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THE ASSOCIATION BASANITIC NEPHELINITE – FELDSPAR IJOLITE – NEPHELINE MONZOSYENITE AT HOUSE MOUNTAIN VOLCANO, NORTH-CENTRAL ARIZONA

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ABSTRACT

Dikes of basanitic nephelinite at the predominantly basaltic House Mountain volcano (Arizona) host ocelli, dikes, pods and sheets of feldspar ijolite and nepheline monzosyenite that may be explained by differentiation according to the series: basanitic nephelinite → feldspar ijolite → nepheline monzosyenite. Titanaugite, nepheline, feldspar and olivine occur in all stages of this sequence, which shows systematic Fe enrichment in mineral chemistry and bulk composition. The nephelinite ($mg = 76$) contains Fo_{85-86} olivine with a thin Fo_{65-77} rim, and $Wo_{48-52}Fs_{8-14}En_{36-44}$ titanaugite. The ijolite (mg in the range 51–61) contains titanaugite with a $Wo_{48-53}Fs_{14-18}En_{30-35}$ core and a $Wo_{48-52}Fs_{20-24}En_{28-31}$ rim. The monzosyenite (mg in the range 46–50) has Fo_{18-29} olivine, and titanaugite zoned from $Wo_{48-50}Fs_{15-27}En_{29-34}$ to $Wo_{48}Fs_{21-42}En_{10-31}$, with a green-brown rim of $Wo_{48}Fs_{37-45}En_{7-15}$. Along the proposed sequence, *LILE* generally show a 2–3× enrichment, and compatible elements show a strong depletion. A petrogenetic model for the association, based on field relationships, geochemistry, and petrography, includes buoyant rise of a heterogeneous body of ijolitic + monzosyenitic magma through a large dike of molten nephelinite to shallow depths (<0.5 km) in the volcano. Turbulence or shear along the boundary may have stirred small globules (ocelli) of felsic magma into the nephelinite. The large body of ijolite – monzosyenite spread as a sheet when it encountered the chilled top of the dike, and fractionated to form cm- to m-scale banding and layering. Large crystals, intergrowth and skeletal textures, and miarolitic cavities with zeolite resulted from rapid crystallization of undercooled, fluid-rich felsic magma. Post-intrusion differentiation of the host nephelinitic magma produced wispy patches and schlieren of felsic liquid that were locally filter-pressed into small dikes of nepheline monzosyenite.

Keywords: ijolite, nephelinite, monzosyenite, ocelli, differentiation, House Mountain, Arizona.

SOMMAIRE

Nous décrivons une suite de filons de néphélinite basanitique qui affleure à House Mountain (Arizona), édifice volcanique à dominance basaltique; la néphélinite contient des enclaves ocellaires, filons, et filons-couches d'ijolite à feldspath et de monzosyénite à néphéline qui témoignerait d'un processus de différenciation selon le schéma: néphélinite basanitique → ijolite à feldspath → monzosyénite à néphéline. Titanaugite, néphéline, feldspath et olivine sont présents à tous les stades de cette séquence, qui montre un enrichissement progressif en Fe, tel qu'illustré par les roches et les minéraux constituants. La néphélinite ($mg = 76$) contient une olivine Fo_{85-86} ayant une bordure étroite de composition Fo_{65-77}, et une titanaugite de composition $Wo_{48-52}Fs_{8-14}En_{36-44}$. L'ijolite ($51 < mg < 61$) contient une titanaugite avec un coeur de composition $Wo_{48-53}Fs_{14-18}En_{30-35}$ et une bordure de composition $Wo_{48-52}Fs_{20-24}En_{28-31}$. La monzosyénite ($46 < mg < 50$) contient une olivine de composition Fo_{18-29} et une titanaugite zonée de $Wo_{48-50}Fs_{15-27}En_{29-34}$ à $Wo_{48}Fs_{21-42}En_{10-31}$, avec une bordure brun-vert de composition $Wo_{48}Fs_{37-45}En_{7-15}$. Dans la séquence proposée, les éléments lithophiles à large rayon montrent généralement un enrichissement, d'un facteur de 2 à 3, tandis que les éléments compatibles font preuve d'un fort appauvrissement. Un modèle pétrogénétique de l'association, fondé sur les relations de terrain, les résultats géochimiques, et la pétrographie, fait appel à la montée vers la surface (<5 km) dans l'édifice volcanique d'une masse hétérogène de magmas ijolitique et monzosyénitique dans un filon nourricier de magma néphélinitique. De petits globules (ocelles) de magma felsique auraient été entraînés dans le magma néphélinitique par turbulence ou cisaillement le long de l'interface. Le volume imposant de magma néphélinitique dans ce filon nourricier s'est par la suite épanché sous forme de filon-couche lorsqu'il entra en contact avec la bordure figée supérieure du filon. Il en résulta un fractionnement responsable du litage sur une échelle centimétrique à métrique et une cristallisation rapide du magma felsique trempé riche en composants fluides, comme en témoigne localement la grande taille des cristaux, les intercroissances et textures squelettiques, et les cavités miarolitiques tapissées de zéolites. La différenciation du magma néphélinitique suite à sa mise en place a produit des taches floues et des schlieren de liquide felsique qui ont été concentrées localement par compression et ségrégation en petits filons de monzosyénite à néphéline.

(Traduit par la Rédaction)

Mots-clés: ijolite, néphélinite, monzosyénite, ocelles, différenciation, House Mountain, Arizona.

Introduction

Newly discovered alkaline rocks at House Mountain in north-central Arizona are of special petrological interest because of their distinctive compositions and textures, and occurrence near the summit of a basaltic volcano. From a distance, House Mountain appears to be an ordinary shield volcano typical of late Cenozoic basaltic volcanism in central Arizona. However, it is unusual in this area because the basaltic rocks, which comprise the bulk of the volcano, are intruded by strongly undersaturated feldspathoidal rocks that include basanitic nephelinite, feldspar ijolite, and nepheline monzosyenite. The undersaturated rocks represent the youngest igneous event in the history of House Mountain, and crop out as dikes and a small flow along the north side of the volcano.

Similar strongly undersaturated rocks are found 20 km to the southeast at Casner Butte and 12 km east–northeast at Lee Mountain (Fig. 1). Casner Butte itself is a large dike of basanitic nephelinite (striking N40°W) that was intruded into a thick section of scoriaceous basaltic tuff. Within the dike are small bodies of coarse-grained felsic rocks that appear identical in hand specimen and thin section to the feldspar ijolites and nepheline monzosyenites at House Mountain. The Lee Mountain locality is a nephelinitic plug about 0.5 km in diameter; coarse-grained felsic rocks are identical in hand specimen to those at House Mountain, but less abundant.

Coarse-grained nepheline-bearing rocks have not been reported elsewhere in Arizona, and are unusual in the southwestern United States (Barker 1974, Woolley 1987). This study was undertaken to characterize the alkaline rocks at House Mountain, to establish their field relations in the host basaltic volcano, and to determine their petrogenesis.

Geological Setting and Age of House Mountain

House Mountain volcano is located on the northeastern side of the Arizona Transition Zone (Fig. 1). The Transition Zone is a tectonic and physiographic province intermediate in character between the relatively undeformed Colorado Plateau and the highly faulted Basin and Range Province (Menges & Pearthree 1989). Paleozoic strata and Cenozoic lava flows in the central part of the Transition Zone are nearly flat-lying, like those on the Colorado Plateau, but large throws on high-angle normal faults create smaller-scale analogs of the horst and graben structures typical of the Basin and Range Province.

House Mountain volcano erupted on faulted and eroded Paleozoic strata in the Verde Valley, one of several structural basins in the Transition Zone (Peirce 1984, Weir *et al.* 1989). Early Proterozoic basalts, andesites, rhyolites, volcaniclastic sediments, and dioritic to granitic intrusions that underlie the Paleozoic strata in the range southwest of the Verde Valley probably also occur below House Mountain (Anderson *et al.* 1971). The conduit area of the volcano lies on the projected traces of several faults that strike northwest, parallel to the trends of the Verde Valley

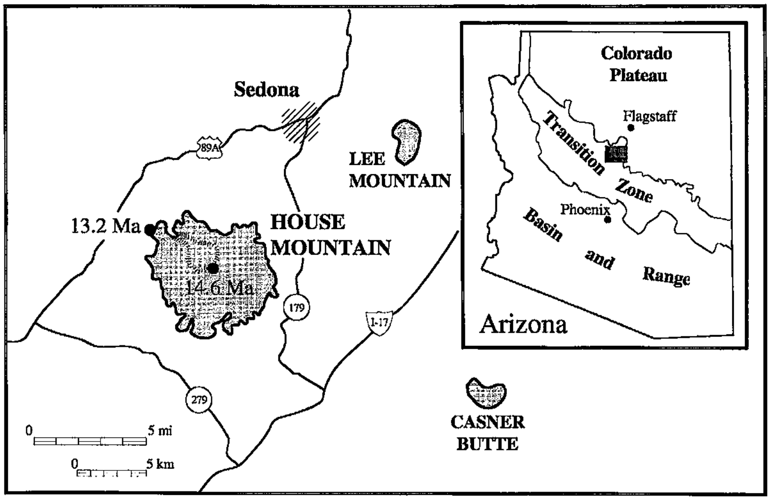

FIG. 1. Location of House Mountain volcano. Large bodies of basanitic nephelinite also are found at Casner Butte and Lee Mountain. Inset map shows the tectonic provinces of Arizona. K–Ar dates are from Ranney (1988).

and the Transition Zone (Weir *et al.* 1989); these faults may reflect Precambrian structures in the crystalline basement (Shoemaker *et al.* 1978).

House Mountain was first identified as a shield volcano by Mahard (1949). He considered volcanism to be roughly contemporaneous with deposition of the 4–8 Ma Verde Formation, a fluvial and lacustrine deposit that partly filled the Verde Valley basin before external drainage developed in late Pliocene to Pleistocene time (Nations *et al.* 1981). Subsequently, investigators who discussed House Mountain either concurred with Mahard on the age of volcanism or simply considered it to be Tertiary (Sabels 1962, Twenter & Metzger 1963, Levings 1980, Nations *et al.* 1981, Elston 1984, Weir *et al.* 1989). Ranney (1988) documented the age of the volcano to be 13–14 Ma, and described onlap relationships of lacustrine strata that show the volcano to be overlain by the Verde Formation. The Middle Miocene age of House Mountain identifies it as an additional volcanic center of the approximately 15–10 Ma Hickey Formation, which consists principally of alkaline to tholeiitic basalt lava flows in central Arizona (McKee & Anderson 1971, Wittke *et al.* 1989).

STRUCTURE AND STRATIGRAPHY OF THE HOUSE MOUNTAIN VOLCANO

The House Mountain volcano is similar in size, structure, and profile to many small-volume basaltic shield volcanoes (Cas & Wright 1987). Cross sections indicate that the volcanic rocks in the central part of the volcano are about 370 m thick (Ranney 1988; Holm & Wittke, in prep.). Although the Verde Formation covers the lower flanks of the volcano, and the distal lavas have not been mapped in detail, the basal diameter is estimated to be at least 13 km. Dip slopes on the flanks are about 4°, and all profiles, except north–south, are symmetrical. The volcano was constructed at the base of an ancestral escarpment edge of the Colorado Plateau, and the topographic barrier prevented northward flow of the lavas (Ranney 1988). Deep erosion of the summit area of House Mountain produced a large circular valley in which the upper 270 m of the volcanic section are exposed.

