JOURNAL OF GEOPHYSICAL RESEARCH, VOL, 96, NO. B8, PAGES 13,529-13,544, JULY 30, 199l

Tertiary Minette and Melanephelinite Dikes, Wasatch Plateau, Utah: Records of Mantle Heterogeneities and Changing Tectonics

DAVID G. TINGEY, ERIC H. CHRISTIANSEN, AND MYRON G. BEST

Department of Geology, Brigham Young University, Provo, Utah

JOAQUIN RUIZ

Department of Geosciences, University of Arizona, Tucson

DANIEL R. Lux

Department of Geology, University of Maine, Orono

A swarm of minette and melanephelinile dikes is exposed over 2500 km^2 in and near the Wasatch Plateau, central Utah, along the western margin of the Colorado Plateaus in the transition zone with the Basin and Range province. To date, 110 vertical dikes in 25 dike sets have been recognized. Strikes shift from about N80°W for 24 Ma dikes, to about N60°W for 18 Ma, to due north for 8-7 m.y. These orientations are consistent with a shift from east-west Oligocene compression associated with subduction to east-west late Miocene crustal extension. Minettes are the most common rock type; mica-rich minette and mica-bearing melanephelinile occurs in 24 Ma dikes, whereas more ordinary minette is found in 8-7 Ma dikes. One melanephelinile dike is 18 Ma. These mafic alkaline rocks are transitional to one another in modal and major element composition but have distinctive trace element patterns and isotopic compositions; they appear to have crystallized from primitive magmas. Major, trace element, and Nd-Sr isotopic data indicate that melanephelinile, which has similarities to ocean island basalt, was derived from small degree melts of mantle with a chondritic Sm/Nd ratio probably located in the asthenosphere, but it is difficult to rule out a lithospheric source. In contrast, mica-bearing rocks (mica melanephelinile and both types of minette) are more potassic and have trace element patterns with strong Nb-Ta depletions and Sr-Nd isotopic compositions caused by involvement with a component from heterogeneously enriched lithospheric mantle with long-term enrichment of Rb or light rare earth elements (REE) (epsilon Nd as low as - 15 in minette). Light REE enrichment must have occurred anciently in the mid-Proterozoic when the lithosphere was formed and is not a result of Cenozoic subduction processes. After about 25 Ma, foundering of the subducting Farallon plate may have triggered upwelling of warm asthenospheric mantle to the base of the lithosphere. Melanephelinite magma may have separated from the asthenosphere and, while rising through the lithosphere, provided heat for lithospheric magma generation. Varying degrees of interaction between melanephelinile and small potassic melt fractions derived from the lithospheric mantle can explain the gradational character of the melanephelinile to minette suite.

INTRODUCTION

Mafic alkaline igneous rocks provide important information about the nature of Earth's heterogeneous upper mantle and the processes that have shaped it. Recognition of such rocks in a swarm of late Tertiary (24-7 Ma) dikes in the Wasatch Plateau area on the northwestern margin of the Colorado Plateaus province (Figure 1) thus provides the opportunity to draw inferences about the petrology of the mantle beneath this section of the North American craton as well as its changing tectonic character during episodes of intrusion in the Tertiary. In the western United States, this interval of time includes marked changes in tectonism and magmatism as subduction of oceanic lithosphere ceased and extension and rifting of the continental lithosphere became dominant.

In this paper, we present data on the Wasatch Plateau dike swarm, parts of which were first described by *Spieker* [1931J and *Thomas* [1976]. Additional information on the swarm is from *Tingey [1989].*

GEOLOGIC SETTING

Colorado Plateaus Province

The Colorado Plateaus consist of a relatively thin veneer of Phanerozoic sedimentary rocks about 3-5 km thick that overlies a basement of Precambrian igneous and metamorphic rocks [*Hintze,* 1988]. Crystallization ages (1.69-1.79 Ga) and Nd model ages (1.8-2.0 Ga) of basement rocks in the region indicate the lithosphere formed during the Proterozoic and that little or no Archean crust is present [*Condie,* 1986; *Bennett and DePaolo,* 1987|. Crustal thickness in the northwestern part of the province is uncertain but has been interpreted to range from 45 km to as low as 25 km in the transition zone [*Smith et al.,* 1989]. Although *Bird* [1979, 1988] suggested that the lithospheric mantle was removed by delamination during middle Tertiary subduction, recent seismic studies show the presence of a high-velocity layer which is reasonably interpreted as normal lithospheric mantle *[Beghoul and Barazangi,* 1989]. The lithosphere appears to be 90-100 km thick, about 1.5-2 times as thick as that of the adjacent Basin and Range province [*Pakiser,* 1989].

The Mesozoic through early Cenozoic history of the western United States was dominated by subduction of oceanic lithosphere, compressive deformation, and magmatism that penetrated far inland [*Severinghaus and Atwater,* 1991]. During the late Cretaceous-early Tertiary Laramide orogeny the Colorado Plateaus were mildly deformed into basement-cored uplifts and adjacent basins. In the central plateaus, no magmatism was associated with this compressive event. About 50-20 Ma, voluminous calc-alkaline magmas were erupted to the east, forming the San Juan volcanic field, and to the west in the Great Basin and transition zone [*Lipman,* 1980; *Best and Christiansen,* this issue]. In contrast, only sparse, essentially alkaline magmas were emplaced at the present level of erosion in the plateaus during this interval, including some of the alkaline dike rocks that are the subject of this report as well as diorite-syenite laccolith complexes 30-20 Ma [*Sullivan et al.,* 1991]; extrusive rocks are absent. Following the demise of subduction, the margins of the Plateaus province were defined by late Cenozoic normal faulting to form the Great Basin on the west (since about 10-12 Ma along the Wasatch fault [*Kowallis et al.,* 1990; *Naeser et al.,* 1983; *Zoback et al.,* 1981] and the Rio Grande rift on the east since the Oligocene. Extension in these flanking provinces has been much greater than in the plateaus and has been accompanied by eruption of small volumes of basaltic lavas since the middle Miocene. Even smaller volumes of alkaline mafic magma were emplaced in the plateaus during this interval of time. The cause and timing of the uplift of the Colorado Plateau remain controversial but may have occurred in the late Cenozoic in response to foundering of the subducting Farallon plate away from the base of the continental lithosphere during the transition from subduction to extension [e.g., *Beghoul and Barazangi,* 1989] and consequent movement of hotter, less dense asthenospheric mantle into its place.

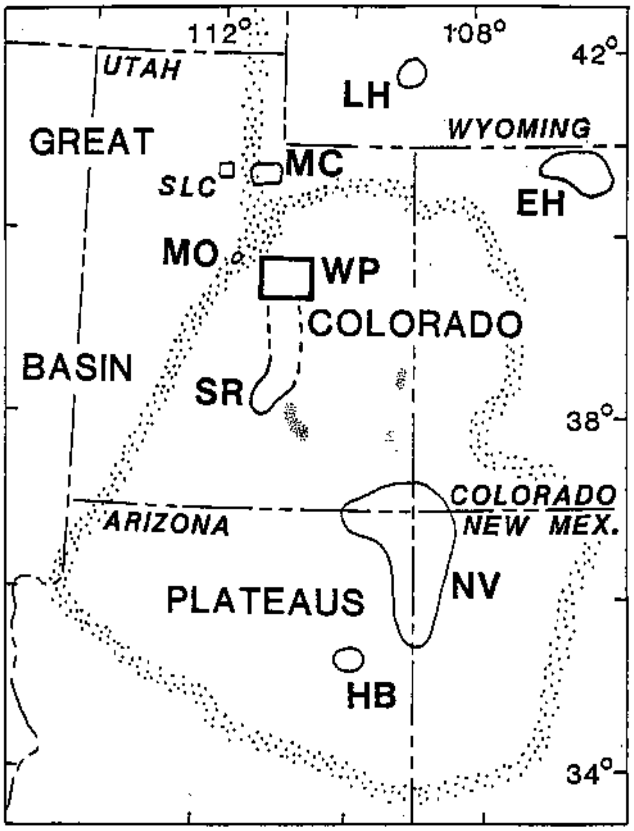

Fig. 1a. Index map of Colorado Plateaus and Cenozoic alkaline magmatic loci referred to in the text. LH, Leucite Hills; MC, Moon and Smith-Morehouse canyons and Park City; EH, Elkhead Mountains; WP, Wasatch Plateau; MO, Mona; SLC, Salt Lake City; SR, San Rafael Swell and Capitol Reef; NV, Navajo; HB, Hopi Buttes. Fine stippled areas in southeastern Utah are diorite-syenite laccolith complexes.

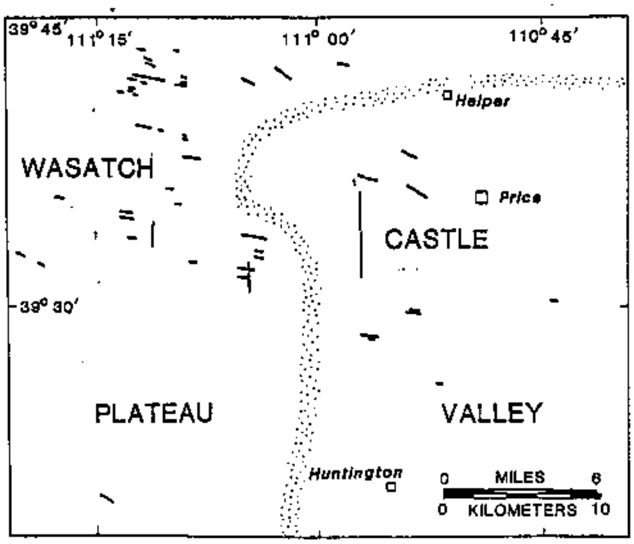

Fig. 1b. Generalized map of dikes within the Wasatch Plateau dike swarm. Stippled band marks the transition between the plateau and Castle Valley.

The Wasatch Plateau lies near the northwestern margin of the Colorado Plateaus in the transition zone to the highly extended Great Basin segment of the Basin and Range province to the west (Figure 1). The transition zone has experienced multiple episodes of fracturing, the most pronounced of which formed steeply dipping normal faults that dissected the Wasatch Plateau into several roughly north trending horsts and grabens (Figure 2). Less common are steeply dipping, northwest striking normal faults of unknown age, which form the Fish Creek graben *[Walton,* 1955], and steeply dipping, small-offset, east and northeast striking normal faults.

Wasatch Plateau Dike Swarm

Field relations and age. The Wasatch Plateau dike swarm is composed of thin vertical dikes, generally less than 2 m in width, that are exposed throughout an area of at least 2500 km^2 encompassing the northern Wasatch Plateau and adjacent Castle Valley (Figure 1b). More than 110 dikes have been located within the swarm. At the surface, the dikes cut nearly horizontal sedimentary rocks of Cretaceous and early Tertiary age. Deuteric alteration is common, particularly in mica-rich dike rock, in which case the dike is manifest by orange soil rich in flakes of altered phlogopite; such dikes are commonly bordered by more erosionally resistant contact metamorphosed wall rock. More resistant dikes generally lack this collar and occur as linear trends of rubble. Where encountered in underground coal mines, dikes have "ballooned" into coal beds, forming sill-like masses as much as several tens of meters wide. Most such masses have no surface outcrop. Some dikes are composite and some show margin-to-core variations in texture. Variations in modal abundance of phlogopite phenocrysts were noted in one large north striking dike (Devils Slide dike [*Tingey,* 1989]).

No associated lava flows have been found in the dike swarm, and no mantle-derived inclusions have been found in any dike, but some contain xenoliths of sedimentary rock. Sparse, widely scattered mafic lamprophyre dikes near Mona, Utah (Figure 1 and *Phillips* [1962]), one of which is 23.2 Ma [*Witkind and Marvin,* 1989], could represent the western end of the swarm.

Dikes may be grouped on the basis of orientation and age (Figure 3 and Tables 1 and 2), and the rocks can be classified (see petrology section) on the basis of mineralogical and chemical composition.

