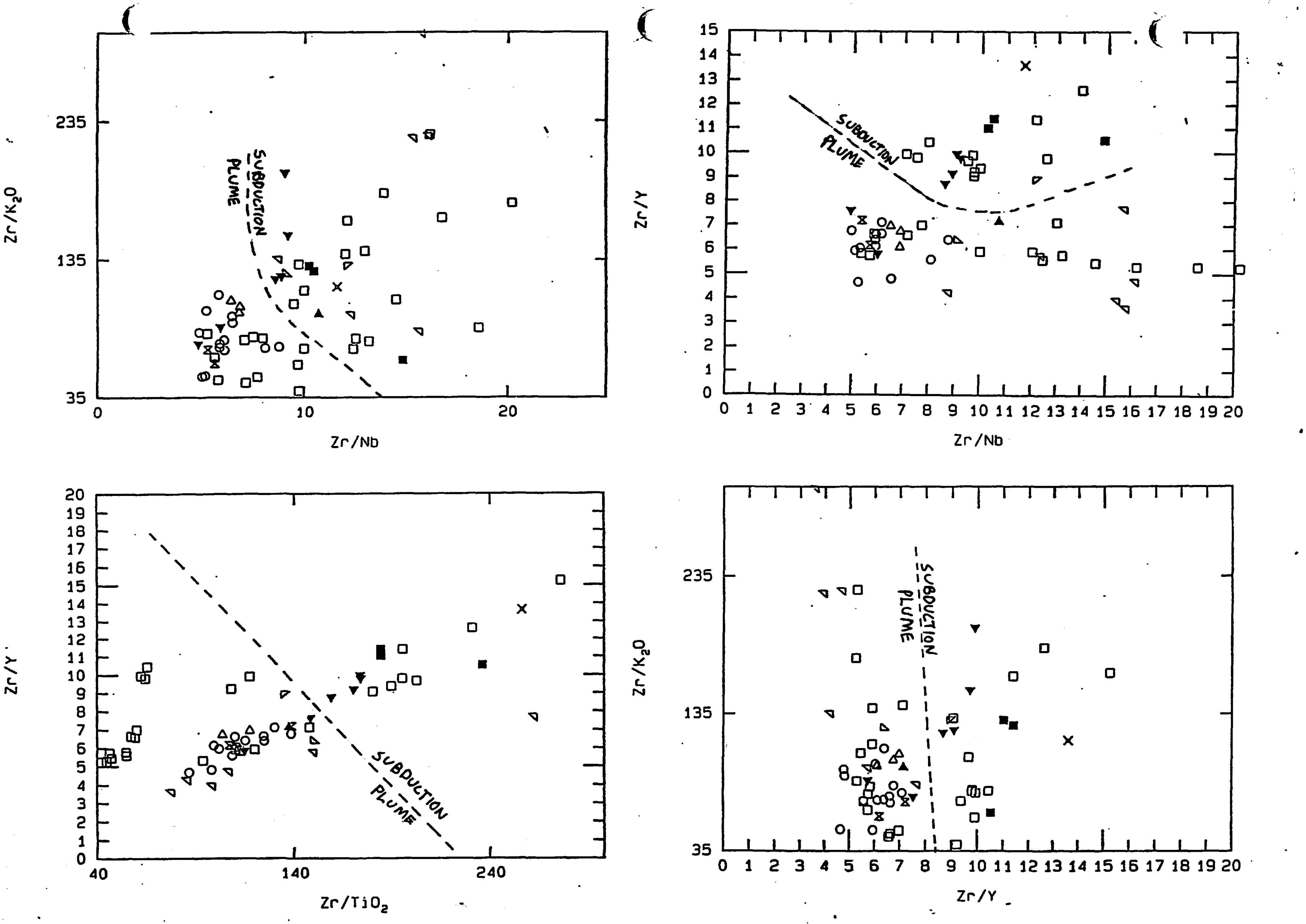

Figure 7. All trace elements in ppm. Suites of additional late Cenozoic samples found north and northeast

Other Data

Results

63 additional Transition zone samples from a 36000 km^2 area 50 km north and northeast of Zion exhibit extraordinary similarities to the author's data; that being of a subduction suite and a plume suite (Figure 7). Provinciality is again observed, this time showing a zone of the plume suite surrounded on three sides by the subduction suite. When projected southwesterly and combined with the author's data, an approximation of an elliptical plume suite zone is achieved (Figure 2). Even though only additional data and mapping will verify such provinciality, the implications suggest an asthenospheric component intruding a lithospheric component.