The lowest volcanic rocks in the valley are subhorizontal mildly alkaline hawaiitic lava flows (Fig. 2). Overlying these lavas is a thick section of basaltic scoriaceous lapilli tuffs, tuff breccias, and agglomerates that display radially outward dips up to 35°. Cross-section reconstruction of the volcano indicates that the pyroclastic deposits formed a cinder cone. This cone was partly buried by an upper section of outwardly dipping hawaiite, mugearite, benmoreite, and basaltic andesite lava flows that completed the shield (Holm *et al.* 1994). The pyroclastic deposits were extensively eroded to produce the central valley.

After construction of the shield, but before dissection, a large, fine-grained dike of basanitic nephelinite and several smaller ones were intruded into the volcanic section on the north side of the volcano (Fig. 2). One dike of basanitic nephelinite that reached the surface of the shield fed a small lava flow about 110 m long. These mafic dikes host mappable large

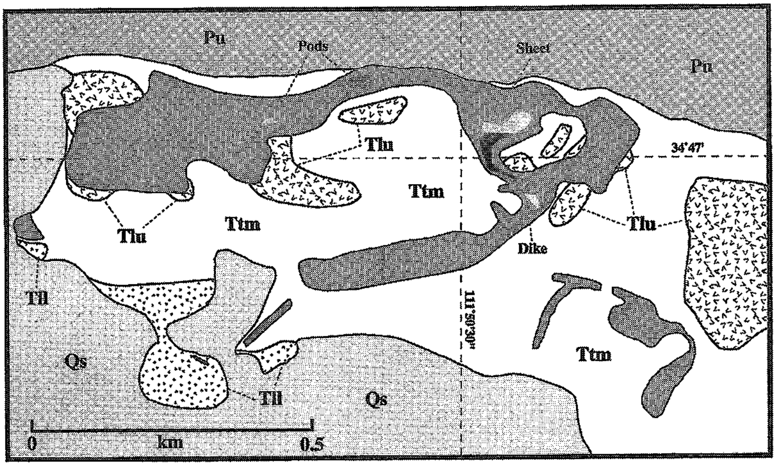

FIG. 2. Simplified geological map of House Mountain summit area. Basanitic nephelinite dikes are shown in dark gray, and the largest bodies of feldspar ijolite and nepheline monzosyenite, in black. The intrusive nature of the basanitic nephelinite is demonstrated by cross-cutting relations. Qs: surficial deposits, Tlu: upper lavas, Ttm: middle tephra unit, Tll: lower lavas, Pu: undifferentiated Permian strata.

bodies of medium- to coarse-grained feldspar ijolite and nepheline monzosyenite, and small dikes, schlieren, and ocelli of the same compositions. The total volume of the nephelinite dikes within the House Mountain shield volcano is about 1.7 × 10^{-2} km^3, and the volume of the felsic rocks is about 1.5 × 10^{-4} km^3.

CLASSIFICATION OF THE ALKALINE SUITE

Lithologic names of the alkaline suite rocks are assigned according to the criteria and nomenclature recommended by the International Union of Geological Sciences (IUGS) for modal classification of igneous rocks (Le Maitre 1989). Modes were determined by counting over 700 points in standard thin sections with a Swift automatic point-counting instrument. Modes (Table 1) were plotted after normalizing the felsic minerals to 100% (Figs. 3a, b).

Because the large mafic dike is aphanitic, the analyzed specimens were plotted on the QAPF diagram for volcanic rocks (Fig. 3b); the modes plot in the feldspar-rich part of the basanitic nephelinite field (Field 15b). The one available chemical analysis of the rock (Table 2, sample 209–1) yields a classification of "olivine melanephelinite" according to the geochemical classification of Le Bas (1989); however, the lithologic name based on the mode, basanitic nephelinite, is used here.

Six specimens of the medium- to coarse-grained felsic rocks contained within the basanitic nephelinite dike were chemically analyzed, and modes of these and five additional samples were determined (Table 1). An additional three modes of ocelli and small felsic dikes hosted by the basanitic nephelinite also were counted. Because these felsic rocks are phaneritic, the modes are shown on the QAPF diagram for plutonic rocks (Fig. 3a); for plotting, analcite was grouped with nepheline as a feldspathoid. All samples plot in the foid monzosyenite and foidolite fields (Fields 12 and 15), and because the principal feldspathoid is nepheline, it is used in place of the term foid. Color indices of the ijolitic rocks between 28.6 and 43.5 (Table 1) indicate that the appropriate lithologic names are urtite and ijolite (Le Maitre 1989).

Ijolites are typically described as feldspar-free rocks (Bailey 1974, Nockolds *et al.* 1978, Williams *et al.* 1982). To emphasize the presence of essential

TABLE 1. MODAL MINERALOGY OF ALKALINE ROCKS, HOUSE MOUNTAIN VOLCANO

	204-1	204-2	204-3	205-1	205-2	205-3	207-1	209-1	210-2	210-5	210-6	210-7	210-9	204-8	204-9	207-2
	ne monz	sy urtite	ne monz	feld ijolite	ne monz	feld ijolite	bas neph	bas neph	ne monz	ne monz	feld ijolite	feld ijolite	feld ijolite	ne monz (ocelli)	ne monz (dike)	ne monz (dike)
N^1	791	772	1255	1262	852	880	1200	956	1309	1061	1463	948	1347	1368	725	710
Olivine	-	-	-	1.0	6.8	2.0	12.9, 7.2^2	16.9, 2.4^2	-	0.1	-	1.1	3.6	0.4	0.5	0.4
Titanaugite	10.5	15.8	12.5	28.1	10.3	33.5	0.1, 55.4^2	0.2, 48.4^2	15.5	10.7	28.2	29.4	28.6	7.0	12.6	4.8
Brown/Green Pyroxene	6.4	7.1	4.4	2.8	0.9	-	-	-	0.5	1.2	3.6	2.5	3.3	-	-	-
Opaque Oxides	6.1	5.7	7.9	4.8	1.4	7.3	3.5	6.3	3.4	4.4	6.1	3.0	4.8	5.3	4.1	5.1
Biotite	tr	-	-	-	tr	-	1.8	2.1	1.3	0.1	-	tr	-	0.4	0.7	1.3
Amphibole	-	-	-	-	-	0.7	-	-	1.5	1.5	-	tr	-	1.0	0.4	0.4
Zeolites	10.1	8.7	12.4	12.4	18.3	7.0	-	-	10.3	10.9	7.2	4.6	4.2	6.0	5.9	11.8
Carbonate	3.5	1.9	1.3	-	3.8	0.8	0.3	0.3	-	-	1.6	-	0.1	tr	0.3	0.3
Apatite	2.1	2.7	1.8	3.5	1.3	3.8	1.2	1.7	3.1	1.7	3.7	3.0	3.0	2.2	1.5	1.1
Nepheline	33.0	37.3	25.4	27.8	15.8	32.2	9.5	8.7	33.5	41.3	32.3	40.6	31.6	9.3	35.4	19.0
Analcite	-	-	tr	1.0	0.5	1.5	2.8	4.7	2.6	-	1.8	-	0.1	27.7	5.9	16.5
Plagioclase	12.7	6.9	14.7	4.2	15.5	4.2	5.3	8.1	11.7	7.8	7.0	5.0	8.7	15.6	6.0	11.9
Anorthoclase	5.1	4.9	5.1	1.6	6.3	1.6	-	-	2.4	4.3	1.4	3.1	4.3	7.7	3.2	9.0
Sanidine	10.4	8.8	14.4	12.8	19.0	5.5	-	-	14.2	16.0	7.2	7.7	7.6	17.4	23.4	18.5
C.I.^{3}	23.0	28.6	24.8	36.7	19.4	43.5	80.9	76.3	22.2	18.0	37.9	36.0	40.3	14.1	18.3	12.0
M	38.7	41.9	40.3	52.6	42.8	55.1	82.1	78.3	35.6	30.6	50.1	43.6	47.6	22.3	26.0	25.2
F	53.9	64.4	42.6	60.8	28.5	74.9	69.9	62.3	56.1	59.5	68.6	72.0	60.6	47.6	55.9	47.4
A	25.3	23.7	32.7	30.4	44.3	15.8	-	-	25.8	29.3	17.3	19.1	22.8	32.3	36.0	36.7
P	20.8	11.9	24.7	8.9	27.1	9.3	30.1	37.7	18.1	11.2	14.1	8.9	16.6	20.1	8.1	15.9

Notes. ne monz = nepheline monzosyenite, sy = syenitic, feld = feldspar, bas neph = basanitic nephelinite, tr = trace; ^{1}N = Number of points counted to determine mode; ^{2} Phenocrysts and groundmass grains, respectively. ^{3} C.I. = Color Index (dark minerals), M = mafic minerals, FAP = IUGS parameters (Fig. 3).

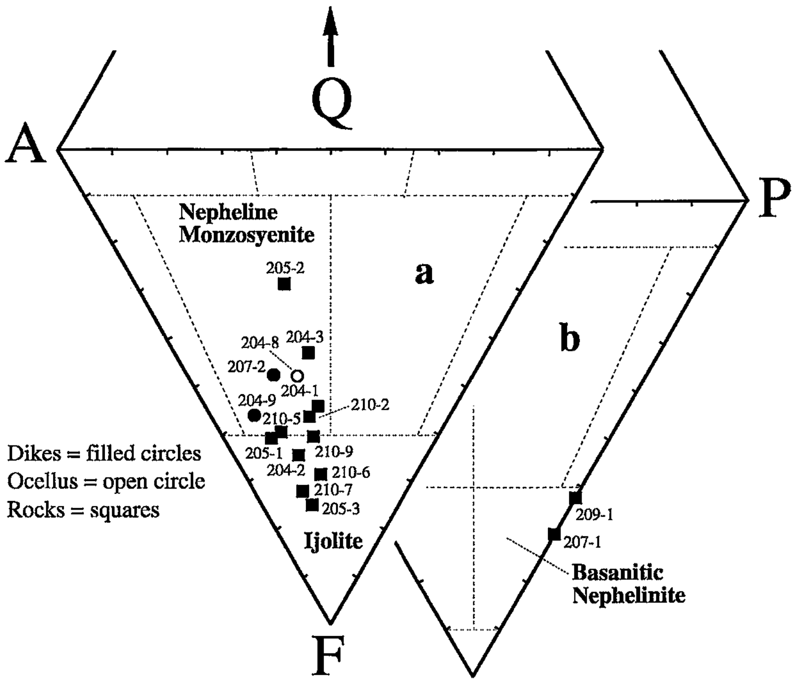

FIG. 3. Modal classification of House Mountain alkaline suite. The plot shows the undersaturated portion of the QAPF diagram with IUGS-approved boundaries (Fig. B10; Le Maitre 1989). a. Phaneritic rocks. Open circle: felsic ocellus, filled circles: small felsic dikes, squares: other felsic rocks. b. Aphanitic intrusive rocks. Filled squares: nephelinitic dike.