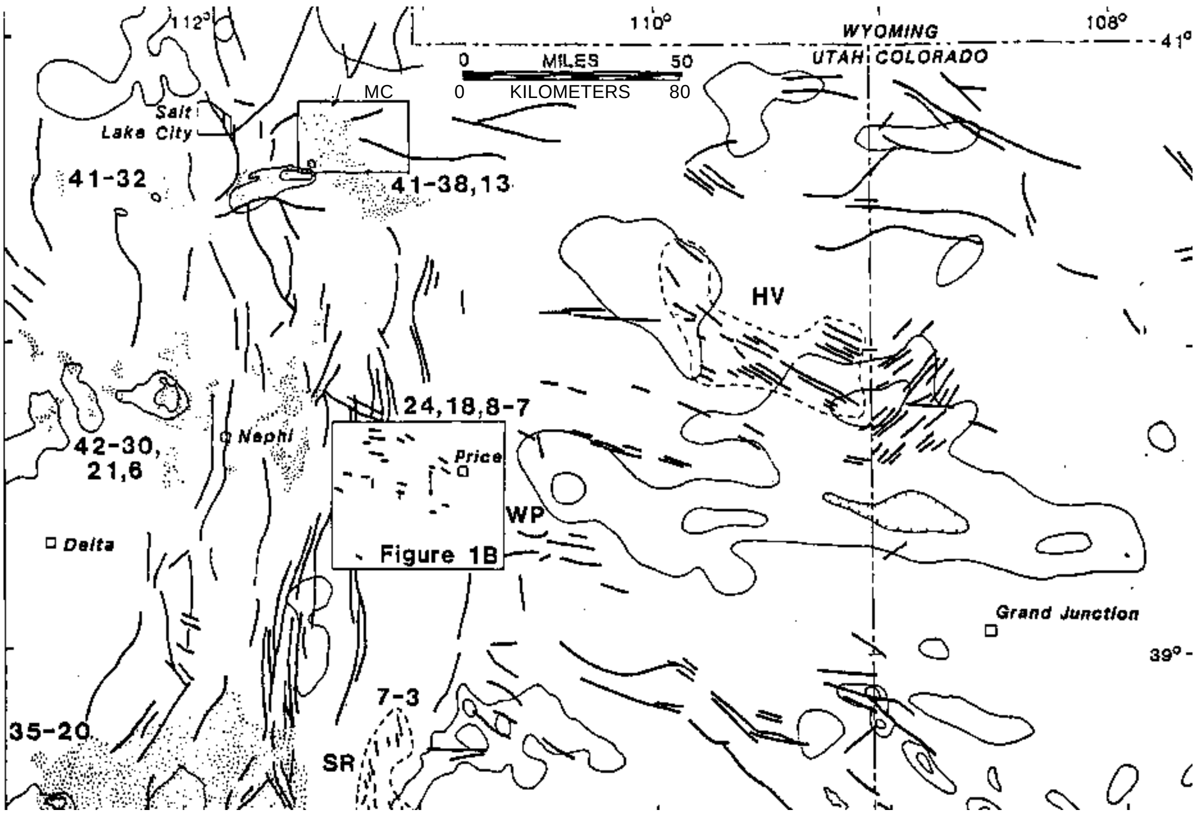

Fig. 2. Tectonomagmatic features in northeastern Utah [Hintze, 1980] and adjacent Colorado. Heavy lines are high-angle normal faults, except in San Rafael Swell dike swarm (SR) and in area of Wasatch Plateau dike swarm (WP; see also Figure la) where heavy lines denote mafic alkaline dikes (faults excluded in latter area) and in area to northeast where heavy lines denote vertical solid hydrocarbon veins (HV). Stippling shows east ends of three east trending, middle Tertiary calc-alkaline magmatic zones in eastern Great Basin [Stewart et al., 1977]; note that the three occurrences of alkaline rocks in northeastern Utah lie near the ends of these three calc-alkaline zones. Times of magmatic activity in calc-alkaline zones and alkaline loci shown in million years. Thin lines are 11,000 and 11,300 gamma aeromagnetic contour lines from *Zietz and Kirby* [1972] and *Zieta et al.* [1976]; note positive aeromagnetic anomalies trend across the Utah-Colorado stateline at about N80°W and N60°W parallel to strikes of most dikes in Wasatch Plateau

Here, it is sufficient to note that a simple classification useful in the field recognizes two types: first, a hard, dense, black, mostly fresh rock containing phenocrysts of Olivine, clinopyroxene, and, in some dikes, phlogopite: such rock we call melanephelinite. Second, a generally altered, nonresistant rock containing abundant phenocrysts of phlogopite which we call minette. Two varieties (see petrology section) of minette occur in westerly and north striking dikes that are, within analytical uncertainties, 24 and 8-7 Ma, respectively. Less common are two varieties of melanephelinite in westerly and in west-northwest striking dikes, one of which is 18.3 Ma (Figure 3).

Relation to regional magmatic trends. The mafic alkaline dikes in the Wasatch Plateau are associated with two major magmatic zones. One is the roughly north-south trending, diffuse zone of Tertiary alkaline rocks that extends from Canada to Mexico, borders the craton *[Barker,* 1974] and is located predominantly just east of and parallel to the Mesozoic thrust belt [*Sullivan and Best,* 1986]. The second is the west trending Tintic-Deep Creek magmatic zone in the eastern Great Basin described by *Stewart et al.* [1977] that is marked by 42-23 Ma predominately calc-alkaline magmatic rocks; the Wasatch Plateau alkaline dikes lie at the eastern end of this zone (Figure 2).

The Wasatch Plateau dikes are of about the same age and composition as dikes and lava flows to the north and south in the alkaline zone, as follows (Figure la): 39.7 Ma melilitic lamprophyre in Smith-Morehouse Canyon, Utah [*Best et al.,* 1968]; 13 Ma and 41-38 Ma lamproites in Whites Creek and Moon Canyon, Utah [*Best et al.,* 1968]: 1.25-1.1 Ma lamproites in the Leucite Hills, Wyoming *[Bergman.* 1987]; 26-19 Ma mafic and felsic minettes in the Navajo volcanic field in the Four Corners area *[Laughlin et al.,* 1986; *Alibert et al.* 1986; *McDowell et al,* 1986; *Roden et al,* 1990]; 5-2 Ma monchiquite (melanephelinite) in the Hopi Buttes in northern Arizona *[Alibert et al, 1986; Fitton et al,* 1988]; 7-3 Ma alkalic mafic dikes in the San Rafael Swell-Capitol Reef area in east central Utah (Table 2 and *Gartner and Delaney* [1988]). Isotopic ages of the San Rafael Swell and Wasatch Plateau swarms overlap somewhat (Table 2): young dikes in the Wasatch Plateau and those in the San Rafael Swell swarm are essentially north striking. Future work may show all of the late Miocene dikes to be one swarm.

Even though the Wasatch Plateau dike swarm and the other two loci of alkaline magmatism in Utah lie at the eastern ends of zones of middle Tertiary calc-alkaline activity that extend far into the Great Basin (Figure 2), temporal and, of course, compositional ties are poor. Tertiary calc-alkaline volcanism in most of the Great Basin clearly swept southward [*Best and Christiansen,* this issue] until sometime in the Miocene, after which more or less bimodal basaltic-rhyolitic activity flared up in many locations at different times. For the alkaline magmatism in Utah, only in the time of inception was there a southward shift (Figure 2); timing of calc-alkaline and alkaline episodes correlate poorly.

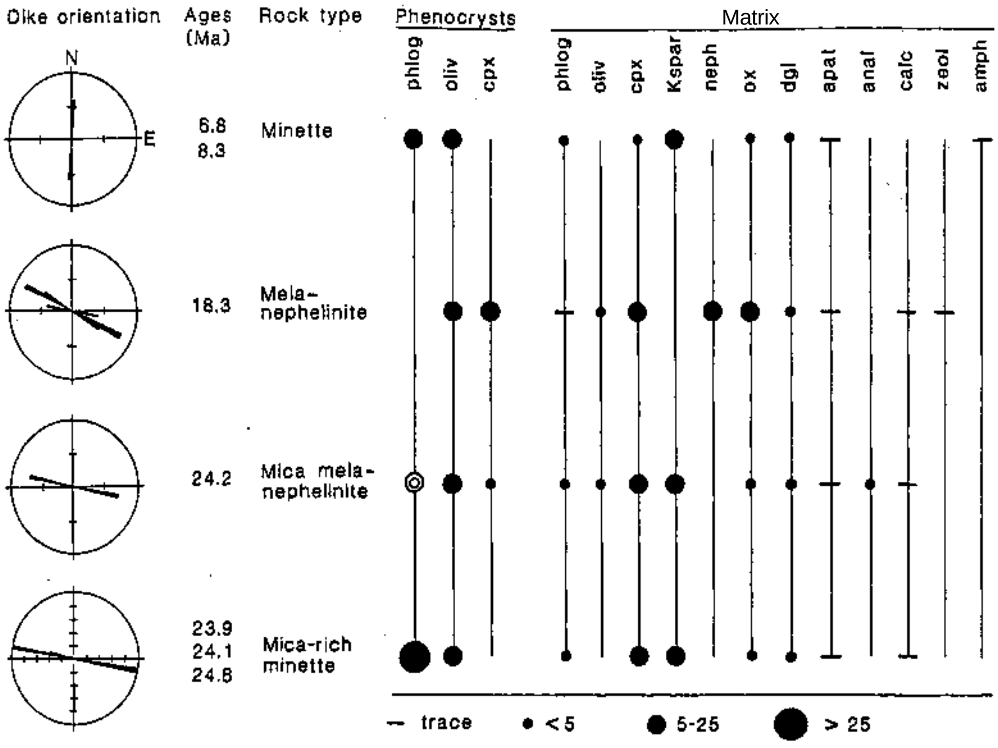

Fig. 3. Strikes, ages (Tables 1 and 2), nomenclature, and modal compositions of dikes in the Wasatch Plateau swarm. Numerous dikes not represented here in now inaccessible coal mines have strikes of about N80°W and N60°W according to available mine maps *[Tingey,* 1989]. Tick marks along radii of rose diagrams represent five dikes; note that dikes of mica-rich minette are more abundant than others. Modal abundance of phlogopite phenocrysts in mica melanephelinite range from about 1 to 20%. Matrix phases include ox, titaniferous magnetite; dgl, turbid devitrified glass; anal, analcime; calc, possible magmatic calcite; zeol, vapor phase mineral in vugs.

TABLE 1. Potassium-Argon Ages of Dike Rocks From the Wasatch Plateau

Sample	Longitude W, Latitude N	Rock+ Type	Material Dated	K_2O, wt %	^{40}*Ar, 10^{-12}mol/g	^{40}*Ar, %	Age,* Ma
PIN-2	110°54'14" 39°35'05"	m	phlog	7.525	108.0	22.0	8.3 ± 0.4
STA-1	110°54'02" 39°38'05"	n	whole rock	0.251	8.000	13.6	18.3 ±2.0
SCO-1	111°11 '53" 39°39'24"	mr	phlog	7.678	320.75	42.1	23.9 ± 1.0
WAT-12	111°04'18" 39°33'45"	mr	phlog	8,517	357.5	38.6	24.1 ± 1.0
CAN-3	111°12'55" 39°34'37"	mm	whole rock	2.538	107.2	62.4	24.2 ± 1.1
WAT-1	111°05'26" 39^{O}31'45"	mr	phlog	6.266	271.5	35.2	24.8 ± 1.0

Age determinations by Geochron Laboratories, Cambridge, Massachusetts, phlog, phlogopite.
tm, minette; n, melanephelinite; mm, mica melanephelinite; mr, mica-rich minette.
*Ar is radiogenic argon.
^Uncertainty is one standard deviation.

Tectonic implications. Dikes in the Wasatch Plateau swarm parallel regionally extensive fractures, solid hydrocarbon fracture fillings, and large-scale positive aeromagnetic anomalies in the Great Basin and northern Colorado Plateaus (Figure 2). The swarm is thus not just a local, isolated tectonic feature but is part of a regional pattern of crustal features. Although it is beyond the scope of this paper to interpret the aeromagnetic anomalies, the possibility that they represent deep crustal mafic intrusions is suggested by the coincident positive gravity anomalies documented by *Smith and Cook* [1985], However, their work discloses that the northwest trending magnetic anomaly from south of Grand Junction to Price (Figure 2) is controlled to some extent by major fault blocks in the Precambrian basement.