Geophysical Implications

In a study of Washington County, Utah (50 km southwest of Zion) Hausel and Nash (1977) assumed that the environment of formation of young mafic lavas has not substantially changed up to the present time. This assumption will be retained for this study.

Eight heat-flow measurements taken near Cedar City (northwest corner of this study) ranged from 1.88 to 2.36 h.f.u. (1 h.f.u.=1 $ucal/cm^2*s$) (Hausel and Nash, 1977). These anomalously high measurements are highly suggestive of partial melts beneath the Zion National Park region.

In Washington County P_n velocities are 7.7 km/s to 7.8 km/s (Hausel and Nash, 1977). Likewise, Perry et al. (1987) found P_n velocities of exactly the same range for the Transition zone located on the southeast margin of the Colorado Plateau. Such low velocities suggest the presence of a "hot" lithosphere beneath these regions.

Electrical conductivities are anomalously high in southwestern Utah (Hausel and Nash, 1977). Again, consistent with the presence of small degrees of partial melting beneath the crust.

Petrogenetic Model

Several authors have suggested a two-layer upper mantle model for the Transition zone surrounding the Colorado Plateau, with alkali basaltic magma equilibrating in the deeper asthenosphere, and tholeiitic magma equilibrating in the shallower lithosphere (i.e. Best and Brimhall, 1974; Hausel and Nash, 1977; Perry et al., 1987). The data of this study strongly disagrees with the above model since both the subduction suite, with a lithospheric origin, and the plume suite, with an asthenospheric origin, contain alkali basalts and olivine tholeiites. Lowder (1973) proposed a model of a single upper mantle layer where differing degrees of partial melting of a common mantle material and the segregation of liquid at different depths produces olivine tholeiites at shallower depths and alkali olivine basalts at deeper depths. Lowder (1973), however, does not recognize the plume and subduction geochemical signatures. In a model by Hausel and Nash (1977), young mafic lavas are derived at shallower depths by a partial melt of spinel peridotite. Again, only a single layer model, with no explanation for geochemical differences or the spatial relationship between alkali basalts and olivine tholeiites.

It has been determined isotopically that olivine tholeiites cannot be related to alkali basalts by low-pressure crystal-liquid fractionation, or by variable degrees of melting of a common mantle source (Francis and Ludden, 1990). The same authors also suggest a single upper mantle layer, for the Canadian Yukon, whereby a host lherzolite embodies amphibole-garnet-clinopyroxene veins. It is the host lherzolite which melts to a transitional alkaline basaltic magma, and the veins which melt to an olivine nephelinitic magma. Since the author of this paper lacks isotopic data, the idea that alkali basalts and olivine tholeiites can be derived from a common mantle material, differentiated by varying degrees of partial melting and fractionation will be retained. Furthermore, Fitton et al. (1988) state that experimentally the latter scenario has been shown to be true.
The author of this paper will also sustain the idea that alkali basaltic magma is derived at deeper depths than olivine tholeiitic magma, regardless of the layer of origin (i.e lithosphere or asthenosphere).