TABLE 2. MAJOR- AND TRACE-ELEMENT CHEMISTRY OF ALKALINE ROCKS, HOUSE MOUNTAIN VOLCANO AND CASNER BUTTE

	204-1	204-2	205-1	205-2	205-3	210-7	209-1	MMT-24
	ne monz	sy urtite	feld ijolite	ne monz	feld ijolite	feld ijolite	bas neph	bas neph
SiO_2	43.85	42.42	43.03	44.60	41.28	44.89	43.46	43.50
TiO_2	1.19	1.55	1.83	0.74	1.76	2.08	1.93	1.80
Al_2O_3	19.73	19.01	17.53	18.74	17.78	16.78	11.78	12.65
Fe_2O_3[1]	3.71	3.68	3.55	3.98	3.80	3.37	4.07	3.62
FeO[1]	4.56	5.16	6.14	5.17	5.57	6.25	7.73	6.63
MnO	0.17	0.17	0.18	0.21	0.16	0.15	0.19	–
MgO	2.53	3.06	3.50	2.44	4.13	5.43	13.46	14.57
CaO	6.94	8.77	9.54	6.22	10.22	12.96	12.22	12.13
SrO[2]	0.32	0.40	0.39	0.34	0.26	0.50	0.13	0.13
BaO[2]	0.44	0.37	0.38	0.51	0.27	0.30	0.16	0.13
Na_2O	5.07	5.21	3.19	4.85	5.25	3.61	2.96	3.35
K_2O	4.51	3.24	3.39	4.17	2.87	2.25	1.25	1.23
P_2O_5	0.87	1.13	1.23	0.60	1.38	1.91	0.89	0.89
LOI	5.00	3.88	4.82	5.76	3.11	2.34	0.98	–
Σ wt.%	98.89	98.05	98.70	98.33	97.84	102.82	101.21	100.63
V (ppm)	113	186	263	29	229	274	230	225
Cr	27	8	9	56	9	123	650	714
Co	–	–	–	–	–	29	58	–
Ni	17	29	48	14	33	76	365	366
Cu	–	–	–	–	–	166	86	70
Zn	127	119	121	125	118	83	116	83
Rb	75	48	68	64	40	51	28	24
Sr	2700	3360	3260	2860	2160	4220	1070	1065
Y	24	22	25	18	28	29	21	24
Zr	231	228	257	208	242	254	230	240
Nb	131	95	107	102	89	56	43	83
Ba	3950	3330	3440	4610	2400	2690	1390	1135
Mg[3]	49.7	51.4	50.4	45.7	56.9	60.7	75.6	79.7

Notes. Rock-type abbreviations as in Table 1, – = not analyzed, [1] Fe_2O_3 and FeO calculated according to Le Maitre (1976), [2] SrO and BaO calculated from trace-element concentrations, [3] Mg = molar 100[Mg/(Mg+Fe^{2+})]. Sample MMT-24 from Gust & Arculus (1986).

plagioclase and alkali feldspar in the House Mountain urtites and ijolites, the nomenclature of Sørensen (1974) is adopted, and the rocks are classified as syenitic urtite and feldspar ijolite. For convenience in the discussion, all the specimens will be referred to as feldspar ijolite.

FIELD RELATIONSHIPS OF THE ALKALINE SUITE

All rocks of the alkaline suite are confined to the north part of the House Mountain volcano, where they were intruded into the Paleozoic strata that underlie the volcano, the lower hawaiite lava flows, the scoriaceous tuffs, and the upper section lava flows (Fig. 2). Most of the rocks are basanitic nephelinite, which was intruded as one large complex dike and several smaller dikes. The large dike of basanitic nephelinite is over 1 km long and ranges from 30 to 230 m in thickness. The dike is irregular, but its general strike is east–west, parallel to the strike of several major faults in this part of the Verde Valley (Weir *et al.* 1989). Smaller dikes of basanitic nephelinite have different strikes and shapes (Fig. 2); the smallest dike mapped is 2 m thick.

Contacts of the basanitic nephelinite dikes are sharp, and vertical to steeply dipping. All the dikes are massive, fine-grained, and nonvesicular. The dike rocks are very dark gray to nearly black on fresh surfaces, which readily distinguishes them from the

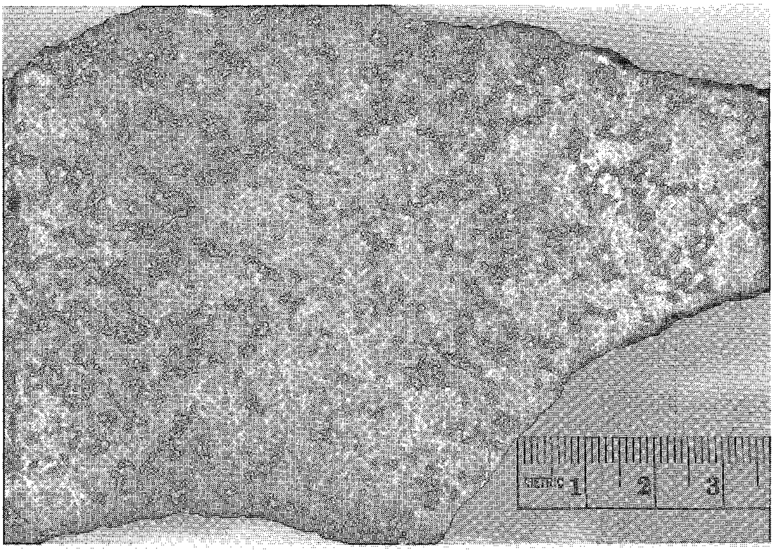

FIG. 4. Hand specimen of basanitic nephelinite containing felsic segregations. Smallest scale divisions are mm.

lighter colored basaltic lavas and dikes of the volcano. Weathered outcrops display reddish olivine phenocrysts in an aphanitic groundmass. Chilled margins are not apparent in the field, but prominent joints normal to the contacts are common in the dikes.

The dikes of basanitic nephelinite host small bodies of feldspar ijolite and nepheline monzosyenite (Fig. 2). These phaneritic rocks were discovered by Ranney (1988), who classified them as essexite and mapped the largest body at 1:24,000 scale. At a larger scale, several bodies of the felsic rocks are mappable (Fig. 2), and detailed examination of outcrops identifies m- to cm-scale pods and dikes, and mm-scale ocelli, schlieren, and irregular patches (Figs. 4, 5). The small schlieren, dikes, pods, and irregular patches occur in most parts of the basanitic nephelinite dikes, but the ocelli have been found only in a zone near the mapped dike of felsic rock, and in the waterwing-shaped dike in the southeast corner of Figure 2.

The largest bodies of feldspar ijolite and nepheline monzosyenite are a vertical dike and a subhorizontal sheet, which are connected by a narrow neck that can be traced by discontinuous outcrops (Fig. 2). The dike is about 15 m thick, and the preserved thickness of the

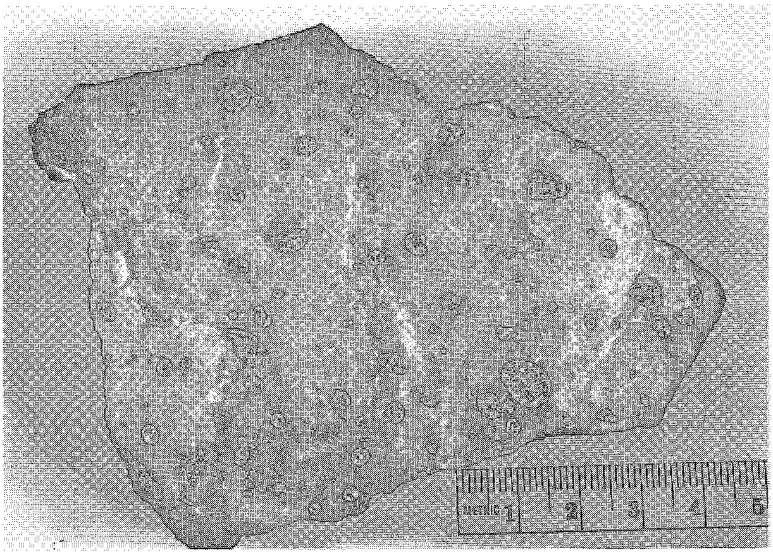

FIG. 5. Hand specimen of basanitic nephelinite containing felsic ocelli.

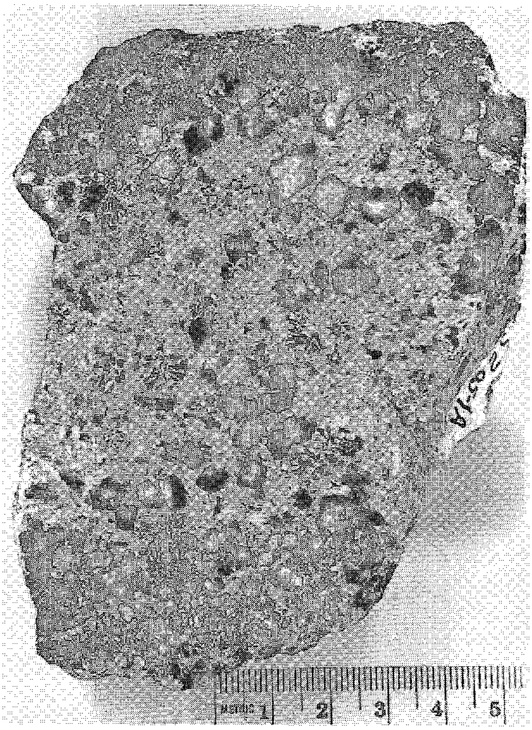

FIG. 6. Hand specimen of nepheline monzosyenite displaying compositional banding. The large dark crystals are clinopyroxene, which also occurs in a graphic-like intergrowth texture with nepheline prominent near the middle of the light-colored band.

sheet, judged to be close to the original thickness, is about 18 m. At contacts with the adjacent basanitic nephelinite, the felsic rocks are medium- to coarse-grained and lack fine-grained or aphanitic textures that could result from chilling. The feldspar ijolites analyzed to date occur in the center of the dike (204–2), and at the bottom and top of the sheet (205–1 and 205–3). The locations of specimens 210–6, 210–7, and 210–9 are not well documented, but they are probably from the sheet. Analyzed specimens of nepheline monzosyenite are from the margin of the dike (204–1, 204–3) and the middle of the sheet (205–2); specimens 210–2 and 210–5 are not documented.

Both the dike and the sheet display internal planar structures. The dike has a coarse-grained interior in vertical contact with a medium-grained margin about 1 m thick. Miarolitic cavities up to 1 cm in diameter in the interior of the dike contain euhedral sanidine and zeolite crystals. The sheet displays subhorizontal compositional banding on a cm scale that resembles rhythmic layering (Fig. 6), and phase variations between the lower, middle, and upper parts are large (compare modes of 205–1 [lower], 205–2 [middle], and 205–3 [upper] in Table 1 and Fig. 3a). Vugs in the sheet are concordant with the banding, up to 43 cm wide and 4.5 cm high, and increase in number and size upward.