Conventionally, the least principal horizontal stress during magma injection is interpreted to be perpendicular to the dike *[Anderson,* 1951]. However, *Best* [1988] suggested caution when using dikes in paleostress determinations because, as *Delaney et al.* [1986] have shown, magma may in certain situations be injected into favorably oriented preexisting fractures not perpendicular to the contemporary least principal stress. Where multiple regional fracture systems are present, as in the transition zone and northern Colorado Plateaus, the possibility that magmas were injected into

TABLE 2. $^{40}Ar/^{39}Ar$ Ages of Dike Rocks From the San Rafael Swell and Wasatch Plateau

Sample	Temperature °C	Longitude W, Latitude N	$^{40}Ar/^{39}Ar$	Rock* Type	37Ar/39Ar	Material Dated	36Ar/39Ar	Area	Cumulative 39Ar (%)	J	Age (Ma)
IRE-2		111°06'54" 38°37'58"		ptb		whole rock		San Rafael Swell			
	750		35.07		2.5243		0.1154		2.0	0.005795	12.03 ± 2.40
	925		4.07		3.9723		0.0127		34.1		6.37 ±0.15
	1000		1.87		0.7629		0.0042		58.2		6.97 ±0.13
	1075 *		1.68		0.8258		0.0037		75.1		6.47 ± 0.36
	FUSE		2.12		4.7839		0.0054		100.0		9.07 ± 0.14
											7.32*
											6.60 ± 0.68$
SOL-3		111°15'05" 38°30'39"		ptb		whole rock		San Rafael Swell			
	750		43.85		1.3016		0.1453		0.4	0.005795	10.27 ± 2.08
	875		4.03		4.9179		0.0131		9.3		5.35 ± 0.45
	1000		1.62		0.9313		0.0040		36.9		5.03 ± 0.21
	1075		1.12		0.6203		0.0022		54.0		5.00 ±0.16
	FUSE		1.17		2.6111		0.0028		100.0		5.28 ± 0.07
											5.19*
											5.17 ±0.38$
WAT-6		111°04'35" 39°31'56"		m		phlog		Wasatch Plateau			
	750		16.30		1.3368		0.0541		1.2	0.005872	3.95 ± 2.00
	875		2.43		7.6773		0.0083		11.2		5.92 ± 0.25
	1000		0.84		1.3074		0.0009		46.7		6.71 ±0.11
	1075		0.87		0.3117		0.0007		65.0		6.86 ± 0.13
	FUSE		1.00		0.6824		0.0011		100.0		7.29 ± 0.11
											6.82*
											6.78 ± 0.25$

Age determinations by D. Lux. For method, see *Lux* [1985]. phlog, phlogopite.
tptb, potassic trachybasalt; m, minette.
*Total.
$Plateau age.

preexisting fractures cannot be discounted. Nonetheless, the pattern of changing stress orientations during the Cenozoic inferred from other parts of the southwestern United States is compatible with the Wasatch Plateau magmas invading self-made or preexisting fractures in a direction more or less perpendicular to the least principal horizontal stress. Easterly striking 24 Ma dikes (Figure 3) agree with the northerly orientation of the least horizontal stress during the Oligocene and early Miocene found by *Eaton* [1982], *Best* [1988], and *Ren et al* [1989]. An 18 Ma melanephelinite dike striking N63°W suggests that the least principal horizontal stress may have rotated clockwise after emplacement of the older, 24 Ma dikes. A Miocene north-northeast orientation of the least horizontal stress has been inferred from fault-slip data along the western margin of the Colorado Plateau *[Barnhard and Anderson,* 1984]. Thompson et al. [1989] show 12-9 Ma dikes in northwestern Colorado (EH in Figure la) that strike about N10°W to N63°W. Younger, 8-7 Ma, minette dikes in the Wasatch Plateau dike swarm strike north and are consistent with the easterly least horizontal stress orientation reported for the western United States during the past 10 m,y. [*Zoback et al.,* 1981; *Eaton,* 1982; *Best,* 1988; *Ren et al.,* 1989] including the western margin of the Colorado Plateaus [*Thompson and Zoback,* 1979; *Barnhard and Anderson,* 1984], A near east-west least principal horizontal stress orientation in the Wasatch Plateau during the latest Miocene is also consistent with the contemporary (less than 5 m.y.) least principal horizontal stress orientation determined from fault-slip interpretations in the eastern Basin and Range nearNephi, Utah *[Smith and Lindh,* 1978].

We conclude that the latest Oligocene-early Miocene (25-18 Ma) minette and melanephelinite dikes formed either (1) in a northerly oriented extensional tectonic regime or (2) in an east-west compressional regime which may have been related to continued east directed subduction of oceanic lithosphere beneath North America. In either setting, magma would be injected more or less parallel to the easterly maximum principal horizontal stress. Emplacement of younger 8-7 Ma minette dikes occurred in an east-west extensional regime similar to that which created the familiar Basin and Range topography.

PETROLOGY

Classification of the dike rocks in the Wasatch Plateau follows the recommendations of the International Union of Geological Sciences (IUGS) *[Le Maitre et al,* 1989; *Le Bas,* 1989] and the suggestions made by *Rock* [1987] (see also *Bergman* [1987]) for lamprophyre. All analyzed samples contain normative Olivine and nepheline and some contain leucite. Below we describe the petrography, major and trace element geochemistry, and Nd and Sr isotopic composition of the dike rocks. Chemical and isotopic analyses were made on freshest samples; the only alteration of magmatic minerals in analyzed samples was serpentinization of Olivine.

Petrographic Distinction of Rock Types

Modal and major element compositions vary more or less continuously in the dike rocks of the Wasatch Plateau swarm, but four rock types can be discerned: minette, mica-rich minette, melanephelinite, and mica melanephelinite (Figures 4 and 5).

In the Wasatch Plateau, both types of minette have phenocrysts of phlogopite and Olivine in a finer-grained, generally aphanitic matrix of K-feldspar and turbid devitrified glass, euhedral Fe-bearing diopside, phlogopite, titaniferous magnetite, apatite, rare amphibole, and possibly magmatic calcite. Mineralogically, Wasatch Plateau minettes resemble the calc-alkaline lamprophyre group [*Rock,* 1987]. Most minettes are deuterically altered, presumably because of high concentrations of volatiles (H_2O + CO_2) in the magmas, to clay minerals, serpentine, carbonate, hematite, and a small amount of quartz, all surrounding residual flakes of phlogopite. Rapid, but partial degassing of volatiles from the magmas at upper crustal levels *[O'Brien et al.,* 1988] may have caused fracturing of the host rock and subsequent incorporation of country rock fragments into the magma.

Some minettes in the Wasatch Plateau dike swarm contain unusually abundant phenocrysts of phlogopite (20-60%; Figures 3 and 5) and are designated mica-rich minette; they make up approximately one half of the swarm and all appear to be 24 Ma. Other minettes in the swarm are mineralogically and modally more like typical minette (Figures 3 and 5) and are called minette in this report; they comprise the 8-7 Ma north striking dikes in the swarm.

Phlogopite phenocrysts in both varieties of minette are euhedral and longest dimensions commonly parallel the margins of the dikes. In coarser-grained rocks, phlogopite oikocrysts enclose euhedral crystals of diopside, apatite, and titaniferous magnetite. In some samples of mica-rich minette, two generations of phlogopite are shown by the presence of phenocrysts and matrix crystals. Chemical zonation in the phlogopite phenocrysts is evident in pleochroic light brown cores and narrow pleochroic dark red-brown rims. Phlogopite grains in at least two mica-rich minette dikes have pleochroic light brown cores and thin, reversely pleochroic dark red-brown rims, probably as a result of the substitution of Fe^{3+} for Al^{3+} in tetrahedral sites [*Faye and Hogarth,* 1969; *Smith et AL,* 1984; *Farmer and Boettcher,* 1981]. Electron microprobe analyses of this phlogopite [*Tingey,* 1989] show low Al concentrations (Si + Al < 4 cations per formula unit), comparable to phlogopite in lamproite [*Bergman,* 1987]. Core to rim Fe/(Fe+Mg) ratios range from 0.095 to 0.192 in mica-rich minette but from 0.221 to 0.316 in minette. F and TiO_2 are highly concentrated in some phlogopite grains, the latter as much as 8.4 wt % in a minette.

Erosionally resistant, hard, black dike rocks containing pyroxene phenocrysts in the Wasatch Plateau swarm are melanephelinites. Their major element compositions, such as MgO concentrations (11.2-16.6%), fall within the range of melanephelinite [*Le Bas,* 1989]. These dikes contain (Figure 5) large (as much as 4 mm) euhedral phenocrysts of zoned, Fe-bearing diopside with partially resorbed cores and euhedral, locally serpentinized Olivine (Fo_{85}-Fo_{87} in two samples) in a matrix of euhedral diopside, devitrified glass, titaniferous magnetite, apatite, and possible magmatic calcite. Two varieties of melanephelinite are recognized (Figure 3). First, ordinary melanephelinites are much like those described by *Le Bas* [1989] in that they contain essential nepheline and, in addition to the phases in the matrix noted above, traces of phlogopite. The nepheline occurs in thin, dike-parallel veinlets and as small grains in the matrix. A few samples have rare residual melt ocelli composed of plagioclase and calcite and some others contain late vapor-phase zeolites. All of the melanephelinite dikes strike west northwest and one dated sample is 18 Ma. Second, 24 Ma mica melanephelinites have major element compositions like melanephelinite of *Le Bas* [1989], but mineralogically, they are transitional to the minettes of the dike swarm because they contain as much as 20% phlogopite as phenocrysts and in matrix (Figure 5); also, K-feldspar and analcime occur in the matrix rather than nepheline.

Chemical Composition

Figure 4 (see also Table 3) reveals the similarities and differences in major element compositions of the various types of minette and

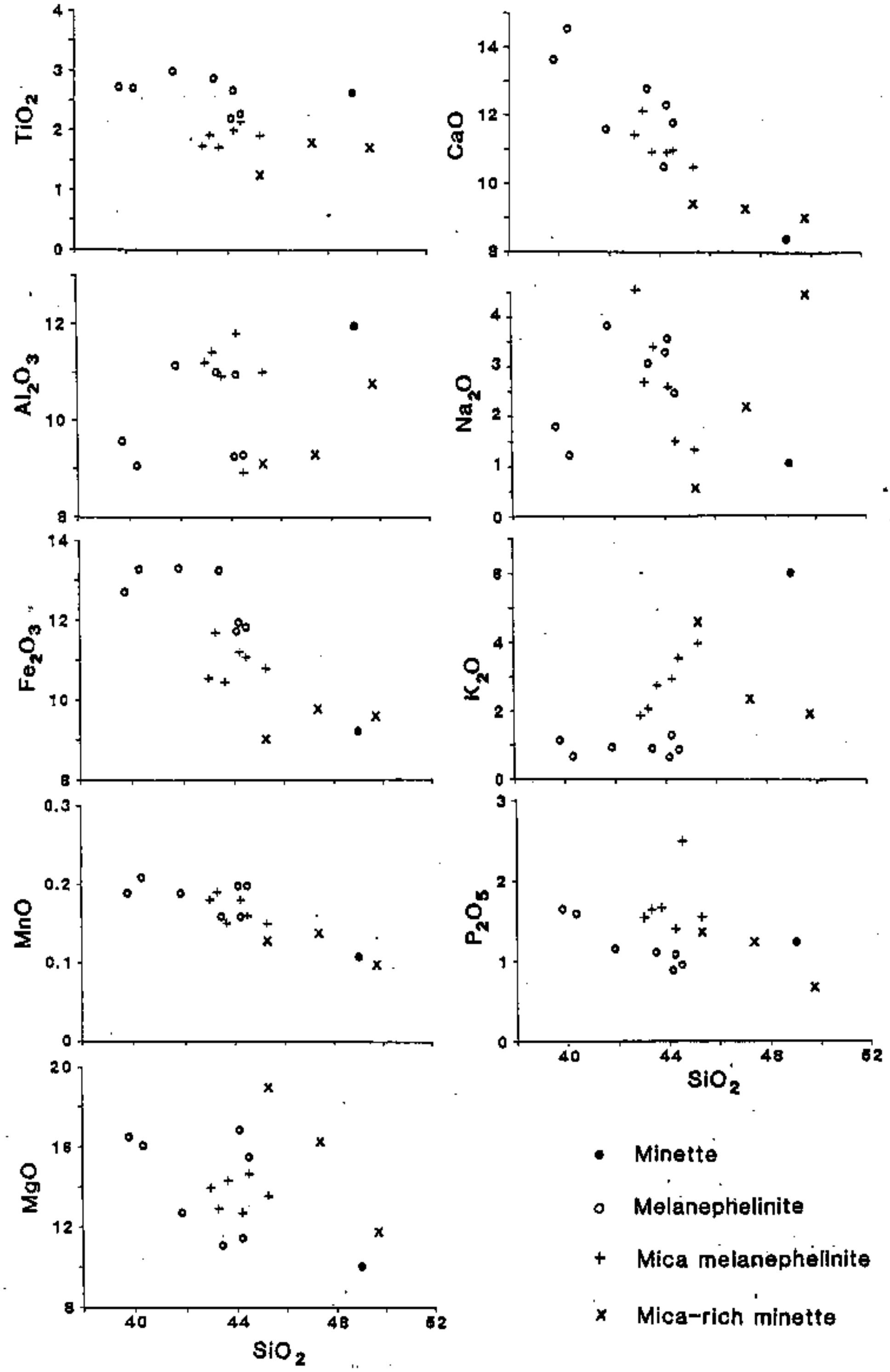

Fig. 4. Major element versus SiO_2 diagrams for Wasatch Plateau dike rocks. See also Table 3.

melanephelinite. The four rock types plot in more-or-less discrete fields on silica variation diagrams. Mica-rich minette and the one analyzed minette have significantly higher concentrations of SiO_2 and lower Fe_2O3, MnO, and CaO than either type of melanephelinite. Relative to typical continental basalts, all Wasatch Plateau dike rocks are strongly enriched in incompatible trace elements (Ba, Rb, Th, Sr, LREE, Zr, and Hf) as well as strongly compatible elements Cr and Ni (Table 3). Each dike type possesses a distinctive Chondrite-normalized trace element pattern (Figure 6). These systematic differences in major and trace element concentrations, patterns, and isotopic ratios (Table 3) correlate with age and show that degassing of a uniform magma composition and crystallization at different water fugacities was not an important factor in their evolution. The rocks of the Wasatch Plateau dikes are not mineralogic heteromorphs of one another (compare *O'Brien et al* [1988]).