Figures 8a-c show the data of this study separated into

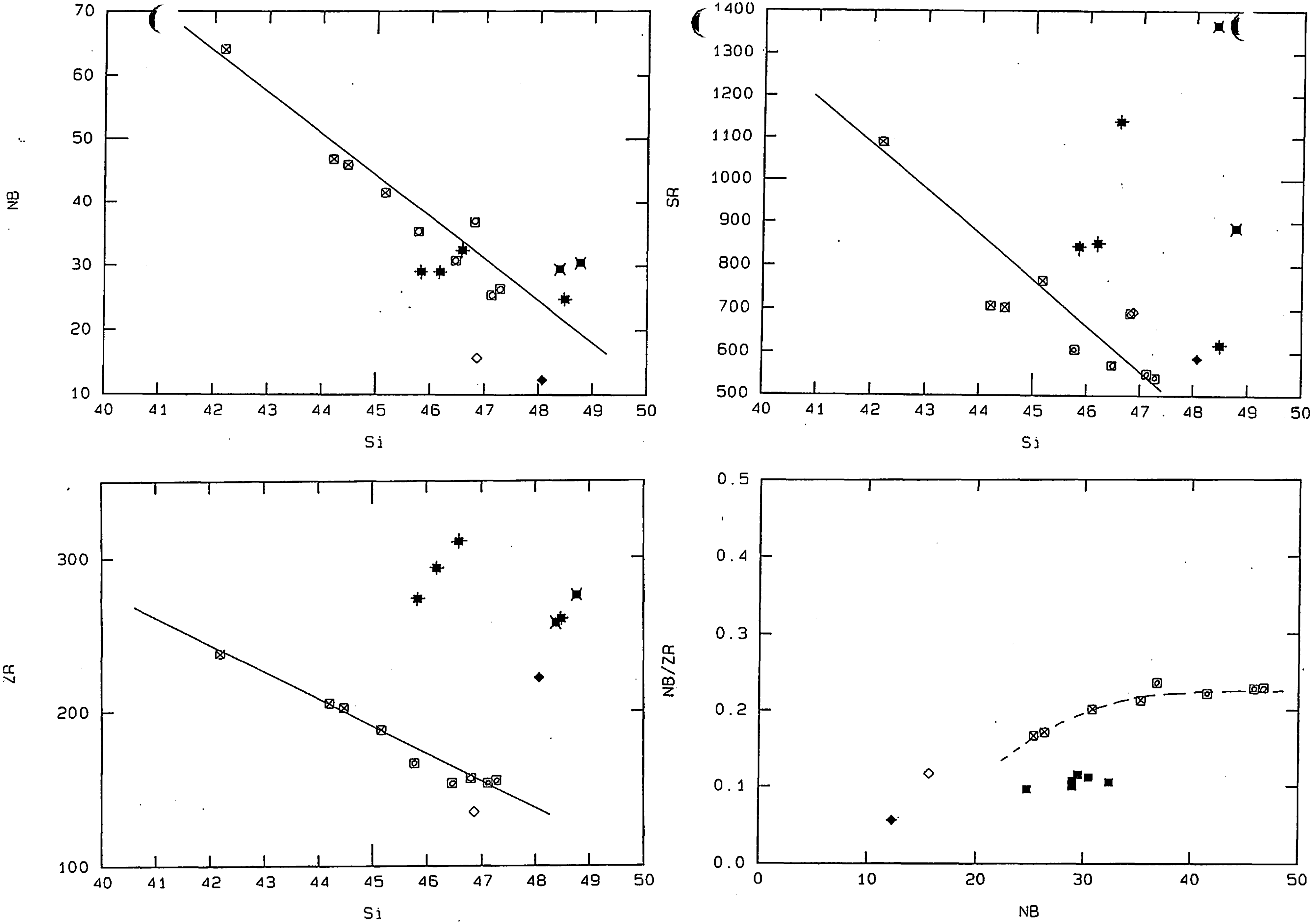

Figure 8. (a) Nb in ppm vs. Si in cation units. (b) Sr in ppm vs. Si in cation units. (c) Zr in ppm vs. Si in cation units. (d) All trace elements in ppm. Plots show mixing of alkali basaltic (⊠) and olivine tholeiitic (⊡) magmas within the plume suite. Subduction suite alkali basalts and olivine tholeiites are represented by ✱ and ✖, respectively. See text for discussion.