Although the felsic rocks are medium- to coarse-grained, with clinopyroxene crystals up to 1 cm in diameter and local nepheline crystals that exceed 2 cm, field relations indicate that the rocks were emplaced near the summit of the volcano, possibly at depths of as little as 30–140 m from the surface, but certainly no deeper than 430 m. These estimates are based on the preserved thicknesses of the upper-section lava flows of the shield, and cross-section reconstructions of the volcano and the ancestral edge of the Colorado Plateau. Upper-section lavas intruded by the dike of basanitic nephelinite are about 30 m thick, and the thickest preserved section (right side of Fig. 2) is 140 m; the base of the thickest section is at approximately the same elevation as the felsic phaneritic rocks. The 430 m maximum depth is the thickness to which the upper section lavas would have piled up before they spilled over onto the surface of the Colorado Plateau, and there is no evidence that this happened.

PETROGRAPHY

Basanitic nephelinite

All basanitic nephelinite dikes and the small lava flow contain identical mineral assemblages and display similar textures; the lava flow differs from the dikes in textural details. In thin sections, the dikes display randomly arranged crystals; however, in the lava flow, olivine and clinopyroxene phenocrysts are flow-oriented, but plagioclase and clinopyroxene crystals in the groundmass are randomly arranged. Abundant phenocrysts of olivine and scattered phenocrysts of clinopyroxene are enclosed by a holocrystalline groundmass of clinopyroxene, nepheline, plagioclase, analcite, opaque oxide, olivine, biotite, and apatite.

Olivine occurs principally as phenocrysts, but small crystals are scattered through the groundmass. Most phenocrysts are euhedral and 0.5 to 2.0 mm long, but some crystals are up to 4.0 mm in length, and a few rare ones display embayments. Small euhedral inclusions of opaque spinel are common. Alteration to iddingsite ranges from incipient to complete. Most clinopyroxene crystals occur as euhedral prisms (0.04 to 0.16 mm) in the groundmass, but scattered euhedral phenocrysts are as large as 1.7 mm. Both phenocryst and groundmass clinopyroxene crystals are tan, and become slightly darker toward the margins of crystals that display color zoning.

Plagioclase in the dikes forms large (up to 2.5 mm) poikilitic grains that enclose the mafic crystals. In contrast, plagioclase in the lava flow occurs as well-formed interstitial microlites, each surrounded by an anhedral mantle of plagioclase that has a noticeably lower index of refraction. Nepheline and analcite (clear, isotropic) also occur as poikilitic grains that enclose the mafic crystals. Small (0.3 mm) subpoikilitic flakes of phlogopite partially enclose groundmass clinopyroxene. Euhedral opaque oxide crystals (0.04 to 0.12 mm), apatite needles, minor carbonate, and possibly local alkali feldspar ($2V_\alpha$ 20–30°) complete the assemblage.

Feldspar ijolite and nepheline monzosyenite

Medium- to coarse-grained ijolitic and monzosyenitic rocks have identical assemblages of essential minerals: clinopyroxene, nepheline, alkali feldspar, plagioclase, and opaque oxide (Table 1). However, the rocks seem very heterogeneous on the outcrop and hand-specimen scales because of significant variations in the proportions and distributions of these essential minerals, the presence or absence of minor phases such as olivine, yellowish brown clinopyroxene, biotite, brown amphibole, and analcite, abrupt changes in grain sizes, and other differences in textures. Zeolites occur in all specimens examined, and carbonate is found in most (Table 1); these minerals appear to be post-magmatic hydrothermal phases. Apatite, both as stout prisms and needles, is ubiquitous. Most specimens display a hypidiomorphic-granular texture and evidence for a volatile phase; miarolitic cavities (up to 15 mm across) may be open or filled with sanidine, zeolites, and carbonate, and zeolite-rich interstitial areas occur throughout the specimens (Fig. 7).

Variations in grain size and proportions of the felsic and mafic minerals in the sheet create heterogeneities that range from conspicuous cm-scale subhorizontal banding (Fig. 6) to subtle layering that may exist through the entire sheet, but that is poorly defined at present, with only three specimens. Specimen 205–1, collected near the bottom of the sheet, is one of the coarsest specimens. It has clinopyroxene crystals over 5 mm and nepheline crystals almost 25 mm in diameter. Specimen 205–3, from the top of the sheet, is the most mafic rock and one of the finest-grained specimens. It contains the same minerals, with respective sizes around 1 mm and 4 mm. Sample 205–2, from the middle of the sheet and richest in feldspar and zeolite, is also richest in olivine, with skeletal crystals over 3 cm long. Although the rocks seem heterogeneous, some regularities are evident; the color index (volume percent of dark minerals) and total nepheline display a positive correlation (Table 1), and the ratio of alkali feldspar to plagioclase remains constant with decrease in nepheline and color index (Fig. 3, Table 1).

Essential minerals that typically display euhedral to subhedral shapes as large crystals (>1 mm) are violet-tan clinopyroxene, nepheline, calcic plagioclase, and opaque oxide. Other common textural relationships include coarse radiate and graphic-like intergrowths of nepheline and clinopyroxene (Fig. 6) and nepheline and feldspar, large skeletal crystals of olivine intergrown with plagioclase and nepheline, and skeletal opaque oxide crystals up to 4 mm in diameter. Locally, large crystals of nepheline enclose several diversely oriented crystals of clinopyroxene and oxide in a poikilitic texture. Nepheline intergrown with clinopyroxene contains many small needles of apatite; other nepheline crystals lack the apatite needles, and other apatite crystals are long (some >5 mm), stout to slender prisms.

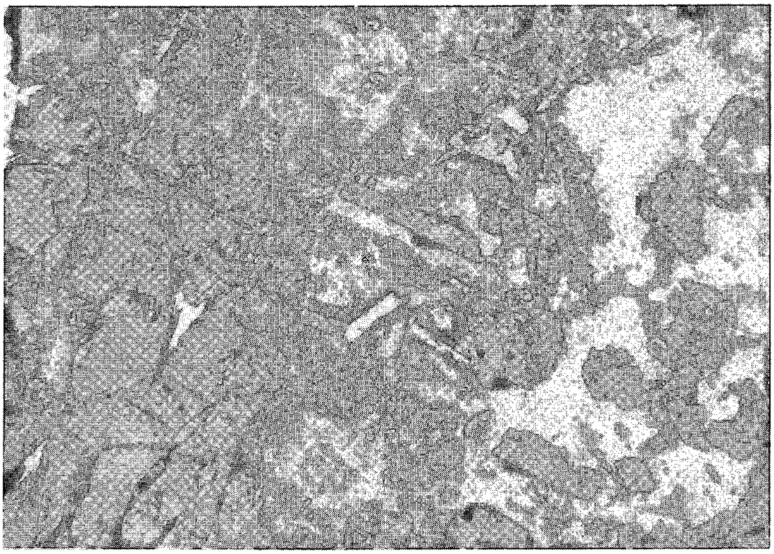

FIG. 7. Photomicrograph of a filled miarolitic cavity (center of photo) in nepheline monzosyenite. The large medium gray crystal on the left is nepheline. The cavity is filled with euhedral crystals of sanidine, the largest of which displays a Carlsbad twin, which are surrounded by zeolite crystals. Width of field of view is 8 mm. Crossed-polarized light.

Alkali feldspar is late magmatic to hydrothermal in the paragenesis. Anorthoclase (optical tartan twins) occurs as a broad mantle on plagioclase crystals. Low sanidine (identified by optics) is one of the latest magmatic phases, and it may have continued to crystallize into the hydrothermal stage. Sanidine occurs as a mantle on anorthoclase, as anhedral crystals interstitial to the early phases, and as euhedral crystals (many >2 mm) in miarolitic cavities, where it is typically associated with zeolites (Fig. 7). Carbonate, common in the miarolitic cavities, also could be a hydrothermal-stage phase.

In thin section, violet-tan clinopyroxene crystals locally may have a green margin, particularly next to interstitial areas. Deep yellow to yellowish brown clinopyroxene occurs as a thin abrupt rim on violet-tan clinopyroxene crystals and locally as small discrete crystals. Varne (1988) described identical textures in Ugandan ijolites, where euhedral titanaugite cores grade outward to an aegirine-augite rim, commonly culminating in a narrow rim of aegirine; however, Varne's description is petrographic, and he did not present microprobe data.

Biotite typically occurs as a minor reaction phase on opaque oxide. Brown amphibole forms small discrete crystals and a minor reaction rim on clinopyroxene in a few specimens. In general, the rocks are very fresh, and display only local alteration of olivine to iddingsite and of nepheline to zeolite.

Small felsic segregations

Felsic segregations in the nephelinitic dikes range from small wispy patches (~1 mm; Fig. 4) to sharply defined ocelli (0.5 mm to 4 cm; Figs. 5, 8), schlieren (around 0.2 to 1 mm wide), and small dikes (0.5 cm to 2 cm wide; Fig. 9). These segregations are readily distinguished from their host rocks by coarser grain-size and lower color-index. Segregations have not been observed in the nephelinitic lava flow, but they do occur in its feeder dike.

The small felsic segregations have similar assemblages of mafic minerals as their nephelinitic hosts, but with the addition of amphibole. Essential alkali feldspar, increased feldspathoid and plagioclase, and conspicuous zeolites, however, distinguish the segregations (Fig. 3, Table 1). The position of analcite in the paragenesis appears to range from primary magmatic to hydrothermal; its abundance is highly variable among different dikes and ocelli, and textures suggest that much of it formed hydrothermally by replacement of magmatic nepheline and feldspar.

The small segregations typically display a hypidiomorphic-granular texture (Fig. 9). Euhedral crystals of nepheline and clinopyroxene (commonly 1 to 2 mm) imply that these phases are early in the paragenesis; rarely, they are graphically intergrown. Clinopyroxene is violet-tan, and grades to a greenish margin where color-zoned. Plagioclase (andesine by extinction angles) forms tabular crystals surrounded by euhedral to anhedral mantles of anorthoclase that crystallized interstitially to the nepheline and clinopyroxene. Sanidine (low sanidine by orientation of optic plane) is anhedral where it formed interstitially to early phases, but is euhedral in association with zeolite crystals where these minerals appear to have crystallized late in miarolitic cavities or vapor-rich interstitial areas. Analcite occurs as anhedral crystals that commonly display replacement textures along boundaries with nepheline and feldspar. Brown amphibole occurs as

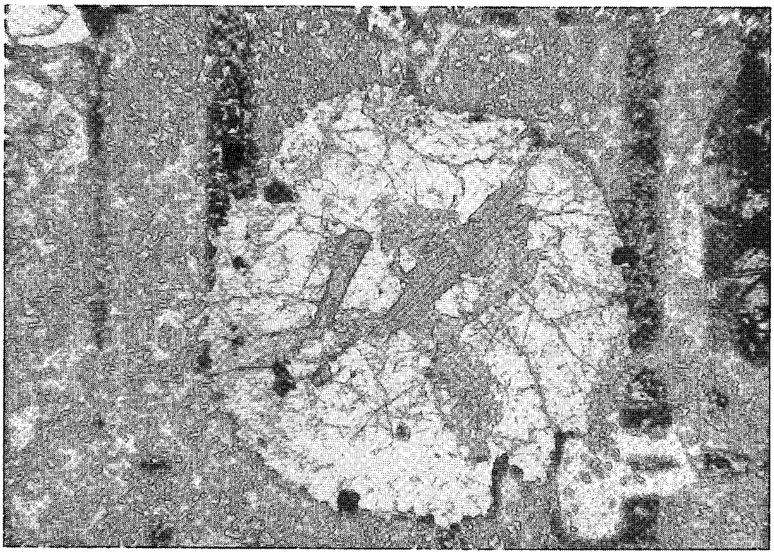

FIG. 8. Photomicrograph of felsic ocellus in host basanitic nephelinite. The higher-relief crystals in the ocellus are biotite (right) and clinopyroxene (left). Ocellus is 1.3 mm wide. Plane-polarized light.