Both types of Wasatch Plateau minette, although mineralogically resembling the calc-alkaline lamprophyre group of *Rock* [1987], are in fact alkaline and have lower SiO_2 and $A1_2O_3$ and higher TiO_2 and

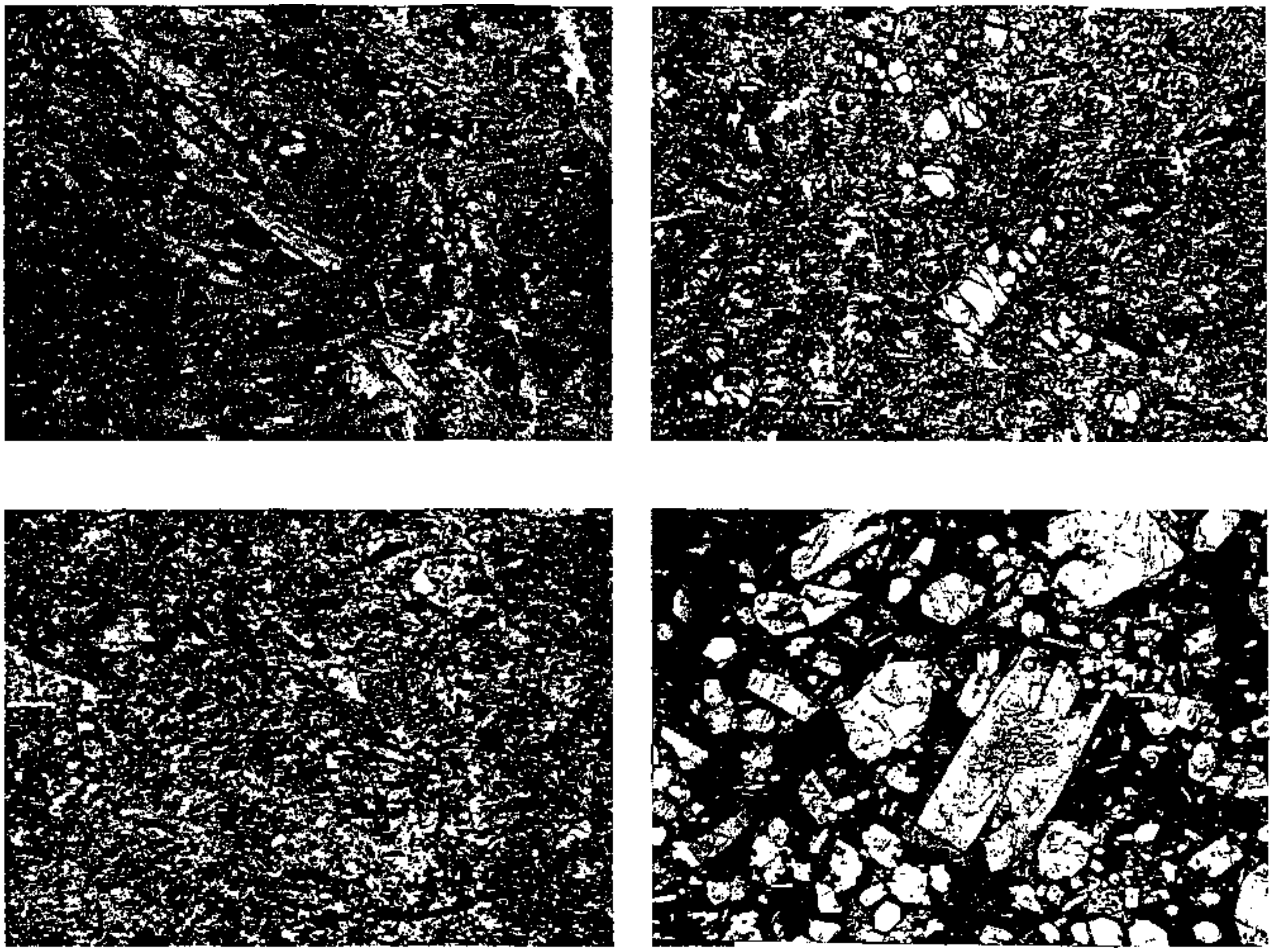

Fig. 5. Photomicrographs of Wasatch Plateau dike rocks. Photographs taken in plane polarized light; largest phenocrysts approximately 1.5 mm long, *(a)* Mica-rich minette in dike SCO-1 contains subparallel phenocrysts of phlogopite and serpentinized Olivine in a matrix of phlogopite, K-feldspar. euhedral diopside, titaniferous magnetite, devitrified glass, and lesser apatite and possible magmatic calcite. Phlogopite phenocrysts have pleochroic light brown cores and reverse pleochroic dark red-brown rims, *(b)* Mica melanephelinite in dike CAN-3 has phenocrysts of fresh Olivine, phlogopite (pleochroic light brown to dark red brown), and sparse diopside in a matrix of the same minerals plus K-feldspar. analcime, titaniferous magnetite, devitrified glass, possible magmatic calcite, and apatite, *(c)* Minette in dike PIN-2 has phenocrysts of phlogopite (pleochroic light brown to dark red brown and altered Olivine (not shown) in a matrix of phlogopite. K-feldspar. needles of diopside, titaniferous magnetite, devitrified glass, apatite, and rare amphibole. *(d)* Melanephelinite in dike STA-1 has large phenocrysts of diopside and Olivine in a matrix of the same minerals plus titaniferous magnetite, nepheline. devitrified glass, phlogopite, apatite, calcite. and vapor-phase zeolite.

MgO concentrations than reported means for this lamprophyre group. Chemically, therefore, these minettes are more like alkaline lamprophyres and lamproites of *Rock* [1987]. This kinship is supported by the low Al and high Ti contents of phlogopite in the mica-rich minettes [*Bergman, 1987;Rock,* 1987]. but both types of minette lack exotic minerals found in lamproites, such as K-amphibole, wadeite, priderite, etc. The high MgO concentrations of the minettes (Figure 4) are similar to those of ultramafic lamprophyres [*cf. Rock,* 1987].

In mica-rich minettes. silica ranges from 45 to 49%, which is higher than in melanephelinites but is similar to that in the younger minette. Analyzed mica-rich minettes range from ultrapotassic (K_2O > 4%) to sodic (Na_2O > K_2O). Of all the rocks in the dike swarm, the mica-rich minettes have the lowest Ba. Sr, La, and the highest Cr concentrations, and although some overlap exists, they generally have the lowest Nb and the highest Ni. Zr, and Hf concentrations. For mica-rich WAT-12. the rare earth element (REE) pattern (Figure 7) shows a distinctive change in slope at Eu. The light REEs have lower concentrations than in the other types of minette and melanephelinite: consequently, this sample has the lowest La/Yb ratio. Chondrite-normalized trace element patterns of mica-rich minettes (Figure 6) are convex upward but marked by depletions (negative anomalies) of Nb-Ta. Sr. and Ti relative to elements of similar compatibility: normalized Ba/Rb ratios are less than 1. The major element compositions and trace element patterns of mica-rich minette are similar to those of mafic minetle in the Navajo volcanic field [*Alibert el al.,* 1986; *Roden et al.,* 1990].

Younger 8-7 Ma minette has the highest Al_2O_3 and K_2O and the lowest Fe_2O_3, MnO, MgO, and CaO in the Wasatch Plateau dike swarm. Although SiO_2 is high, so are total alkalies (7.1%: thus the analyzed sample is silica undersaturated with normative Olivine and nepheline. Unlike the other mica-bearing rocks. TiO2 is high and similar to melanephelinite. In the enrichment of incompatible and compatible trace element, younger minette is similar to 24 Ma

TABLE 3. Analyses of Representative Dike Rocks From the Wasatch Plateau

	WAT-12 iMica-Rich Minette	SCO-1 Mica-Rich Minette	CAN-3 Mica Melanephelinite	PIN-2 Minette	STA-1 Melanephelinite
SiO2, wt%	47.4	45.33	44.2	49.0	39.8
TiO2	1.82	1.28	2.00	2.66	2.76
AM),	9.3	9.14	11.8	12.0	9.6
Fe2O3	9.82	9.07	11.21	9.26	12.70
A12O3	0.14	0.13	0.18	0.11	0.19
MgO	16.4	19.04	12.7	10.1	16.6
CaO	9.32	9.46	10.93	8.45	13.70
Na2O	2.14	0.52	2.52	1.02	1.77
K2O	2.41	4.65	2.95	6.10	1.20
P2O5	1.27	1.39	1.41	1.27	1.67
LOI	4.76	4.92	3.31	2.46	3.10
Sc, ppm	23.6	14	24.7	17.8	26.2
V	183	149	22.7	187	230
Cr	1022	998	630	430	753
Co	61.0		57.0	54	82
Ni	699	603	296	311	391
Cu	99	70	60	49	66
Zn	114	93	102	102	108
Ga	14	11	13	14	16
Rb	132	271	62	72	23
Sr	678	666	1551	2398	1627
Y	47	40	30	18	35
Zr	682	441	363	303	278
Nb	26	10	36	39	83
Cs	3.6		0.9	0.7	0.8
Ba	621	2076	3646	4892	1279
La	58	101	151	111	160
Ce	127		270	212	301
Nd	70		96	91	117
Sm	16.8		14.4	13.9	20.2
Eu	5.33		4.19	3.96	5.99
Tb	2.0		1.2	0.7	1.8
Yb	2.26		2.10	1.29	1.96
Lu	0.28		0.27	0.16	0.24
Hf	19		11	11	8
Ta	1.8		2.7	2.5	4.5
Th	8.7		11.0	5.2	30.0
U	3.1		2.0	1.9	7.0
$^{87}Sr/^{86}Sr_i$	0.70768		0.70426	0.70662	0.70621
$^{143}Nd/^{144}Nd_i$	0.51244		0.51193	0.51182	0.51259
T_{DM}(Ga)	1.4		1.5	1.6	0.64

LOI is loss on ignition at 1000°C for4 hours. T_{DM} is Nd model age calculated relative to depleted mantle, using $^{143}Nd/^{144}Nd = 0.51235$ and $^{147}Sm/^{144}Nd = 0.225$. Analyses of Sc, Co, Cs, REE, Hf, Ta, Th, and U by INAA, other elements analyzed by XRF. Major element analyses normalized to 100% on volatile-free basis. Isotope ratios by mass spectrometry *[Patchett and Ruiz,* 1987].

mica-rich minette; however, minette generally has higher Ba, Sr, and LREE and lower Th, Nb, Ta, Zr, Hf, Cr, and Ni concentrations (Figure 6). HREE (heavy rare earth elements, Tb, Yb, Lu) are lower in concentration in PIN-2 than in any of the other dikes (Figure 7). The trace element pattern of the minette is relatively smooth, but there are negative anomalies for Rb-Th and Nb-Ta. Minette is distinct from other mica-bearing dikes (mica-rich minette and mica melanephelinite) because it lacks Sr and Ti anomalies and because normalized Ba/Rb and K/Th ratios exceed 1. Equivalent compositions have not been reported from the southern Colorado Plateaus. Minettes with the same SiO_2 content from the Navajo volcanic field have much lower Ba/Rb ratios and are depleted in TiO_2, $A1_2O_3$, K_2O, and P_2O_5[Laughlin et al., 1*986; Alibert et al.*$_t$ 1986].

Melanephelinites of the Wasatch Plateau have less silica than the minettes, yet because of relatively low total alkalies and especially K_2O ($Na_2O > K_2O$) they are no more silica undersaturated. Distinctive characteristics of the melanephelinites include high concentrations of TiO_2, Fe_2O_3, and CaO and $CaO/Al_2O_3 > .1$. They have the lowest K_2O contents of the swarm and all are sodic with Na_2O greater than K_2O. All of these characteristics are typical of melanephelinite on a worldwide basis *[Le Bas,* 1989; *Fitton and Dunlop,* 1985]. REE patterns of melanephelinite are smooth and quite steep with normalized Ce/Yb about 50 (Figure 7). Chondrite-normalized trace element patterns are generally convex upward with deep anomalies at Rb and K (normalized Ba/Rb > 1) and with small negative Sr anomalies (Figure 6). In contrast to the minettes, melanephelinites have smoother patterns and lack negative Nb-Ta anomalies. The patterns are, however, similar to those for nephelinitic rocks in Hopi Buttes [*Alibert et al,* 1986; *Fitton et al.,* this issue] and to continental and oceanic nephelinite means [*Fitton et AL,* 1988], except for slightly lower Nb and Ta abundances in the Wasatch Plateau melanephelinites. Compared to average ocean island basalt, the melanephelinites are enriched in Ba and La. However, La/Nb and La/Ba ratios are for the most part comparable to ocean island basalts but extend into the field occupied by the minettes (Figure 8).