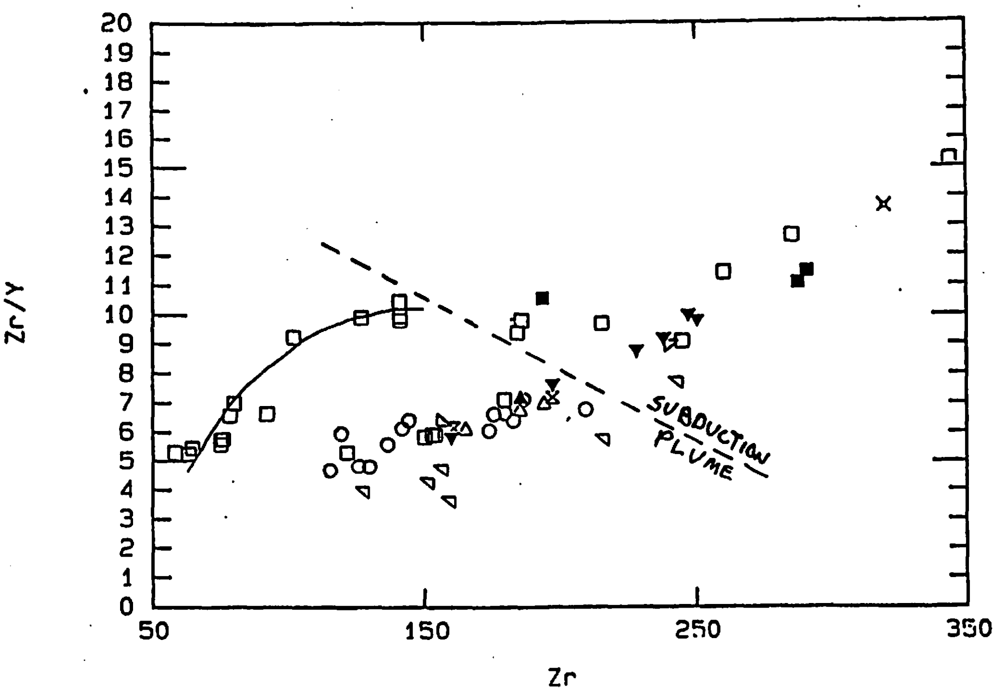

Figure 9. All trace elements in ppm. Plot shows mixing curve among plume suite magmas from the region north and northeast of Zion National Park.

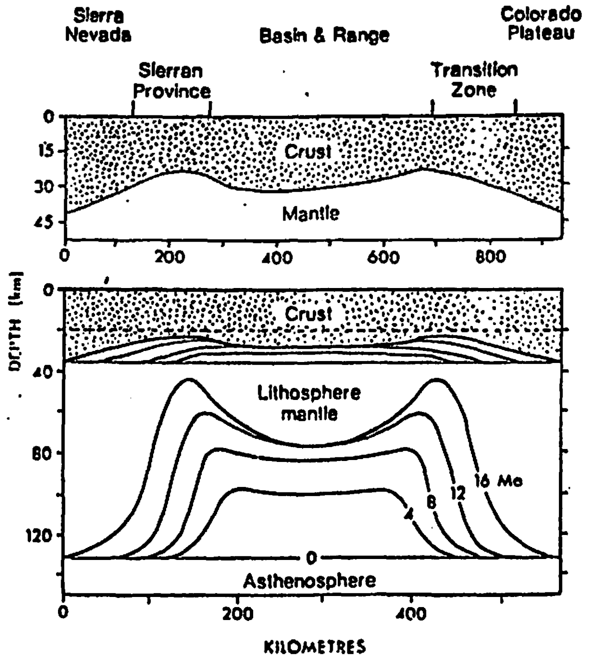

Figure 10. Upper diagram: refraction seismic profile across the Great Basin (from Allmendinger et al., 1987). Lower diagram: lithospher stretching model (Keen, 1985, Fig. 7a). The two sets of curves represent crust-mantle and lithosphere-asthenosphere profiles at various times (in Ma) after the beginning of extension. The horizontal broken line in the crust represents the brittle-ductile transition. Viscosity decreases exponentially by about five orders of magnitude from this horizon to the base of the lithosphere. In this model the lithosphere is extended by side-driven stretching at a rate of 1 cm/yr over an initial horizontal distance of 240 km. Note the similarity between the model crustal profile at 16 Ma and the seismic profile (top) despite the differences in scale.

the subduction suite, magmas of which originated in the lithosphere, and the plume suite, magmas of which originated in the asthenosphere. Note that within the plume suite an anti-correlation exists between incompatible trace elements, particularly Nb and K, and the degree of fractionation. If varying degrees of partial melting and fractionation are the only processes involved in petrogenesis, than the line should have a positive slope. Such a trend can only be explained by magma mixing. Figure 8d expresses this mix as a curve. Mixing is also observed in the plume suite of the samples found near Panguitch, Utah (Figure 9). This mixing appears to occur between olivine tholeiitic magmas, higher in silica and lower in Nb, Sr, K, and Zr, and alkali basaltic magmas (Figure 8). A very similar mixing model has been suggested by Francis and Ludden (1990) for alkaline lavas from the Canadian Yukon.