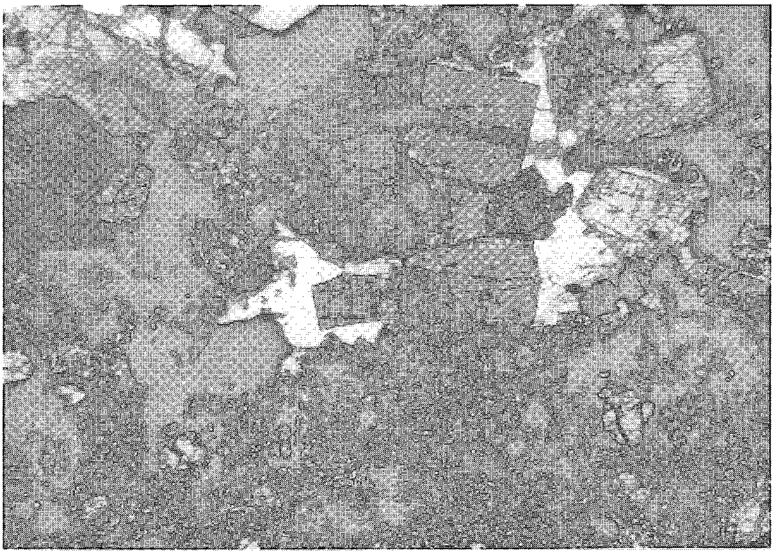

FIG. 9. Photomicrograph of small nepheline monzosyenite dike (top half of photo) in contact with host basanitic nephelinite. Euhedral crystals of nepheline in the dike are partly surrounded by interstitial alkali feldspar. Total thickness of dike is 7 mm. Width of field of view is 8 mm. Crossed-polarized light.

small discrete crystals and as a reaction rim on clinopyroxene. The intimate association of carbonate and zeolite is interpreted to constitute a hydrothermal assemblage.

MINERAL CHEMISTRY

Mineral chemistry of the major magmatic phases in the House Mountain rocks was determined by electron-microprobe analysis using an ETEC Autoprobe equipped with Krisel automation at Northern Arizona University. All analyses were performed using an accelerating voltage of 15 keV and sample currents of 10–30 nA. Calibration was performed using natural and synthetic mineral standards provided by the Smithsonian Institution and the C.M. Taylor Corporation.

Olivine

Olivine in the nephelinite is magnesian (Table 3, samples 207–1, 209–1), with a core uniformly Fo_{85-86} and a rim, Fo_{65-77}. Groundmass olivine in the nephelinite has a composition similar to the most mafic rim on the phenocrysts (Fo_{76}). Olivine cores equilibrated with the host rock composition at about 1350°C (Roeder & Emslie 1970). The variation in Ca content from core (0.20 ± 0.06% CaO) to rim (0.40 ± 0.06% CaO) is consistent with crystallization of the cores at a higher pressure than the rims, and the increase in Mn and decrease in Ni from core (0.22 ± 0.03% MnO, 0.27 ± 0.07% NiO) to rim (0.47 ± 0.18% MnO, 0.16 ± 0.04% NiO) is consistent with fractional crystallization (Brown 1982). Contents of Ni in the core (~2100 ppm) are consistent with derivation of the basanitic nephelinite by direct melting of mantle peridotite.

Most of the olivine in the ijolite and monzosyenite is altered. However, there are small fresh patches within

TABLE 3. REPRESENTATIVE COMPOSITIONS OF OLIVINE, HOUSE MOUNTAIN ALKALINE SUITE

	205-2	207-1 core	207-1 rim	209-1 core	209-1 rim
SiO_2	32.3	40.4	37.2	40.0	37.6
FeO	55.3	14.5	30.4	14.1	27.4
MnO	1.68	0.20	0.77	0.27	0.72
NiO	-	0.36	0.13	0.19	0.13
MgO	9.57	45.8	32.9	45.0	34.4
CaO	1.09	0.14	0.36	0.32	0.38
Σ wt.%	100.0	101.4	101.8	99.9	100.6
Structural formulae on the basis of 4 (O)					
Si	1.012	0.999	0.992	1.002	0.999
Fe	1.447	0.300	0.678	0.296	0.609
Mn	0.045	0.004	0.017	0.006	0.016
Ni	-	0.007	0.003	0.004	0.003
Mg	0.447	1.688	1.308	1.681	1.363
Ca	0.037	0.004	0.010	0.009	0.011
Σ cations	2.988	3.002	3.008	2.998	3.001
Fo	22.6	84.6	65.0	84.4	68.2
Fa	73.3	15.0	33.7	14.8	30.5
La	1.9	0.2	0.5	0.4	0.5
Te	2.3	0.2	0.9	0.3	0.8

Notes. Monzosyenite: 205-2; nephelinite: 207-1, 209-1.

the skeletal crystals in the middle of the sheet (Table 3, sample 205–2). Olivine elsewhere in the sheet is unanalyzable; its pervasive alteration may indicate that it was more magnesian. Olivine in 205–2 is fayalitic ($Fa_{67–78}$) with high larnite and tephroite components ($1.01 < CaO < 1.28\%$, $1.56 < MnO < 1.93\%$), consistent with formation at hypabyssal depths (Brown 1982).

Clinopyroxene

The composition of the clinopyroxene in the basanitic nephelinite is fairly restricted; most grains are $Wo_{48–52}Fs_{8–14}En_{36–44}$ (Table 4, samples 207–1, 209–1; Figs. 10, 11). The most En-rich cores are more magnesian than the most En-rich clinopyroxene in the phaneritic rocks. The optical zoning is produced by variations in Ti and Al over the range of 0.73–3.31% TiO_2 and 3.19–10.3% Al_2O_3. Na contents are more uniform, with a range from 0.25 to 0.56%, averaging 0.33 ± 0.11% Na_2O. The clinopyroxene in 207–1 is generally more magnesian than that analyzed in 209–1, consistent with its slightly more mafic mode (Table 1). Several of the groundmass grains in 209–1 are significantly displaced toward higher Fs (17–25) and Hd (30–39) contents, along the trend observed in the phaneritic rocks (Figs. 10, 11).

The clinopyroxene in the ijolite and monzosyenite has wide compositional variability (Table 4, Figs. 10, 11). The composition of the most magnesian cores ($1.41 < TiO_2 < 3.55\%$, $4.73 < Al_2O_3 < 11.6\%$ and $0.48 < Na_2O < 1.16\%$) overlaps that of clinopyroxene from the basanitic nephelinite (Figs. 10, 11). Core–rim relationships are systematic and uniform throughout: the rim is depleted in Mg, Ca, Ti and Al, and enriched in Si, Na and Fe relative to the core (Table 4). The strongly colored yellowish brown rim in the phaneritic rocks is characterized by relatively high Hd; it consistently has higher Fe and Na, and lower Mg, Al and Ti than the titanaugite core. The sharp optical zoning does not correspond with any abrupt chemical changes.

Cores in 205–3, from the top of the sheet, have a relatively restricted compositional range ($Wo_{48–53}Fs_{14–18}En_{30–35}$), similar to that in clinopyroxene in the nephelinite, and a slightly Fe-enriched

TABLE 4. REPRESENTATIVE COMPOSITIONS OF CLINOPYROXENE, HOUSE MOUNTAIN ALKALINE SUITE

	204-1 TiA-c	204-1 TiA-r	204-2 TiA-c	204-2 BR-c	204-2 BR-r	205-2 TiA-c	205-2 TiA-r	205-2 GR	205-3 TiA-c	205-3 TiA-R	207-1 GM	209-1 GM
SiO_2	49.1	50.0	45.3	47.4	48.2	48.7	48.6	47.8	44.2	48.8	43.5	42.5
TiO_2	1.51	0.59	3.26	2.14	1.35	1.62	0.71	0.63	3.01	1.04	2.80	3.31
Al_2O_3	5.45	1.61	9.54	7.22	3.83	5.06	1.59	1.39	10.4	3.70	9.65	10.3
Fe_2O_3	3.38	3.82	3.18	1.80	2.56	0.48	2.42	1.68	3.72	3.21	7.89	8.86
FeO	5.64	15.2	5.04	9.18	14.9	10.9	18.4	22.9	4.75	11.0	0.46	0.77
MnO	0.17	0.52	0.18	0.28	0.40	0.20	0.47	0.54	0.17	0.39	0.08	0.15
MgO	12.1	6.91	11.5	10.4	7.44	9.87	4.88	2.20	10.5	9.32	12.3	12.0
CaO	23.2	21.6	22.5	22.0	21.5	22.2	21.1	20.2	23.0	22.2	23.0	23.6
Na_2O	0.64	1.00	0.55	0.52	0.59	0.54	0.89	0.95	0.53	0.61	0.56	0.27
Σ wt.%	101.2	101.2	101.0	100.9	100.8	99.5	99.1	98.3	100.3	100.3	100.2	101.8
Structural formulae on the basis of 4 cations												
Si	1.815	1.928	1.677	1.774	1.864	1.853	1.939	1.959	1.653	1.863	1.620	1.570
Ti	0.042	0.017	0.091	0.060	0.039	0.046	0.021	0.019	0.085	0.030	0.078	0.092
Al	0.237	0.073	0.416	0.318	0.211	0.227	0.075	0.067	0.460	0.167	0.423	0.449
Fe^{3+}	0.094	0.111	0.089	0.051	0.030	0.014	0.073	0.052	0.105	0.092	0.221	0.246
Fe^{2+}	0.174	0.489	0.156	0.287	0.421	0.347	0.613	0.786	0.148	0.352	0.014	0.024
Mn	0.005	0.397	0.006	0.009	0.013	0.006	0.016	0.019	0.005	0.013	0.003	0.005
Mg	0.667	0.017	0.635	0.580	0.501	0.560	0.290	0.134	0.585	0.531	0.683	0.661
Ca	0.919	0.893	0.892	0.882	0.874	0.906	0.903	0.887	0.921	0.908	0.918	0.934
Na	0.046	0.075	0.039	0.038	0.047	0.040	0.069	0.076	0.038	0.045	0.040	0.019
Wo	49.6	47.2	50.4	49.0	47.5	49.6	48.1	47.7	52.4	482	50.0	50.1
Fs	14.5	31.7	13.8	18.8	29.7	19.7	36.5	45.1	14.4	23.6	12.8	14.5
En	36.0	21.0	35.8	32.2	22.9	30.7	15.4	7.2	33.3	28.2	37.2	35.4
Ae	4.9	7.5	4.5	4.1	4.5	4.3	7.1	7.8	4.6	4.6	4.4	2.1
Hd	23.8	52.7	23.3	32.7	52.0	34.8	63.2	78.4	25.6	40.9	21.2	26.9
Di	71.3	39.8	72.2	63.2	43.5	60.8	29.7	13.8	69.8	54.4	74.4	71.0

Notes. Ijolite: 204-2, 205-3; monzosyenite: 204-1, 205-2; nephelinite: 207-1, 209-1; TiA = Titanaugite, BR = Brown Rim, GM = Groundmass, GR = Green Rim, -c = core, -r = rim; Fe^{3+}/Fe^{2+} calculated by charge balance.