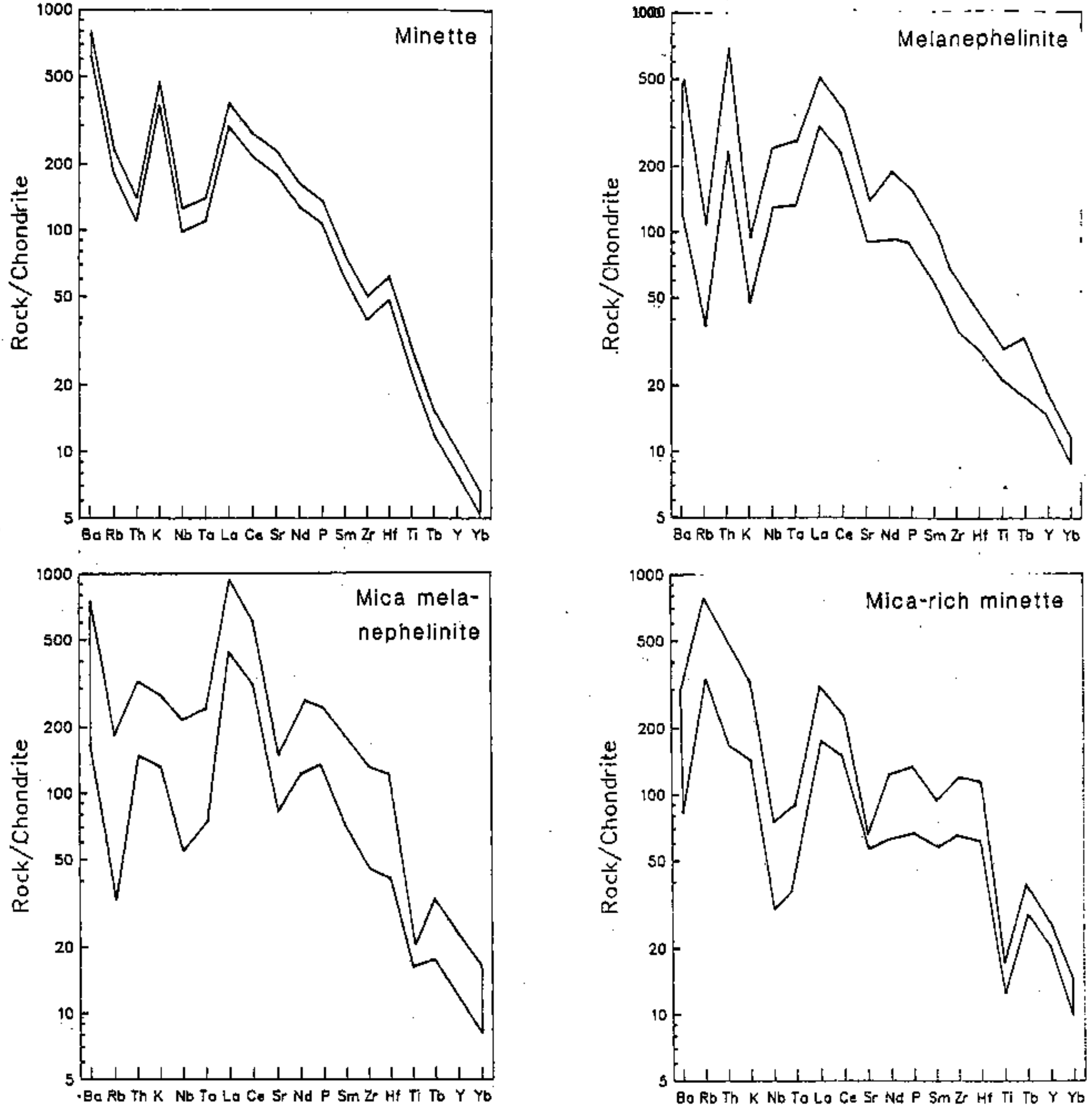

Fig. 6. Chondrite-normalized (except for Rb, K, and P *[Thompson et al.,* 1984]) trace element patterns for alkaline rocks in the Wasatch Plateau dike swarm. All types are strongly enriched in incompatible elements. Note the Ba-K-depletion of mica-rich minette (residual phlogopite?) compared to mica-poor minette. All minettes also have negative Nb-Ta-anomalies consistent with a subduction zone component in their sources.. The patterns of melanephelinites lack Nb-Ta depletions but are strongly depleted in Rb and K relative to elements of similar incompatibility.

Mica melanephelinites of the Wasatch Plateau are transitional in major element composition between the minettes and the melanephelinites (Figure 4). All mica melanephelinites are silica undersaturated with normative Olivine, nepheline, and, in most rocks, leucite. Like the melanephelinites, most but not all have Na_2O greater than K_2O. They partially overlap the high end of the SiO_2 range observed for the melanephelinites; in this overlapping interval, the micaceous variety is richer in K_2O and P_2O_5 and poorer in TiO2 and Fe_2O_3 than ordinary melanephelinite. The high Ba/Rb ratios and REE patterns of the two types of melanephelinite are very similar, but the mica-bearing variety has a slight depletion of middle REEs (Figures 6 and 7). However, the mica melanephelinites have higher K_2O and generally lower Th, Nb, and Ta than the melanephelinites. As a result, their trace element patterns show deeper Nb-Ta, Sr, and Ti anomalies. Although quite distinct in major element composition, minettes from the Elkhead Mountains province of northeastern Colorado have trace element patterns, including Ba/Rb ratios greater than 1 and negative Sr and Ti anomalies, that are similar to those of the mica melanephelinites from the Wasatch Plateau swarm [*Thompson et al.,* 1989].

Isotopic Composition

Although our data are meager (Table 3), the alkaline dike rocks of the Wasatch Plateau show considerable variation in Nd and Sr isotopic composition (Figure 9). However, their compositions fall near those of similar alkaline rocks found in the Cordilleran region.

The analyzed melanephelinite has the most radiogenic Nd isotopic composition found in the Wasatch Plateau dikes, with a nearly

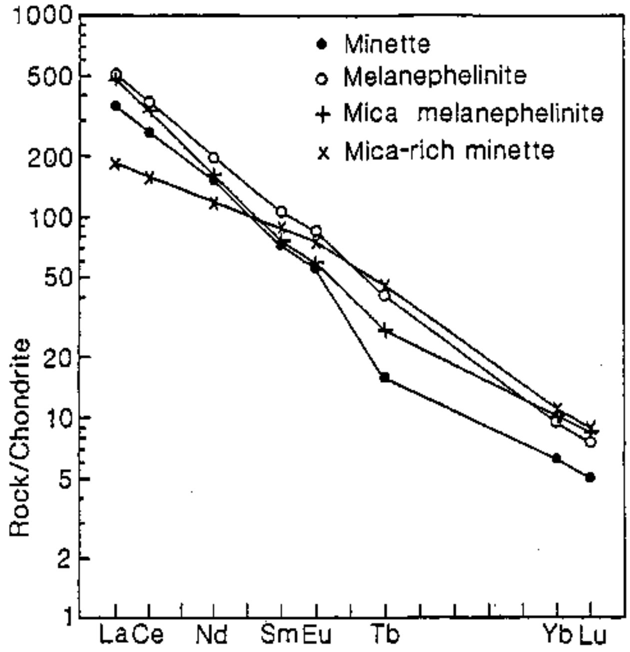

Fig. 7. Chondrite-normalized rare earth element patterns for alkaline rocks in the Wasatch Plateau dike swarm.

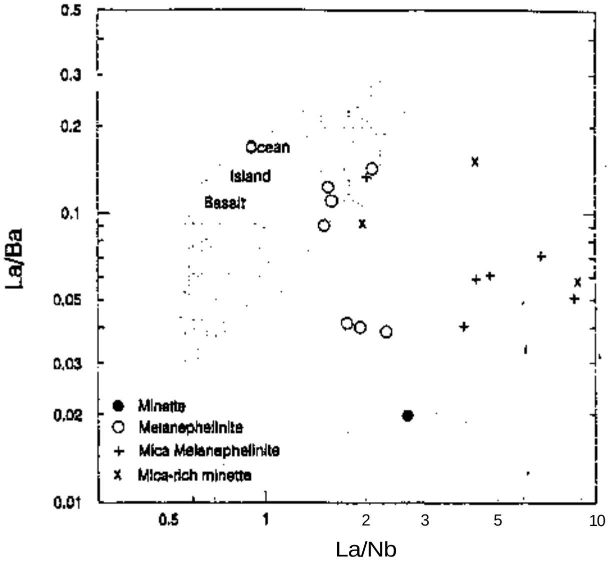

Fig. 8. La/Ba versus La/Nb ratios in alkaline rocks of the Wasatch Plateau compared to the field for ocean island basalts [*Fitton et al.,* this issue]. Melanephelinites show the greatest similarity to ocean island basalt and may have an asthenospheric source. Higher La/Nb or lower La/Ba ratios of the mica melanephelinites and minettes may reflect a component derived from enriched lithospheric mantle.

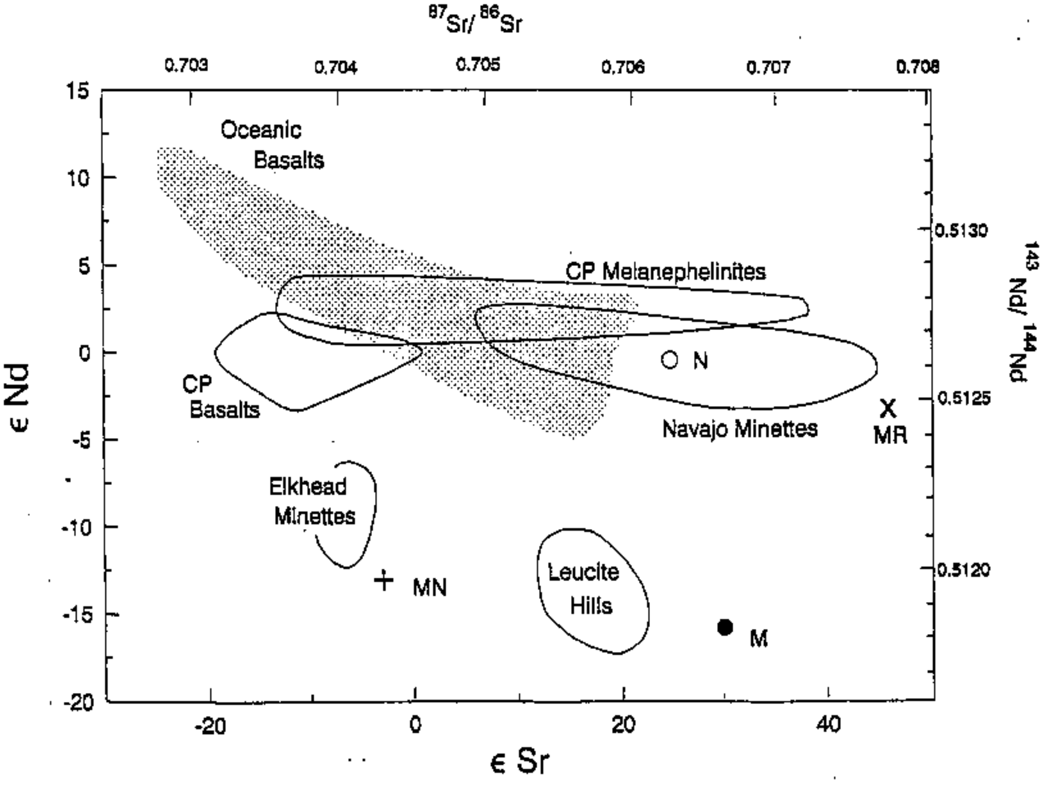

Fig. 9. Nd and Sr isotopic composition of Wasatch Plateau dikes and other Cenozoic mafic rocks from in and near the Colorado Plateaus. Samples from the Wasatch Plateau are melanephelinite (N, STA-1); mica-rich minette (MR, WAT-12); mica melanephelinite (MM. CAN-3); minette (M, PIN-2). Shown for comparison are compositions of oceanic basalts [*Zindler and Hart,* 1986). basaltic lavas from the margins of the Colorado Plateaus (CP) [*Alibert et al.,* 1986], minette from the Navajo volcanic field *[Roden et al., 1990; Alibert et al.,* 1986], minette from the Elkhead Mountain province of western Colorado [*Thompson et al.,* 1989], and potassic to ultrapotassic volcanic rocks from the Leucite Hills, Wyoming [*Vollmer et al.,* 1984].

chondritic ratio that is only slightly lower than those found by *Alibert et al.* [1986] and *Fitton et al.* [this issue] for melanephelinites from Hopi Buttes and for ocean island basalts in general. Epsilon Sr for this sample is within the range of Hopi Buttes melanephelinites (Figure 9), but higher than almost all ocean island basalts.

All of the other dike rocks fall far away from the array defined by oceanic basalts. The Nd and Sr isotopic composition of a 24 Ma mica melanephelinite (CAN-3) contrasts strongly with the melanephelinite (Figure 9). CAN-3 falls far below the oceanic mantle array and has an extremely nonradiogenic Nd isotope ratio (epsilon Nd -13.2), and its Sr isotope ratio is just less than that estimated for bulk Earth and within the EM I field of *Zindler and Hart* [1986]. CAN-3 is most similar in isotopic composition to minettes from the Elkhead Mountains province. Young minette PIN-2 has the lowest Nd isotope ratio (epsilon Nd -15.8) of those analyzed. It is similar in this regard to the ultrapotassic rocks of the Leucite Hills *[Vollmer et al.,* 1984], other lamproites, and Group II kimberlites [e.g., *Menzies et al.,* 1987]. The trace element pattern and isotopic composition of mica-rich minette WAT-12 is most similar to the minettes from the Navajo volcanic field (Figure 9).