Strangely, no mixing has been observed in the subduction suite. It is possible that this may simply be the result of sampling bias since the Zion region is only represented by six data points. However, no mixing of subduction suite lavas found north and northeast of Zion is apparent either.

This trend of mixing in the plume suite and not in the subduction suite may be explained by mantle dynamics. It is readily apparent that magmas derived in the asthenosphere have a greater distance to travel to the base of the crust than do lithosphere-derived magmas. Figure 10 shows that at least 10 km of lithosphere separate the shallowest asthenosphere from the crust. It may be this distance ($\geq$10 km) which permits asthenosphere-derived magmas to mix. Appropriately, lithosphere-derived magmas, particularly those at very shallow depths, would almost immediately ascend to the crust, greatly reducing the possibility of mixing. If this is indeed the scenario, then the subduction suite lavas should cluster into an alkali basalt group and an olivine tholeiite group, with no overlap whatsoever. In figure 8a two groups can be readily identified. The lower Si group is indeed entirely alkali basalt, as would be expected. However, of the 3 data points of the higher Si group, 2 are olivine tholeiites and 1 is an alkali basalt. It is not unreasonable to suspect that small amounts of mixing may occur in the subduction suite, perhaps explaining the one odd alkali basalt (Z-7) found among the two olivine tholeiites (Z-15 and Z-31). Based on only 6 data points it is difficult to distinguish the two groups. Moreover, mixing among the lavas found north and northeast of Zion may be so small that any curvature in a ratio plot may be consumed in the scatter. Only additional data will truly test such a hypothesis.

As discussed earlier, plume suite lava and subduction suite lava are provincially related within the Transition zone. Figure 10 shows a mantle dynamics model of the aforementioned area. Best and Brimhall (1974) and Fitton et al. (1988) suggest the same mechanism of passive extension producing faulting and thus magma conduits. This paper accepts this model of "...a steep, keellike asthenosphere-lithosphere boundary...," which began sometime in the middle to late Cenozoic (Best and Brimhall, 1974). It is the upwelling of the asthenosphere which is responsible for the approximately elliptical plume suite contained within a subduction suite as expressed surficially (Figure 2).

Alkali basaltic and olivine tholeiitic magmas are both derived by partial melting of spinel lherzolite (Best and Brimhall, 1974; Hausel and Nash, 1977). The alkali basalts, however, represent essentially unmodified partial melts, as indicated by the higher concentrations of incompatible elements (Figure 8), at depths in the range of 65 km to 95 km (20 kb-30 kb) (Best and Brimhall, 1974; Hausel and Nash, 1977). Both the lithosphere and the asthenosphere are contained in this depth range, thus explaining why both the plume and the subduction suites contain alkali basalts (Figure 10). The olivine tholeiites represent greater degrees of partial melting, suggested by lower concentrations of incompatible elements (Figure 8), of spinel lherzolite at lower pressures, thus shallower depths, with modification by fractionation and accumulation of plagioclase, identified as phenocrysts petrographically (Table 1) (Best and Brimhall, 1974). Again, figure 10 shows that both lithosphere and asthenosphere reside above 65 km deep, and explain why olivine tholeiites are encountered in both suites. All geophysical studies are consistent with such a model.

Though erupted in an extensional environment, the chemical characteristics of the lavas are reminiscent of calc-alkaline magmas (Figure 3). Fitton et al. (1977) have suggested that these basalts had a lithospheric mantle source which may have been hydrated or metasomatized by fluids released by the Farallon plate during subduction which had ceased up to 28 Ma before eruption of some of the Transition zone lavas. Such a conclusion is maintained in this study, particularly since the lavas of the subduction suite all possess the low Nb anomaly, characteristic of fluids released from a subducting slab. Fitton et al. (1988) also argues that the absence of convection in the lithosphere helps retain a subduction signature, even as much as 28 Ma following cessation of subduction. Furthermore, mantle xenoliths of metasomatized lherzolite have been identified (Francis and Ludden, 1990).

THE FUTURE

Smith and Leudke (1984) have reported on potential volcanism in the western United States. They show that the loci of volcanism in the past 5 Ma has been concentrated in linear zones, appropriate with the Transition zone (Figure 2).

According to Smith and Leudke (1984), volcanism in the past 5 Ma reflects a mantle source likely to be active today, and in the future. Since periods of volcanism in earth history have spanned greater than 10 million years, the conclusion that volcanism may return to the Zion National Park region in not unsub stantiated.