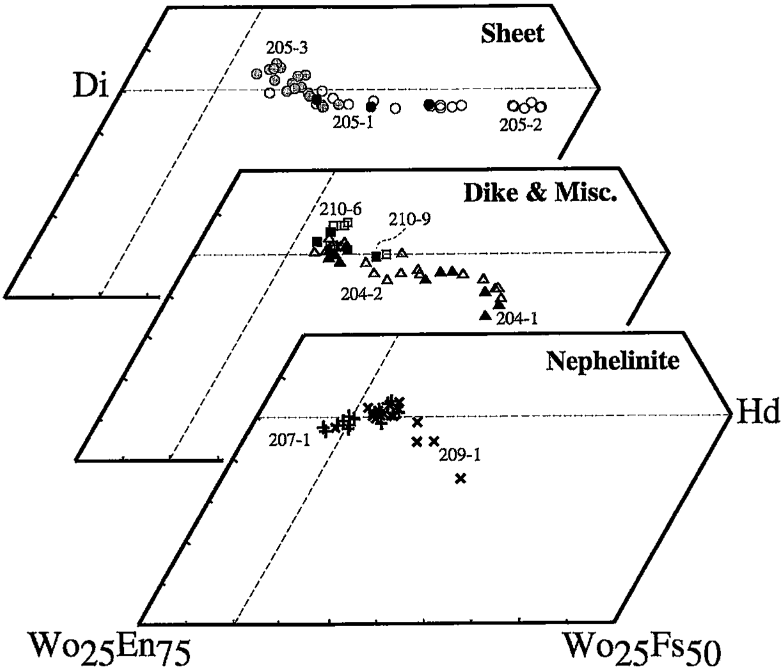

FIG. 10. Composition of clinopyroxene projected onto the plane Wo–Fs–En. Clinopyroxene compositions from the phaneritic sheet (top) and dike (middle) show strong Fe-enrichment trends. Compositions of the clinopyroxene from the nephelinite (bottom) show evidence of differentiation, with the most Fe-rich compositions overlapping those in the phaneritic rocks. Core–rim pairs (tie lines omitted for clarity) show consistent Fe enrichment in the rims.

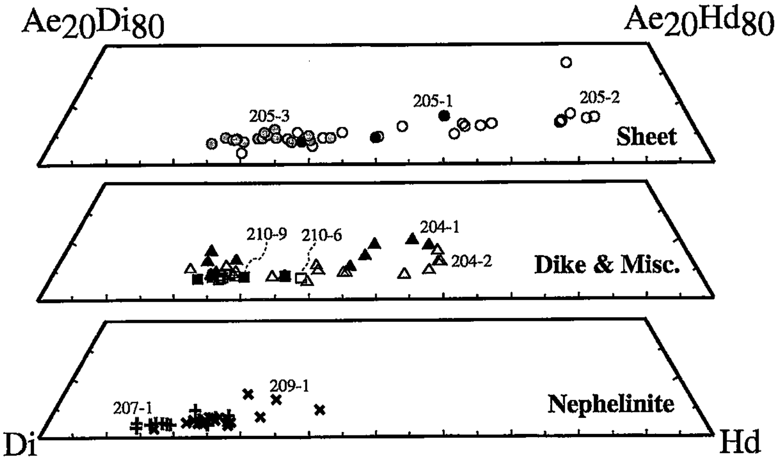

FIG. 11. Composition of clinopyroxene projected onto the plane Ae–Hd–Di. Clinopyroxene trends at House Mountain, although displaying marked Fe-enrichment, do not show commensurate Na enrichment. Compositions of the most evolved clinopyroxene in the nephelinite (bottom) overlap those from the phaneritic sheet (top) and dike (middle). Traverses across individual grains of pyroxene show consistent Fe enrichment from core to rim (tie lines omitted for clarity).

rim ($Wo_{48-52}Fs_{20-24}En_{28-31}$). In contrast, pyroxene in 205–2, from the central part of the sheet, shows the widest variability (Figs. 10, 11). Lilac-colored titanaugite cores are $Wo_{48-50}Fs_{15-27}En_{29-34}$, rims are $Wo_{48}Fs_{21-42}En_{10-31}$, and the brown-green outer rims are $Wo_{48}Fs_{37-45}En_{7-15}$. These trends are paralleled by a monotonic decrease in Mg, Al, and Ti, and increase in Fe, Na, and Si, from core to rim. Sample 205–1, at the base of the sheet, has pyroxene of intermediate composition (Figs. 10, 11), but displays consistent Fe-enrichment from core to rim. Pyroxene in samples from the large phaneritic dike (204–1, 204–2) show less extreme compositional variability, but trends similar to those in the sheet samples.

Feldspar

The overall range of feldspar compositions observed in the nephelinite is An_{26-60}; the crystals are moderately Ba-rich (Table 5, sample 207–1). The plagioclase in the ijolite and monzosyenite is An_{20-55}, compositionally comparable to its counterpart in the nephelinite, but it generally displays lower Ba contents (Fig. 12). Intermediate feldspar compositions in the nephelinite are displaced further from the Ab apex than their counterparts in the monzosyenite and ijolite. The monzosyenites are dominated by sanidine (Or_{30-80}). Sanidine with more than 60 mol.% Or is Ca- and Ba-poor (Cn and An < 2 mol.%). In contrast, feldspar in the interval Or_{40-60} typically has >10 mol.% Cn, with the highest Cn content approximately 30 mol.% (BaO ≈ 10%), a composition that should be termed hyalophane. A similar enrichment of Ba in mid-range sanidine has been reported from potassic rocks (*e.g.*, Zhang *et al.* 1993).

Nepheline

The nepheline in the House Mountain rocks has a very restricted range of composition (Table 6: $Ne_{78-82}Ks_{13-17}Qtz_{2-9}$, molar). All contain moderate amounts of Ca and Fe (2.28% < CaO < 4.26%, 0.32% < Fe_2O_3 < 0.68%), with crystals in the nephelinite generally richest in both elements. Nepheline compositions are slightly more sodic than the Morozewicz–Buerger composition typical of plutonic rocks ($Ne_{74.6}Ks_{20.5}Qtz_{4.9}$, molar). Edgar (1984) noted that the exchange of alkalis with an aqueous vapor will reset nepheline to apparently lower temperatures of formation (lower Ks and Qtz). Such exchange seems likely to have occurred in the House Mountain rocks.

TABLE 5. REPRESENTATIVE COMPOSITIONS OF FELDSPAR, HOUSE MOUNTAIN ALKALINE SUITE

	204-1 Sa	204-1 Hy	204-1 Pl	204-2 Sa	204-2 Hy	204-3 Hy	204-3 Pl	204-3 Sa	205-1 Hy	205-1 Sa	205-1 Pl	205-2 Sa	205-2 Pl	205-3 Hy	205-3 Sa	207-1 Pl	207-1 Pl
SiO_2	65.1	55.7	52.4	64.6	58.7	56.3	59.4	66.9	52.8	65.7	54.4	66.0	56.8	59.2	65.2	56.0	51.6
Al_2O_3	19.8	23.0	30.7	19.6	21.8	23.4	25.0	19.2	23.2	19.6	28.3	19.2	27.8	23.4	19.6	27.3	31.1
FeO*	0.13	0.24	0.34	0.13	0.09	0.23	0.28	0.26	0.26	0.13	0.24	0.11	0.23	0.24	0.07	0.34	0.44
CaO	0.24	1.39	11.5	nd	0.99	1.05	4.58	nd	1.14	0.40	8.57	0.12	7.51	1.20	nd	7.76	11.6
BaO	0.55	9.18	0.69	nd	5.94	9.76	1.49	nd	14.8	nd	1.61	nd	0.57	6.55	nd	1.28	0.65
Na_2O	3.65	3.73	3.86	3.05	4.42	3.72	6.87	4.61	3.20	3.28	4.84	2.71	5.28	3.91	2.43	5.70	3.84
K_2O	11.7	6.24	0.34	13.0	7.11	5.85	1.16	10.1	5.43	11.9	0.72	12.3	0.65	5.87	13.0	0.68	0.41
Σ wt.%	101.2	99.5	99.8	100.4	99.0	100.3	98.8	101.1	100.8	101.0	98.7	100.4	98.8	100.4	100.3	99.1	98.6
Structural formulae on the basis of 8 (O)																	
Si	2.946	2.702	2.383	2.950	2.792	2.706	2.698	2.992	2.633	2.963	2.501	2.989	2.571	2.763	2.968	2.555	2.380
Al	1.056	1.315	1.646	1.055	1.222	1.326	1.338	1.012	1.364	1.042	1.534	1.025	1.483	1.287	1.051	1.468	1.636
Fe	0.005	0.010	0.013	0.005	0.004	0.009	0.011	0.010	0.011	0.005	0.009	0.004	0.009	0.009	0.003	0.013	0.017
Ca	0.012	0.072	0.560	-	0.050	0.054	0.223	-	0.061	0.019	0.422	0.006	0.364	0.060	-	0.379	0.573
Ba	0.010	0.174	0.012	-	0.111	0.184	0.027	-	0.289	-	0.029	-	0.010	0.120	-	0.023	0.012
Na	0.320	0.351	0.340	0.270	0.408	0.347	0.605	0.400	0.309	0.287	0.431	0.238	0.463	0.359	0.214	0.504	0.343
K	0.675	0.386	0.020	0.757	0.432	0.359	0.067	0.576	0.345	0.685	0.042	0.711	0.038	0.349	0.755	0.040	0.024
Σ cations	5.024	5.010	4.974	5.037	5.019	4.984	4.969	4.990	5.013	5.001	4.969	4.973	4.938	4.948	4.991	4.983	4.986
Or	67.2	42.4	5.3	73.7	45.4	40.3	9.6	59.0	34.4	69.1	4.6	74.5	4.3	39.3	77.9	4.2	2.5
Cn	1.0	17.7	1.3	-	11.1	19.5	2.9	-	28.8	-	3.1	-	1.2	13.5	-	2.4	1.2
Ab	31.5	35.7	36.5	-	40.8	36.8	65.6	41.0	30.8	28.9	46.7	24.9	52.9	40.4	22.1	53.3	36.1
An	1.1	7.3	60.1	26.3	5.0	5.7	24.2	-	6.1	2.0	45.6	0.6	41.6	6.8	-	40.1	60.2

Notes. Ijolite: 204-2, 205-1, 205-3; monzosyenite: 204-1, 204-3, 205-2; nephelinite: 207-1; Hy = hyalophane, Sa = sanidine, Pl = plagioclase.