Neodymium model ages, calculated with reference to depleted, mantle, fall in two groups. The mica-bearing rocks have T_{DM} of 1.4 to 1.6 Ga and are slightly less than crystallization ages *[Condie,* 1986] and Nd model ages *[Bennett and DePaolo,* 1987] for basement rocks from the Colorado Plateau. The melanephelinite has a much younger T_{DM} of 0.6 Ga.

PETROGENESIS

The minettes and melanephelinites of the Wasatch Plateau dike swarm formed in a continental intraplate tectonic setting after subduction of an oceanic plate had begun to cease off the continental margin. They were intruded contemporaneously during the late Tertiary in a small region, are strongly enriched in large-ion lithophile elements (LILE) compared to mid-ocean ridge basalts, and are silica undersaturated. Similar associations of contemporaneous lamprophyres and melanephelinites are found worldwide, suggesting a strong genetic link between these distinctive magma types *[Bachinski and Scott, 1979; Stille et al.,* 1989]. In the sections that follow, we first consider whether the Wasatch Plateau alkaline rocks are primitive magmas and then speculate about the nature of their sources and their origins based on correlations of the isotopic and trace element composition of the rocks with petrography, major element composition, and age.

Primitive Magmas?

Minettes and melanephelinites have high concentrations of the strongly compatible elements Ni, Cr, and Co along with high MgO, characteristics which suggest primitive, perhaps even primary magmas *[Basaltic Volcanism Study Project (BVSP)* 1981]. However, the very high MgO (>16%) and Ni (> 500 ppm) concentrations of some samples could indicate that Olivine and/or phlogopite accumulated. Doubtlessly, some sorting of phenocrysts has occurred as demonstrated by the presence of zoned minette dikes, but it does not seem to be solely responsible for the high MgO and Ni. We reject the notion that mica-rich minette is purely a micaceous cumulate developed from minette or mica melanephelinite because mica-rich minette consistently has lower Ba/Rb ratios than the mica-poor rocks. Accumulation of phlogopite, with its high partition coefficient for Ba compared to Rb, would cause higher Ba/Rb ratios in the accumulative rock.

MgO-Ni relationships are consistent with the idea that most samples represent primitive magmas. Figure 10 shows possible compositions of primitive melts derived from peridotite using a range of partition coefficients for Ni. Only two samples, both mica-rich minettes. fall clearly outside this "primitive magma envelope", one below and one above. Similarly, most sample compositions fall on the mantle (ol-opx-cpx) fusion curve as modelled by *Albarede and Tamagnan* [1988]. The criteria used to identify primitive magmas in Figure 10 apply to magmas derived from lherzolite and in equilibrium with magnesian Olivine: however, there is no guarantee that a phlogopite- or amphibole-bearing, orthopyroxene-free source would produce similar primitive melts. It is conceivable that the high MgO contents of some samples of mica-rich minette may reflect partial melting in the presence of phlogopite (compare the experimental study of *Barton and Hamilton* [1982]).

Perhaps the most convincing evidence for the derivation of Wasatch Plateau alkaline rocks from primitive magmas is the composition of their Olivine phenocrysts. Olivine compositions in melanephelinile (Fo_{85}) and mica melanephelinite (Fo_{87}) are near the range (Fo_{88} to Fo_{94}) expected for primitive magmas derived from a "normal" mantle *[BVSP,* 1981] and are also near the compositions of olivines (Fo_{87} to Fo_{94}) in phlogopite-bearing mantle inclusions *[Erlank et al.,* 1987]. Such inclusions may be more like the sources of the Wasatch Plateau magmas.

Despite their primitive character, none of the Wasatch Plateau magmas seem to have brought mantle-derived xenoliths to the present level of exposure. However, chemically and mineralogically similar minette in the Navajo volcanic field contains such xenoliths *[Roden,* 1981; *Roden et al.,* 1990; *Ehrenberg,* 1982], suggesting that crustal contamination is not a necessary process to produce the characteristics of minette [cf. *Rutter,* 1987].

The isotopic compositions of the Wasatch Plateau rocks confirm that the sources for their magmas were heterogeneous and had experienced long-term enrichments of Rb compared to Sr and LREE compared to heavier REE (Figure 9). The positions of these mafic alkaline rocks off the mantle array defined by oceanic basalts could be taken to indicate significant crustal contamination of the magmas as they passed through the Proterozoic continental crust. However, we believe that crustal contamination was not significant (except perhaps in the case of the mica-rich minette WAT-12). as found by *Alibert et al.* [1986] and *Roden et al.* [1990] for similar rocks in the southern Colorado Plateaus. The high epsilon Sr value for WAT-12 and its relatively low Ce/Yb ratio place it off the array defined by apparently uncontaminated magmas from the southern Colorado Plateaus (Figure 7 *of Alibert et al.* [1986]). Moreover, this sample of mica-rich minette came from a dike that contains xenoliths of sedimentary material which may have radiogenic Sr. In addition, the mica-rich minettes have the lowest Sr concentrations (670-780 ppm) of the types identified here and could be most easily contaminated by crustal materials.

The high Sr concentrations (1000-2400 ppm) of the other dikes would tend to buffer their Sr isotopic compositions during assimilation of lower Sr crustal rocks. Minette breccias from the Navajo field also appear to have been contaminated by crustal materials *[Alibert et al.,* 1986].

Nature of the Mantle Sources

If the primitive character of the Wasatch Plateau magmas is accepted, they reveal information about the mineralogical character of their sources. As reviewed by *Edgar* [1987] and *Green et al.* [1987], it is difficult, if not impossible, to derive minette from normal dry lherzolite; rather, H_2O and CO_2 seem to be required and must be present in some mineral in the source rock. The experiments of *Esperanca and Holloway* [1987] with a minette composition slightly more felsic than those described here showed a near-liquidus assemblage of Olivine, diopside. and phlogopite. Accord-

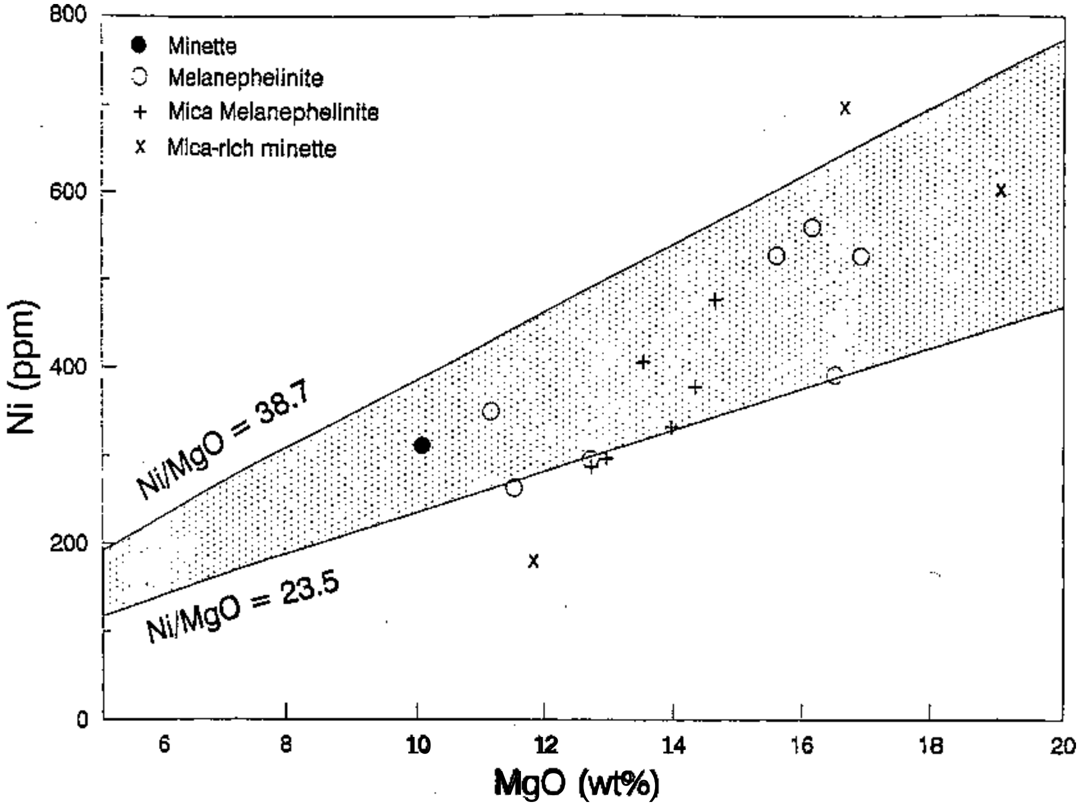

Fig. 10. MgO-Ni relationships for primitive mantle-derived magmas. Primitive magmas in equilibrium with peridotite are considered to have MgO/Ni ratios between 23.5 and 38.7 based on different exchange partition coefficients for Ni and Mg between Olivine and basaltic liquid *[BVSP,* 1981].

ingly, we suggest that the Wasatch Plateau minettes were derived from phlogopite-bearing sources. In fact, the low Ba/Rb ratios of the mica-rich minettes are consistent with mica remaining in the mantle after partial melting. Residual apatite in the source of the mica-rich minettes may also be indicated by the relatively low LREE concentrations and high P_2O_5 concentrations. In the source of the young minette, apatite and phlogopite may have been consumed during melting, yielding higher concentrations of LREE and higher Ba/Rb ratios in the melt. This could explain the different trace element patterns (Figure 6) for the two types of minette without appealing to major differences in trace element concentrations in their sources. An alternative, and favored, explanation is that the minette source had an intrinsically different trace element pattern than the source of the mica-rich minette, including stronger LREE enrichment as suggested by the low Nd isotope ratio in PIN-2.

For the melanephelinites, a source dominated by clinopyroxene and amphibole is suggested by their sodic (rather than potassic) character, their low alkali abundances, and Rb/Sr ratios; experimental evidence showing melanephelinite is produced by partial melting of amphibole peridotite *[Eggler,* 1978], and the studies of a suite of alkaline lavas that included melanephelinite by *Francis and Ludden* [1990].

In recent years, several models have been employed to explain the origin and source regions for alkaline magmas like those injected in the Wasatch Plateau dike swarm. In one model, magma generation occurs by extremely small degrees of partial melting of convecting asthenosphere similar to that which gives rise to ocean island basalts. In a second model, generation of LILE-enriched magma occurs by melting larger proportions of enriched (metasomatized) lithospheric mantle. As outlined below, elements of both of these models may be applicable to the alkaline rocks of the Wasatch Plateau. Two broadly different sources are suggested by the lack of negative Nb anomalies in melanephelinites and the presence of such anomalies in the mica-bearing rocks (minettes and mica melanephelinites) (Figure 6) and by the complementary differences in isotopic compositions and Nd model ages between the two groups. The Nd and Sr isotopic composition of the melanephelinite is near the oceanic mantle array; data for the three types of Nb-deficient micaceous rocks fall far from the array and demand long-lived enrichment of incompatible elements. Long-term enrichment could be created in the mantle lithosphere under technically stable continental crust.

Origins of the Alkaline Rocks

We have already noted the chemical similarity of melanephelinite to ocean island basalts, including their major element compositions, relatively smooth trace element patterns (Figure 6), lack of negative Nb anomalies, and trace element ratios (Figure 8). All of these features are consistent with an asthenospheric origin of the melanephelinites. Batch partial melting calculations for melanephelinites of the Wasatch Plateau dike swarm show less than 0.1% melting of a LILE-depleted mantle source *[Wood,* 1979] can produce the general levels of incompatible element abundance, but some details are not matched (depletions of Rb, K, and Nb compared to Th and La); either the mineralogy of the assumed residue or the trace element pattern of the hypothetical depleted source is inappropriate. In addition, the Nd and Sr isotopic composition of the analyzed melanephelinite is slightly shifted away from the field of ocean island basalts (Figure 9). We suggest that primary magma, derived from asthenosphere having characteristics of the source of ocean island basalt, interacted with enriched mantle lithosphere to slightly modify incompatible element compositions and isotope ratios; such slightly contaminated magma might have formed the melanephelinite dikes:

Nonetheless, the similarity of melanephelinites to ocean island basalts does not conclusively demonstrate that their source was in the asthenosphere. For example, *Roden et al.* [1990] have identified garnet peridotite inclusions from the southern Colorado Plateaus with the REE and Nd isotopic characteristics of ocean island basalt (and melanephelinite); but mineral geothermometry shows that the peridotites resided within the lithosphere. Likewise, *Hartmann and Wedepohl* [1990] studied metasomatized inclusions from the lithosphere beneath the Hessian depression, Germany, which have incompatible trace element ratios (La/Nb, La/Ba, Zr/Nb) like ocean island basalt. Partial melting calculations using the high-K metasomatized peridotite of *Hartmann and Wedepohl* [1990] allow the proportion of melting to be as high as 3-4% for the melanephelinites of the Wasatch Plateau. If the melanephelinite source was enriched by metasomatism, the high epsilon Nd of STA-1 suggests that the enrichment is not as old or as extensive as in the source of mica-rich minette (Figure 9). Thus it is difficult to preclude a lithospheric source. Finally, we note that *Roden et al.* [1990] and *Alibert et al.* [1986] suggested that the source of Hopi Butte melanephelinite magmas was in the lithospheric mantle.