The rocks of this study fall in the Northeast-trending St. George Zone (Smith and Leudke, 1984), and are less than 3 Ma (Best et al., 1980). Interestingly, this linear zone parallels the major axis of the elliptical surface expression of the plume suite (Figure 2). Hausel and Nash (1977) disclose heat-flow measurements ranging from 1.88 h.f.u. to 2.36 h.f.u., P_n=7.8 km/s, and anomalously high electrical conductivity measurements for southwestern Utah. The above, combined with the youthfulness of the cinder cones suggests that southwestern Utah, particularly the Zion National Park region, will be a site of volcanism in the future.

SUMMARY AND CONCLUSIONS

Transition zone lavas of southwestern Utah were erupted during extensional-block faulting. These mafic flows geochemically group into a subduction suite and a plume suite, with sources in the lithosphere and asthenosphere, respectively.

This paper suggests a two-layer mantle model, an upper metasomatized lithospheric layer underlain by an asthenospheric layer, with both olivine tholeiitic magma and alkali basaltic magma being generated by varying degrees of partial melting in each individual layer. Due to the greater depth at which asthenospheric magmas are generated, mixing occurs between the alkali basaltic and the olivine tholeiitic magmas during ascent through the lithosphere. Since lithosphere-derived magmas ascend to the crust soon after formation, significantly less mixing occurs, if at all. Time-space relations support such model.

Geophysically determined magma source regions and the youthfulness of the lavas suggests future eruptions in the Zion National Park region of southwestern Utah.

ACKNOWLEDGEMENTS

Partial funding for this project was granted by the Honors Council of the Illinois Region. Supplemental data was supplied by Steven Mattox and James Walker. Many thanks to Neil Dickey for all of his instruction and patience, and the Department of Geology at Northern Illinois University.

REFERENCES

Best, M.G., and Brimhall, W.H., 1974, Late Cenozoic Alkalic Basaltic Magmas in the Western Colorado Plateaus and the Basin and Range Transition Zone, U.S.A., and Their Bearing on Mantle Dynamics: Geological Society of America Bulletin, v. 85, pp. 1677-1690.

Best, M.G., McKee, E.H., and Damon, P.E., 1980, Space-Time-Composition Patterns of Late Cenozoic Mafic Volcanism, Southwestern Utah and Adjoining Areas: American Journal of Science, v. 280, pp. 1035-1050.

Fitton, J.G., James, D., Kempton, P.D., Ormerod, D.S., and Leeman, W.P., 1988, The Role of Lithospheric Mantle in the Generation of Late Cenozoic Basic Magmas in the Western United States: Journal of Petrology, Special Lithosphere Issue, pp. 331-349.

Francis, D., and Ludden, J., 1990, The Mantle Source for Olivine Nephelinite, Basanite, and Alkaline Olivine Basalt at Fort Selkirk, Yukon, Canada: Journal of Petrology, v. 31, Part 2, pp. 371-400.

Gregory, H.E., 1950, Geology and Geography of the Zion Park Region, Utah and Arizona: U.S. Geological Survey Professional Paper 220, 200 pp.

Hausel, W.D., and Nash, W.P., 1977, Petrology of Tertiary and Quaternary Volcanic Rocks, Washington County, Southwestern Utah: Geological Society of America Bulletin, v. 88, pp. 1831-1842.

Lowder, G.G., 1973, Late Cenozoic Transitional Alkali Olivine-Tholeiitic Basalt and Andesite from the Margin of the Great Basin, Southwest Utah: Geological Society of America Bulletin, v. 84, pp. 2993-3012.

Mattox, S.R., Personal Communication

Perry, F.V., Baldridge, W.S., and DePaolo, D.J., 1987, Role of Asthenosphere and Lithosphere in the Genesis of Late Cenozoic Basaltic Rocks from the Rio Grande Rift and Adjacent Regions of the Southwestern United States: Journal of Geophysical Research, v. 92, pp. 9193-9213.

Smith, R.L., and Luedke, R.G., 1984, Potentially Active Volcanic Lineaments and Loci in Western Conterminous United States: In Explosive Volcanism: Inception, Evolution and Hazards, National Academy Press, Washington, D.C., pp. 47-66.

Walker, J.A., Personal Communication