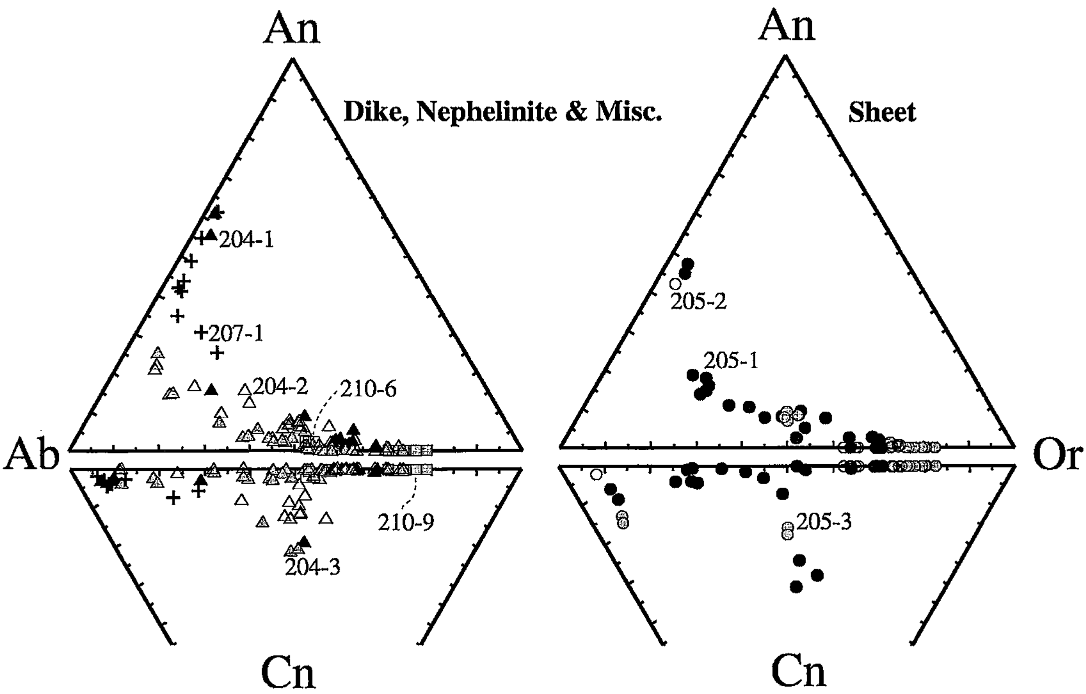

FIG. 12. Feldspar compositions. The upper triangle shows the plane An–Or–Ab and ignores Cn, whereas the lower triangle ignores An. Sanidine with higher Or contents occurs in samples with higher color index. Strong Ba enrichment is observed in about half of the feldspar compositions in the range Or_{40-50}. These features are consistent with early fractionation of potassium feldspar that decreases K and increases Na and Ba contents in the residual liquid. Plagioclase compositions from the nephelinite (left: crosses) and ijolites and monzosyenites (left: triangles, squares) overlap.

Biotite and amphibole

Mica in the nephelinite is titaniferous phlogopite ($6.40 < TiO_2 < 8.93\%$) with *mg* [100Mg/(Mg + Fe)] in the range 69–77 (Table 7). Amphibole in the ijolites is edenitic hornblende, marked by high Na and K contents ($2.55 < Na_2O < 3.13\%$, $1.41 < K_2O < 1.75\%$). Amphibole in 205–3 is less magnesian than 210–5 (*mg* ≈ 50 *versus* 63), despite the significantly higher color-index of the rock sample (Table 1).

WHOLE-ROCK GEOCHEMISTRY

Chemical compositions obtained by X-ray fluorescence analysis are available for six samples of feldspar ijolite and nepheline monzosyenite, and one of basanitic nephelinite from House Mountain; a composition of the basanitic nephelinite at Casner Butte is provided for comparison (Table 2; MMT–24 from Gust & Arculus 1986). The proportions of ferric to ferrous iron in the samples were calculated using the IUGS-recommended method of Le Maitre (1976).

Le Bas (1987) recognized two groups of nephelinites worldwide, with distinctive mineralogy and geological associations. A Group-I nephelinite is dominated by olivine phenocrysts, has lilac Ti-rich clinopyroxene, is commonly associated with alkali basalt, and commonly carries mantle xenoliths. In contrast, a Group-II nephelinite carries Ti-poor clinopyroxene and rare olivine phenocrysts, is associated with carbonatite and ijolite, and generally lacks mantle xenoliths. Chemically, a Group-I nephelinite has a high level of Mg (averaging 12.8 ± 1.8% MgO) and high *mg* of about 74, reflecting low degrees of fractionation. In contrast, Group-II nephelinites are more fractionated (8.1 ± 2.0% MgO, *mg* ≈ 67). The House Mountain nephelinite contains 13.46% MgO and has an *mg* value of 75. However, the House Mountain nephelinite is unusual for Group-I rocks because it is associated with ijolite and lacks mantle xenoliths. Because the House Mountain basanitic nephelinite has essential plagioclase, it may not be directly comparable with nephelinites *sensu stricto.*

Trace-element concentrations in the House Mountain nephelinite also are similar to Group-I nephelinites. Abundances of compatible [Ni, V, Cr,

TABLE 6. REPRESENTATIVE COMPOSITIONS OF NEPHELINE, HOUSE MOUNTAIN ALKALINE SUITE

	204-1	204-2	204-3	205-1	205-3	207-1	209-1
SiO_2	44.3	43.3	45.7	42.1	43.6	43.8	44.8
Al_2O_3	35.0	34.6	32.8	34.7	35.5	33.7	33.8
Fe_2O_3	0.42	0.40	0.64	0.49	0.53	0.67	0.41
CaO	2.25	1.31	0.91	0.97	1.26	3.66	3.51
Na_2O	14.8	15.8	16.6	15.8	15.3	14.1	14.2
K_2O	4.07	4.58	4.23	5.09	4.75	4.26	3.52
Σ wt.%	100.8	100.0	100.9	99.2	100.9	100.2	100.2
Structural formulae on the basis of 32 (O)							
Si	8.324	8.254	8.609	8.130	8.228	8.318	8.453
Al	7.751	7.774	7.282	7.898	7.896	7.543	7.517
Fe^{3+}	0.059	0.057	0.091	0.079	0.076	0.096	0.065
Ca	0.453	0.268	0.184	0.201	0.255	0.867	0.710
Na	5.392	5.840	6.063	5.916	5.598	5.192	5.195
K	0.976	1.114	1.017	1.254	1.144	0.887	0.847
Σ cations	22.955	23.307	23.246	23.487	23.197	22.903	22.787
Ne[1]	80.6	81.0	78.9	81.0	80.3	81.2	80.0
Ks	14.6	15.5	13.2	17.2	16.4	13.9	13.0
Qtz	4.8	3.5	7.9	1.8	3.3	5.0	7.0

Notes. Ijolite: 204-2, 205-1, 205-3; monzosyenite: 204-1, 204-3; nephelinite: 207-1, 209-1; [1]Ne, Ks, and Qtz calculated on a molecular basis.

TABLE 7. REPRESENTATIVE COMPOSITIONS OF PHLOGOPITE AND AMPHIBOLE, HOUSE MOUNTAIN ALKALINE SUITE

	207-1 Phlogopite	209-1 Phlogopite	205-3 Amphibole	210-5 Amphibole
SiO_2	38.3	37.3	43.1	43.6
TiO_2	7.52	6.92	2.05	2.16
Al_2O_3	14.2	15.4	9.26	9.29
FeO*	11.1	10.5	17.8	13.7
MnO	0.10	0.08	0.42	0.39
MgO	15.8	16.2	10.1	12.9
CaO	0.05	0.14	11.2	11.4
Na_2O	0.52	0.31	2.55	2.90
K_2O	9.55	9.49	1.68	1.55
H_2O calc.	4.16	4.14	1.97	2.01
Σ wt.%	101.3	100.5	100.1	99.9
Structural formulae on the basis of 22 & 23 (O)				
Si	5.522	5.408	6.543	6.516
Ti	0.812	0.755	0.234	0.243
Al	2.413	2.632	1.657	1.636
Fe	1.338	1.273	2.260	1.712
Mn	0.012	0.010	0.054	0.049
Mg	3.396	3.502	2.286	2.874
Ca	0.008	0.022	1.822	1.825
Na	0.145	0.087	0.751	0.840
K	1.757	1.755	0.325	0.296
(K+Na)	1.902	1.842	1.076	1.036
Mg[1]	71.7	73.3	50.3	62.7

Notes. Ijolite: 205-3; monzosyenite: 210-5; nephelinite: 207-1, 209-1; [1]Mg = molar 100[Mg/(Mg+Fe)]; H_2O calculated on the basis of 4 & 2 (OH).

Co] and large-ion lithophile trace elements [*LILE*: K, Rb, Sr, Ba, Pb] are comparable to those in Group-I nephelinites; only the concentrations of Ba and Pb are high in the House Mountain nephelinite, a characteristic shared by other alkaline rocks of the Arizona Transition Zone (Wittke *et al.* 1989). The concentrations of high-field-strength elements [*HFSE*: Zr, Nb, Ti, P, Y] are likewise comparable. The high compatible-element concentrations, coupled with an OIB-like normalized multi-element pattern (Thompson *et al.* 1984), ε_{Nd} of –1.4, and $^{87}Sr/^{86}Sr$ (initial) of 0.7049 (L.D. Nealey, written comm., 1993) indicates that the House Mountain basanitic nephelinite potentially represents a primary mantle-derived magma.

Several rocks with compositions similar to the House Mountain basanitic nephelinite have been reported elsewhere in the Transition Zone. Gust & Arculus (1986) reported a single composition from Casner Butte that is essentially identical in major- and trace-element geochemistry to the nephelinite dike at House Mountain. In addition, the nephelinite's composition is very similar to that of a small dike (about 50 × 300 m) and associated flow about 40 km W of House Mountain (PRS–34 of Wittke *et al.* 1989).

The ijolite–monzosyenite samples have variable geochemistry reflecting their modal variability. The rocks at House Mountain are not typical ijolites because they are associated with Group-I nephelinites, contain essential feldspar, and are dominated by titanaugite rather than aegirine. It is possible that there are systematic variations in ijolites that parallel those observed in nephelinites (M.J. Le Bas, pers. comm., 1995). For example, titanaugite-bearing ijolites associated with Group-I nephelinites have been reported from several localities, including the Comores Islands of the Indian Ocean (Strong 1972), Talzast, Morocco (Le Maitre 1989, p. 120), and Moroto, northeast Uganda (Varne 1988).

The House Mountain ijolites and monzosyenites have a restricted range of SiO_2 (41.3–44.9%), Al_2O_3 (16.78–19.7%), and FeO (7.90–9.33%), with other major oxides displaying wide variations ($6.22 < CaO < 12.96\%$, $2.44 < MgO < 5.43\%$, $3.18 < Na_2O < 5.27\%$, $2.25 < K_2O < 4.51\%$). Volatile contents are high, as reflected by LOI (3.11–5.76%) and modal zeolites. Low analytical totals probably result from unanalyzed volatiles (CO_2, F, Cl) and trace elements (*LREE*). The mineralogical variability of the monzosyenites is also reflected in their trace-element contents. Compatible elements show particularly wide ranges of concentrations ($29 < V < 274$ ppm, $8 < Cr < 56$ ppm, $14 < Ni < 48$ ppm). *LILE* abundances, except for Rb (40–75 ppm), are high ($2700 < Sr < 3360$ ppm, $2400 < Ba < 4610$ ppm). The *HFSE* elements show an unusual behavior: Zr contents are relatively uniform (208–257 ppm), whereas Ti, P and Nb show twofold variations in abundance ($0.74 < TiO_2 < 1.76\%$, $0.60 < P_2O_5 < 1.38\%$, $89 < Nb < 131$ ppm).