On the Wasatch Plateau, mica-bearing rocks (mica-rich minette, minette, and mica melanephelinite) have isotopic compositions, trace element patterns (including negative Nb-Ta and Ti anomalies), and Proterozoic Nd model ages that preclude their direct derivation from asthenosphere; these facts are consistent with a source component from metasomatized but strongly heterogeneous lithospheric mantle. Xenoliths of metasomatized mantle containing hydrous minerals occur in minettes from the Navajo volcanic field and in alkali basalts from the Grand Canyon of northern Arizona [*Menzies et al.*, 1987; *Wilshire et al.,* 1988; *Ehrenberg,* 1982; *Roden et al.,* 1990], but as pointed out by *Roden et al.* [1990], many of these inclusions show LREE depletions and are not appropriate sources chemically or isotopically for the minettes. However, generalized partial melting calculations using a metasomatized source, assumed to be the high-K peridotite of *Hartmann and Wedepohl* [1990], show that 3-5% melting can produce the enrichments of many incompatible trace elements found in mica-bearing rocks of the Wasatch Plateau. But depletions of Th, Nb, Ta, and Ti in these rocks (Figure 6) are not produced by melting of this enriched peridotite. Distinctive minerals (phlogopite, apatite, amphibole, carbonate, and various titanates) may have been residual to the melting events and thus retained these elements. For example, Sr might be retained in preference to Ce and Nd if a carbonate mineral was residual; it seems unlikely that residual clinopyroxene could fractionate Sr and Nd in this fashion. Alternatively, the magma sources may have been distinctively depleted in Th, Nb, Ta, and Ti compared to the metasomatized Hessian peridotites used in the calculations.

Negative Nb-Ta and Ti anomalies on Chondrite-normalized diagrams, such as those found in the micaceous dikes, are generally considered to be subduction zone signatures [e.g., *Fitton et al.,* 1988, this issue]. Negative anomalies may be caused by hydrous fluids or magmas with higher concentrations of K and LREE (as compared to less soluble Nb, Ta, and Ti) reacting with overlying mantle to produce magma or metasomatic rock. The fluids may be derived by dehydration of a subducting slab of oceanic lithosphere in an underlying subduction zone. As an alternative explanation, *Roden et al.* [1990] have suggested that Nb-Ta depletion in felsic minette from the Navajo volcanic field is the result of fractionation of a Nb-Ta mineral or Ti-rich phlogopite. We consider this to be unlikely for the rocks studied here because (1) we have not found a Nb-Ta phase in the minettes, (2) Nb is not correlated with any index of fractionation such as SiO_2. MgO, or Ni. (3)'Nb is not correlated with TiO_2 abundances as it would be if controlled by fractionation of TiO_2-rich phlogopite, and (4) the Nb-Ta depletions are larger in the mafic minettes of the Wasatch Plateau than in the felsic minettes of the Navajo field. Thus we consider it more likely that the differences in Nb-Ta concentrations are controlled more by differences in the chemical or mineralogical composition of the source than by fractional crystallization.

Various kinds of metasomatic agents in the mantle sources are indicated by the compositions of the alkaline dikes of the Wasatch Plateau. For example, mica-rich minette is similar to Group II (micaceous) kimberlite, which is characterized by high Rb/Sr, K/Ti, and low Rb/Ba ratios (Figure 6). These features have been taken to indicate the presence of phlogopite resulting from metasomatism by hydrous fluids. The resultant high Rb/Sr ratios in mica-bearing mantle could, over time, produce the shallow trend of Navajo minette on the epsilon Sr-epsilon Nd diagram (Figure 9). In contrast, Wasatch Plateau minette and mica melanephelinite show evidence of metasomatism resulting from the introduction of small volume melts [e.g., *Menzies et al.,* 1987). These distinctive rocks have low epsilon Nd (indicative of the long term LREE enrichment of their sources), high Ce/Yb ratios, low Rb/Sr, and high Ba/Rb ratios compared with the mica-rich varieties. Moreover, mineralogic and elemental gradations between melanephelinite, mica melanephelinite, minette, and mica-rich minette suggest the involvement of melanephelinite magmas in the generation of the mica-bearing rocks.

We, thus, suggest that Wasatch Plateau minettes and mica melanephelinites crystallized from volatile-rich magmas which had some sort of subduction zone component. The older mica-rich minettes and mica melanephelinite were both emplaced 24 Ma, shortly after the apparent disappearance of a subducting slab of oceanic lithosphere beneath the region *[Severinghaus and Atwater,* 1990]. However, metasomatizing fluids rising from a Cenozoic subduction zone and interacting with lithospheric mantle cannot explain the isotopic characteristics of the alkaline rocks discussed here. Rather, their sources appear to have been modified anciently, perhaps by enrichment processes associated with subduction when the lithosphere formed. For the minettes and mica melanephelinite, Nd model ages calculated with reference to depleted mantle (TDM = 1.4 to 1.6 Ga) suggest long-term LREE enrichment of their sources. These are likely to be minimum age estimates because the magmas probably had lower Sm/Nd ratios than their sources and the model ages are several hundred million years less than the age of the craton beneath the Colorado Plateaus *[Bennett and DePaolo,* 1987].

If the isotopic ratios of the mica-bearing dikes reflect the composition of parts of the lithospheric mantle, then it appears that the lithospheric mantle became enriched shortly after or while the overlying crust formed during the Proterozoic, presumably by subduction zone processes *[Condie,* 1986]. Nd and Sr isotopic compositions for minette of the Navajo volcanic field *[Alibert et al.,* 1987; *Roden et al.,* 1990] and Leucite Hills lamproite *[Vollmer et al.,* 1984] also indicate that these Cenozoic rocks also originated in old, enriched, lithospheric mantle.

CONCLUSIONS

Mafic alkaline rocks in the Wasatch Plateau dike swarm were emplaced 24, 18. and 8-7 Ma. Changing dike orientations are consistent with clockwise rotation of the least principal horizontal stress from north-south 24 Ma to east-west by 8-7 Ma. The alkaline rocks are interpreted from their elemental, isotopic, and mineral compositions to have formed from primitive magmas. The generation of mica melanephelinite and both types of minette appears to have involved phlogopite-bearing mantle sources that were heterogeneous with respect to LREE enrichments, Rb/Sr ratios, and

Nb-Ta-Ti depletions. Metasomatic enrichment probably occurred during the Proterozoic when this part of the lithosphere formed. Melanephelinite was probably generated from an amphibole-bearing source with strong depletions in Cs, Rb, and K and little or no depletion of Nb, Ta, or Ti. Because of the similarity of the melanephelinites to ocean island basalt, we suggest that their source was in the asthenosphere. Mineralogical and elemental gradations between melanephelinite and both kinds of minette are consistent with varying degrees of interaction of melanephelinite with enriched lithospheric mantle to produce the range of dike rocks. We suggest that melanephelinite magma was produced in response to foundering of the subducting Farallon plate away from the lithosphere and the consequent back flow of asthenosphere into the zone above the plate. In some dike intrusion episodes, melanephelinite magma interacted only slightly with the overlying enriched lithosphere; in other episodes, interaction of melanephelinite magma with small melt fractions derived from the lithospheric mantle may have been more extensive, producing mica melanephelinite, minette, or mica-rich minette. In this scenario, melanephelinite provided at least the heat for, and in some instances significant mass to be contaminated by, lithospheric magma generation. Such a two-source model can account for the world wide association of melanephelinite and minette in intracontinental settings. An alternative that we cannot completely exclude is that all of the magmas were derived from partial melting of lithospheric mantle enriched by metasomatism during the Proterozoic but to significantly varying degrees. This model lacks a source of heat for melting of lithospheric mantle. Late Tertiary extension in the Colorado Plateaus province was small and unlikely to have caused significant melting by decompression. In either case, it is still unclear to us why Tertiary magmatism in the Colorado Plateaus province was episodic and of such low volumes compared to adjacent areas to the east and west.

The Wasatch Plateau dike swarm is but one of many Tertiary alkaline magmatic loci that define a diffuse north-south zone from Canada to Mexico just east of the late Mesozoic-early Tertiary compressional fold and thrust belt. Although broadly contemporaneous with subduction activity off the continental margin, and therefore conceivably a consequence of it, some magmatic centers may have been active after a subducting oceanic plate no longer underlay the locus. This possibility, plus (1) the poor temporal correlation between alkaline activity in Utah with zones of spatially related, presumably subduction-caused calc-alkaline activity to the west in the Great Basin and, especially, (2) the growing body of elemental and isotopic data indicating derivation of alkaline magmas from anciently metasomatically enriched lithospheric mantle indicate that the sources and/or processes of alkaline and calc-alkaline magmatism differed.

Acknowledgments. This research was made possible with the help of Colleen Tingey, Bart Kowallis, Paul Proctor, Bill Nash, Keith Rigby, Mark Bunnell, Greg Hunt, Keith Fenstermaker, and Ken Flick. Isotopic analyses were performed in the laboratories of J. P. Patchett. Dan Barker, Sonia Esperanca, Michael Roden, and Stephen Nelson provided helpful reviews. Funding was provided by Getty Oil Company Minerals Division, Utah Geological and Mineral Survey, Utah Fuels Company, and NSF grant EAR-8618323. Logistical and other support was provided by Camp Valley Mining Company and Beaver Creek Coal Company.

REFERENCES

Albarede, F., and V. Tamagnan. Modelling the recent geochemical evolution of the Piton de la Fournaise volcano. Reunion Island, 1931-1986, *J. Petrol., 29,* 997-1030. 1988.

Alibert, C, A. Michard. and F. Albarede. Isotope and trace element geochemistry of Colorado Plateau volcanics, *Geochim. Cosmochim. Acta.50,* 2735-2750. 1986.

Anderson, E. M., *The Dynamics of Faulting and Dyke Formation With Applications to Britain,* 206 pp., Oliver and Boyd, Edinburgh, 1951.

Bachinski, S. W., and R, B. Scott, Rare earth and other trace element contents and the origin of minettes (mica-lamprophyres), *Geochim. Cosmochim. Acta, 43,* 93-100, 1979.

Barker, D. S., Alkaline rocks of North America, in The Alkaline Rocks, edited by H. Sorensen, pp. 160-171, John Wiley, New York, 1974.

Barnhard, T. P., and R. E. Anderson, Extensional and compressional paleostress states in the western Colorado Plateau, central Utah, *Geol. Soc. Am. Abstr. Programs, 16,* 437, 1984.

Barton, M., and D. L. Hamilton, Water-undersaturated melting experiments bearing upon the origin of potassium-rich magmas, *Mineral. Mag., 45,* 267-278, 1982.

Basaltic Volcanism Study Project, *Basaltic Volcanism on the Terrestrial Planets,* 1286 pp., Pergamon, New York. 1981.

Beghoul, N., and M. Barazangi, Mapping high *Pn* velocity beneath the Colorado Plateau constrains uplift models, *J. Geophys. Res., 94,* 7083-7104, 1989.

Bennett, V. C, and D. J. DePaolo, Proterozoic crustal history of the western U. S. as determined by neodymium isotopic mapping, *Geol. Soc. Am. Bull., 99,* 674-685, 1987.

Bergman, S. C, Lamproites and other potassium-rich igneous rocks: A review of their occurrence, mineralogy and geochemistry, in Alkaline Igneous Rocks, edited by J. G. Fitton and B. G. J. Upton, *Geol. Soc. Spec. Publ. London*, 30, 103-190, 1987.

Best, M. G., Early Miocene change in direction of least principal stress, southwestern United States: Conflicting inferences from dikes and metamorphic core-detachment fault terranes, *Tectonics,* 7(2), 249-259, 1988.

Best, M.G., and E.H. Christiansen, Limited extension during peak Tertiary volcanism, Great Basin of Nevada and Utah, *J. Geophys. Res.,* this issue.

Best, M. G., L. Henage, and J. A. S. Adams, Mica peridotite, wyomingite, and associated potassic igneous rocks in northeastern Utah, *Am. Mineral., 53,* 1042-1048,1968.

Bird, P., Continental delamination and the Colorado Plateau, 7. *Geophys. Res., 84,* 7561-7571, 1979.

Bird, P., Formation of the Rocky Mountains, western United States: A continuum computer model, *Science, 239,* 1501-1507, 1988.

Condie, K. C, Geochemistry and tectonic setting of Early Proterozoic supracrustal rocks in the southwestern United States, J. *Geol., 94,* 845-864, 1986.

Delaney, P. T., D. D. Pollard, J. I. Ziony, and E. H. McKee, Field relations between dikes and joints: Emplacement processes and paleostress analysis, *J. Geophys. Res,, 91,* 409-440, 1986.

Eaton, G. P., The Basin and Range province: Origin and tectonic significance, *Annu. Rev. Earth Planet. Sci., 10,* 409-440, 1982.

Edgar, A. D., The genesis of alkaline magmas with emphasis on their source regions: Inferences from experimental studies, in Alkaline Igneous Rocks, edited by J. G. Fitton and B. G. J. Upton, *Geol. Soc. Spec. Publ. London, 30,29-52,* 1987.

Eggler, D. H., The effect of CO_2 upon partial melting of peridotite in the system Na_20-$Ca0$-Al_20_3-$Mg0$-$Si0_2$-$C0_2$ to 35 kb, with an analysis of melting in a peridotite-H2O-CO2, system", *Am. J. Sci., 278,* 305-343, 1978.

Ehrenberg, S.N., Rare earth element geochemistry of garnet lherzolite and megacrystalline nodules from minette of the Colorado Plateau province, *Earth Planet. Sci. Lett., 57,* 191-210, 1982.

Erlank, A. J., F. G. Waters. C. J. Hawkesworth, S. E. Haggerty, H. L. Allsop, R. S. Rickard, and M. A. Menzies, Evidence for mantle metasomatism in peridotite nodules from the Kimberley Pipes, South Africa, in *Mantle Metasomatism,* edited by M. A. Menzies and C. J. Hawkesworth, pp. 221-311, Academic, San Diego, Calif., 1987.

Esperanca, S., and J. R. Holloway, On the origin of some mica-lamprophyres: Experimental evidence from a mafic minette, *Contrib. Mineral. Petrol., 95,* 207-216, 1987.

Farmer, G. L., and A. L. Boettcher, Petrologic and crystal-chemical significance of some deep-seated phlogopites, *Am. Mineral., 66,* 1154-1163, 1981.

Faye, G. H., and D. D. Hogarth, On the origin of "reverse pleochroism" of a phlogopite, *Can. Mineral., 10,* 25-34, 1969.

Fitton, J. G., and H. M. Dunlop. The Cameroon line, West Africa, and its bearing on the origin of oceanic and continental alkali basalt, *Earth Planet. Sci. Lett., 72,* 23-38. 1985.

Fitton, J. G., D. James. P. D. Kempton, D. S. Ormerod, and W. P. Leeman, The role of lithospheric mantle in the generation of late Cenozoic basic magmas in the south-western United States, *J. Petrol., Spec. Lithosphere Issue,* 331-349, 1988.

Fitton, J. G.. D. James, and W. P. Leeman, Basic magmatism associated with late Cenozoic extension in the western United States: Compositional variations in space and time. *J. Geophys. Res.,* this issue.

Francis, D.. and J. Ludden, The mantle source for Olivine nephelinite, basanite, and alkaline Olivine basalt at Fort Selkirk, Yukon. Canada, *J. Petrol. 31, 371-400,* 1990.

Gartner, A. E., and P. T. Delaney, Geologic map showing a late Cenozoic basaltic intrusive complex, Emery, Sevier, and Wayne counties, Utah, *U.S. Geol. Surv. Map, MF-2052,* 1988.

Green, D. H., T. J. Falloon, and W. R. Taylor. Mantle-derived magmas-Roles of variable source peridotite and variable C-H-0 fluid compositions, in Magmatic Processes: Physicochemical Principles, edited by B. O. Mysen. *Spec. Publ. Geochem. Soc,* 139-154, 1987.

Hartmann, G., and K. H. Wedepohl, Metasomatically altered peridotite xenoliths from the Hessian Depression (Northwest Germany), *Geochim. Cosmochim. Acta, 54,* 71-86, 1990.

Hintze, L. F., Geologic map of Utah, Utah Geol. and Miner. Surv., Salt Lake City, 1980.

Hintze, L. F., Geologic history of Utah, *Brigham Young Univ. Geol. Stud. Spec. Publ. 7,* 202 pp., 1988.

Kowallis, B. J., J. Ferguson, and G. J. Jorgensen, Uplift along the Salt Lake segment of the Wasatch fault from apatite and zircon fission track dating in the Little Cottonwood stock, *Nucl. Tracks. 17,* 325-329, 1990.

Laughlin. A. W., M. J. Aldrich, Jr., M. Shafiqullah, and J. Husler, Tectonic implications of the age. composition, and orientation of Lamprophyre dikes, Navajo Volcanic Field, Arizona, *Earth Planet. Sci. Lett., 76,* 361-374,1986.

Le Bas, M. J., Nephelinitic and basanitic rocks. *J. Petrol., 30,* 1299-1312, 1989.

Le Maitre, R. W., *A Classification of Igneous Rocks and Glossary of Terms,* Blackwell, Oxford, 1989.

Lipman, P. W., Cenozoic volcanism in the western United States: Implications for continental tectonics, in *Studies in Geophysics: Continental Tectonics,* pp. 161-174, National Academy of Sciences, Washington, D.C., 1980.

Lux, D.R., ^{40}Ar/^{39}Ar ages for minerals from the amphibolite dynamothermal aureole, Mont Albert, Gaspe. Quebec. *Can. J. Earth Sci., 23,* 21-26,1985.

McDowell, F. W., M. F. Roden, and D. Smith, Comments on "Tectonic implications of the age, composition, and orientation of lamprophyre dikes, Navajo volcanic field, Arizona", *Earth Planet. Sci. Lett., 80,* 415-417,1986.

Menzies. M. A., R. J. Arculus, M. G. Best. S. C. Bergman, S. N. Ehrenberg, A. J. Irving, M. F. Roden, and D. J. Shulze, A record of subduction process and within-plate volcanism in lithospheric xenoliths of the southwestern USA, in *Mantle Xenoliths,* edited by P. H. Nixon, pp. 59-74, John Wiley, New York, 1987.

Naeser, C. W., R. A. Zimmerman, and G. T. Cebula, Fission-track ages of apatite in the Wasatch Mountains, Utah: An uplift study *.Mem. Geol. Soc. Am. 157,* 29-36, 1983.

O'Brien, H.E., A.J. Irving, and I.S. McCallum, Complex zoning and resorption of phenocrysts in mixed potassic mafic magmas of the Highwood Mountains, Montana. *Am. Mineral., 73,* 1007-1024, 1988.

Pakiser, L. C, Geophysics of the Intermontane system, *Mem. Geol. Soc. Am. 172,* 235-247, 1989.

Patchett, J. P., and J. Ruiz, Nd isotopic ages of crust formation and metamorphism in the Precambrian of eastern and southern Mexico, *Contrib. Mineral. Petrol., 96,* 523-528, 1987.

Phillips, W.R., Igneous rocks of north central Utah, *Brigham Young Univ. Geol. Stud.* 9, 65-69, 1962.

Ren, X., B. J. Kowallis, and M. G. Best, Paleostress history of the Basin and Range province in western Utah and eastern Nevada from healed microfracture orientations in granites, *Geology, 17*(6), 487-490, 1989.

Rock; N. M. S., The nature and origin of lamprophyres: An overview, in Alkaline Igneous Rocks, edited by J. G. Fitton.and B. G. J. Upton, *Geol. Soc. Spec. Publ. London, 30,* 191-226, 1987.

Roden, M. F., Origin of coexisting minette and ultramafic breccia, Navajo volcanic field. *Contrib. Mineral. Petrol., 77,* 195-206, 1981.

Roden, M. F., D. Smith, and V. R. Murthy, Chemical constraints on lithosphere composition and evolution beneath the Colorado Plateau, *J. Geophys. Res., 95,* 2811-2831, 1990.

Rutter, M. J., Evidence for crustal assimilation by turbulently convecting, mafic alkaline magmas: Geochemistry of mantle xenolith-bearing lavas from northern Sardinia, *J. Volcano!. Geotherm. Res., 32,* 343-354, 1987.

Severinghaus, J., and T. Atwater, Cenozoic geometry and thermal condition of the subducting slabs beneath western North America, in Basin and Range Extensional Tectonics Near the Latitude of Las Vegas, Nevada, edited by B. Wernicke, *Mem. Geol. Soc. Am., 176,* 1-22. 1991.

Smith, J. T., and K. L. Cook, Geologic interpretation of gravity anomalies of northeastern Utah, *Utah Geol. Assoc. Publ. 12,* 121-146, 1985.

Smith, R. B.. and A. G. Lindh, A compilation of fault plane solutions of the western United States, in Cenozoic Tectonics and Regional Geophysics of the Western United States, edited by R. B. Smith and G. P. Eaton, *Mem. Geol. Soc. Am., 152,* 107-110, 1978.

Smith, R. B.. W. C. Nagy, K. A. Julander, J. J. Viveiros, C. A. Barker, and D. C. Gants, Geophysical and tectonic framework of the eastern Basin and Ranee-Colorado Plateau-Rocky Mountain transition, *Mem. Geol. Soc. Am.,* 772,205-233, 1989.

Smith, S. B. H., R. V. Danchin, J. W. Harris, and K. J. Stracke, Kimberlites near Orrodoo, South Australia, in *Kimberlites 1: Kimberlites and Related Rocks,* edited by J. Kornprobst, pp. 83-105, Elsevier Science, New York, 1984.

Spieker, E. M., The Wasatch Plateau coal field, Utah, *U.S. Geol. Surv. Bull.* 879,210 pp., 1931.

Stewart, J. H., W. J. Moore, and I. Zietz, East-west patterns of Cenozoic igneous rocks, aeromagnetic anomalies, and mineral deposits, Nevada and Utah, *Geol. Soc. Am. Bull., 88,* 67-77. 1977.

Stille, P., R. Oberhansli, and K. Wenger-Schenk, Hf-Nd isotopic and tracelement constraints on the genesis of alkaline and calc-alkaline lamprophyres, *Earth Planet. Sci. Lett., 96,* 209-219, 1989.

Sullivan, K. R., and M. G. Best, Tectono-thermal controls on Tertiary magmatism in the intermountain west, *Geol. Soc. Am. Abstr. Programs, 18(5),* 416, 1986.

Sullivan, K. R., B. J. Kowallis, and H. H. Mehnert, Isotopic ages of igneous intrusions in southeastern Utah: Evidence for a mid-Cenozoic Reno-San Juan magmatic zone, *Brigham Young Univ. Geol. Stud., 37,* in press, 1991.

Thomas, W. D., Dikes of the Clear Creek area, Wasatch Plateau, Utah, M.S. thesis, 73 pp., Utah State Univ., Logan, 1976.

Thompson, G. A., and M. L. Zoback, Regional geophysics of the Colorado Plateau, *Tectonophysics, 61,* 149-181, 1979.

Thompson, R. N., M. A. Morrison, G. L. Hendry, and S. J. Parry, An assessment of the relative roles of crust and mantle in magma genesis: An elemental approach, *Philos. Trans. R. Soc. London, Ser. A, 310,* 549-590, 1984.

Thompson. R. N.. P. T. Leat, A. P. Dickin, M. A. Morrison, G. L. Hendry, and S.A. Gibson. Strongly potassic mafic magmas from lithospheric mantle sources during continental extension and heating: Evidence from Miocene minettes of northwest Colorado, U.S.A., *Earth Planet. Sci. Lett., 98.* 139-153, 1989.

Tingey, D. G.. Late Oligocene and Miocene minette and Olivine nephelinite dikes, Wasatch Plateau, Utah, M.S. thesis, 75 pp., Brigham Young Univ., Provo. Utah, 1989.

Vollmer, R.. P. Ogden. J. G. Schilling, R. H. Kingsley, and D. G. Waggoner. Nd and Sr isotopes in ultrapotassic volcanic rocks from the Leucite Hills. Wyoming, *Contrib. Mineral. Petrol., 87,* 359-368, 1984.

Walton, P. T., Wasatch Plateau gas fields, Utah, *Am. Assoc. Pet. Geol. Bull., 39(4).* 385-421, 1955.

Wilshire, H. G.. C. E. Meyer, J. K. Nakata. L. C. Calk, J. W. Shervais, J. E. Nielson. and E. C. Schwarzman. Mafic and ultramafic xenoliths from volcanic rocks of the western United States. *CS. Geol. Surv. Prof. Pap. 1443,* 179 pp.. 1988.

Witkind. I. J., and R. F. Marvin, Significance of new potassium-argon ages from the Golden Ranch and Moroni Formations. Sanpete-Sevier Valley area, central Utah. *Geol. Soc. Am. Bull., 101,* 534-548. 1989.

Wood, D. A.. A variably veined suboceanic upper mantle—Genetic significance for mid-ocean ridge basalts from geochemical evidence, *Geology,* 6,499-503.1979.

Zietz, I. and J.R. Kirby, Jr., Aeromagnetic map of Colorado, *U.S. Geol. Surv. Geophys. Invest. Map. GP-880,* 1972.

Zietz, I., R. Shuey, and J. R. Kirby, Jr., Aeromagnetic map of Utah, *U.S. Geol. Surv. Geophys. Invest. Map, GP-907,* 1976.

Zindler, A., and S. Hart, Chemical geodynamics. *Annual Reviews of Earth and Planetary Science, 14,* 493-571, 1986.

Zoback, M. L.. R. E. Anderson, and G. A. Thompson, Cainozoic evolution of the state of stress and style of tectonism of the Basin and Range province of the western United States, *Philos. Trans. R. Soc. London. Ser. A, 300.* 407-434,1981.

M.G. Best, E.H. Christiansen, and D. G. Tingey, Brigham Young University, Department of Geology, 258 ESC, Provo. UT 84602.

D. R. Lux, Department of Geology, University of Maine, Orono, ME 04469.

J. Ruiz, Department of Geosciences, University of Arizona, Tucson. AZ 85721

(Received July 11. 1990:
revised January 17, 1991;
accepted January 24, 1991.)