DISCUSSION AND CONCLUSIONS

Any model for the origin of the association of basanitic nephelinite, feldspar ijolite, and nepheline monzosyenite at House Mountain must account for the following distinctive features: (a) the presence of felsic rocks (mm-scale ocelli and schlieren, and m-scale pods, dike and sheet) within the nephelinite, (b) the range of modal compositions in the felsic rocks, (c) the lack of chilled margins between the felsic and mafic rocks, (d) the overlapping mineral compositions in the felsic and mafic rocks, (e) the extensive range of compositions observed in clinopyroxene, feldspar, and olivine, and (f) petrographic features suggestive of strong undercooling such as the nepheline–clinopyroxene intergrowths and long skeletal crystals of olivine.

Three principal mechanisms could produce some or all of the features noted above: (1) mixing of independently derived nephelinitic and ijolitic or syenitic magmas, (2) separation of a late-stage fluid-rich residual ijolitic–monzosyenitic magma from a crystallizing nephelinitic magma, and (3) production of a fluid-rich ijolitic melt by liquid immiscibility from a nephelinitic parent. Although preliminary work at House Mountain favored liquid immiscibility to produce a felsic liquid (Wittke *et al.* 1993, Wittke & Holm 1994), there is no compelling reason to invoke this process. All features, with the possible exception of the ocelli, can be easily explained as the result of differentiation of nephelinitic magma to produce felsic magma, followed by intrusion, mixing and continued differentiation of the liquids. Segregation lenses and m-scale dikes of felsic rocks that originate by differentiation have been described in many thick tholeiitic flows, intrusions and lava lakes (*e.g.*, Puffer & Horter 1993) and undersaturated rocks (*e.g.*, Wilkinson & Stolz 1983). The intimate association of nephelinite and ijolite–monzosyenite is observed in three separate localities in north-central Arizona, suggesting strongly that the rocks are cogenetic and did not arise independently.

The rocks at House Mountain can be explained by differentiation according to the series: basanitic nephelinite → feldspar ijolite → nepheline monzosyenite. This sequence is consistent with the evolutionary trends observed in modal mineralogy, mineral chemistry, and whole-rock geochemistry. The rocks retain the same essential mineral assemblage of clinopyroxene + nepheline + feldspar ± olivine during all stages of this sequence. The step from nephelinite to ijolite is dominated by the separation of olivine by either crystal settling or filter pressing of an interstitial liquid from a crystal mush. Olivine remains in the mineral assemblage throughout the fractionation, but with a greatly reduced abundance in the felsic rocks. The felsic rocks display a systematic decrease in the color index along the proposed sequence (Table 1). The dominant trend is a decrease in the modal abundances of nepheline and clinopyroxene in favor of feldspar.

The trends observed in the composition of phases in the House Mountain rocks are also consistent with differentiation. Clinopyroxene compositions in the nephelinite are identical to the most magnesian clinopyroxene in the ijolite and monzosyenite. Clinopyroxene in the felsic rocks displays strong Fe enrichment (Figs. 10, 11); comparable, but less dramatic, Fe enrichment also is seen the clinopyroxene of the nephelinite (209–1). Clinopyroxene is systematically zoned toward increasing Fe and Na contents and decreasing Ti, Al, and Mg (Table 4). Clinopyroxene cores in the felsic rocks are identical in composition to the more Fe-rich clinopyroxene rims in the basanitic nephelinite, indicating that fractionation of the nephelinitic magma occurred before separation of the felsic liquid. The olivine is also strongly Fe-enriched in the felsic rocks (Table 3). Trends in sanidine chemistry, from potassium-rich to more sodic compositions, also are consistent with differentiation as a controlling mechanism in the felsic rocks. The compositions of the sodic alkali feldspars in the more evolved samples are displaced toward the Ab apex of the feldspar system relative to the less evolved samples (Fig. 12), reflecting increasing degrees of fractionation and, presumably, decreasing temperatures. In contrast, nepheline compositions show little chemical variation, consistent with previous observations of chemical uniformity in this phase (*e.g.*, Edgar 1984).

The whole-rock geochemistry available also is consistent with differentiation. There is a systematic decrease in *mg* from nephelinite (76) to ijolite (51–61) to monzosyenite (46–50) and a corresponding decrease in CaO and increase in K_2O and BaO. The trace-element chemistry also is consistent with differentiation, showing enrichment in *LILE* and depletion in compatible elements along the proposed sequence. However, the behavior of individual trace elements is complicated, consistent with the proposal that their behavior is strongly controlled by phases such as apatite and Fe–Ti oxides. For example, Nb shows a general enrichment along the sequence, whereas Zr does not. Sodic clinopyroxene has been demonstrated to control Zr behavior in rocks of the Monteregian province of Quebec (Bédard 1994); however, titanaugite and Fe–Ti oxides in the House Mountain nephelinite contain less than 400 ppm Zr, such that another, as yet unidentified, phase may be involved. The *LILE* show comparably complex behavior: Ba and Rb are enriched by 2–4×, following K, but Sr is not. The observed crystallization of apatite and plagioclase can explain the decrease in P and Sr from ijolite to monzosyenite.

The ocelli observed in the nephelinite, however, seem to require a more complex interpretation than *in situ* differentiation, and are consistent with the coexistence of two liquids. Ocelli have often been cited as evidence of liquid immiscibility (*e.g.*, Philpotts 1976), but several investigators have proposed segregation of late-stage liquid into gas vesicles to produce ocelli (*e.g.*, Cooper 1979, Foley 1984). This process might be driven or enhanced by the contraction of the mafic liquid associated with crystallization and cooling, which produces a pressure gradient within the crystallizing liquid (Petersen 1987). However, in order for such a mechanism to operate, the gas must be expelled from the vesicle. At House Mountain, there is little evidence for a separate gas phase; the basanitic nephelinite is remarkably dense and free of vesicles, even in the small lava flow.

The felsic ocelli observed at House Mountain are essentially identical to those described from rocks of the Monteregian province that have been interpreted as resulting from immiscibility (Philpotts 1972, 1976, Eby 1980). In the Monteregian alkaline intrusions, which have received much attention as examples of liquid immiscibility, syenitic material is concentrated into sheets, schlieren, and small globules (ocelli); there are also larger syenitic bodies that are presumed to have formed as diapirs by coalescence of immiscible globules (Philpotts 1968, 1972, Eby 1979, 1980, 1983). However, Bédard (1994) demonstrated that the chemical characteristics of the felsic ocelli and dikes are better explained by segregation of a late-stage liquid into joints and subsequent coalescence and diapiric rise. He argued that low concentrations of *REE*, Ta, Zr, Nb, and Hf in ocelli from Monteregian camptonites do not result from immiscibility but instead from the scavenging of these elements by *REE*- and *HFSE*-sequestering phases in the host liquid (apatite, oxides and titanite) during crystallization.

As noted above, trends observed in the mineral chemistry are consistent with differentiation; however, they also could be explained by silicate-liquid immiscibility. In liquid immiscibility, crystals present in one liquid must be in equilibrium with those in the other. Although it is possible for a mineral to occur in only one of the two liquids, if it does occur in both liquids, its composition must be identical in both (Bowen 1928). However, if immiscibility occurs after crystallization of a significant part of the initial melt, the effects of fractional crystallization will be imposed upon the chemistry of the resulting liquids (*e.g.*, Roedder & Weiblen 1970, Philpotts 1979), and immiscibility and fractional crystallization will yield similar crystal-chemical signatures. For example, if the initial combined liquid undergoes extensive fractionation before separation of an immiscible liquid, the rim compositions of phases in the host liquid will be in equilibrium with cores of matching phases in the daughter liquid; the overlapping compositions in the nephelinite and ijolite–monzosyenite at House Mountain (Figs. 10, 11) could be produced by such a process.

The partitioning of trace and minor elements between the mafic and felsic rocks at House Mountain is not consistent with experimental studies of liquid immiscibility. During immiscible separation, the mafic liquid will retain the *HFSE*, P, and the *REE* (Watson 1976, Ryerson & Hess 1978). This is not observed in the House Mountain rocks, but complete trace-element data are not available, and this test must be viewed as inconclusive at present. Unless one accepts that both immiscible liquids (ocelli) and residual liquids (wispy patches) are present at House Mountain, the ocelli must represent some pre-existing liquid that mixed with the nephelinite.

All the features described are consistent with a two-stage model for the petrogenesis of the House Mountain rocks. The felsic schlieren and wispy felsic patches within the nephelinite demonstrate that fractionation of a basanitic nephelinitic magma will produce small-scale accumulations of felsic liquid. However, this late-stage magma must have accumulated into larger batches prior to incorporation in the nephelinitic magma, as is suggested by the field occurrence of the large felsic bodies in the nephelinite dike. Postulating a previously derived felsic liquid helps explain why the felsic dike and sheet are mineralogically heterogeneous: it is proposed that some of the heterogeneity may have been inherited; these bodies represent magma mobilized and intruded into the molten nephelinite occupying the dike. Whereas this is conceptually comparable to mixing independently produced ijolitic–monzosyenitic and nephelinitic magmas, the coexistence of these two unusual rock types at three localities in Arizona suggests that they are cogenetic.

According to a two-stage model, an initial batch of nephelinitic magma underwent fractionation in a crustal magma-chamber to produce a residual ijolitic to monzosyenitic liquid. This differentiate would collect at the top of the chamber, owing to its lower density. Calculated densities (McBirney 1984) are 2.84 g/cm^3 for nephelinite (209–1) and 2.75 g/cm^3 for monzosyenite (205–3) at 1100°C; the density contrast is not sensitive to water content. Separation of the ijolitic magma from the host nephelinite would be efficient owing to the very low viscosities (8.4 and 3.3 Pa s, respectively at 1100°C), as inferred by the methods of Shaw (1972). However, viscosities increase with lower temperature and the presence of phenocrysts, and decrease with increased H_2O contents; thus, these numbers should be considered only illustrative. For example, viscosity is approximately tripled by a temperature drop of 100°C and halved by 1% dissolved H_2O. Ascent rates, as calculated using a general form of Stokes's law for spherical bodies (McBirney 1984, p. 55), would be very high. A 1-mm-diameter globule of ijolitic liquid would rise at a rate of ~0.006 cm/s (24 cm/hr) at 1100°C, assuming the anhydrous case; the addition of 1% H_2O approximately doubles the ascent rate (41 cm/hr). Larger globules of ijolitic liquid would ascend more rapidly than smaller ones: a 1-cm-diameter globule rises at approximately 0.66 cm/s (2.4 m/hr), assuming the anhydrous case. Clearly, as globules coalesced, the separation would become increasingly efficient and effectively sweep the nephelinite clear of felsic material. Residence in a crustal magma chamber would permit a longer period for more efficient separation of the felsic differentiate than in the high-level volcanic dikes.

The layered magma chamber was disrupted by a new injection of nephelinitic magma that incorporated the accumulated bodies of differentiate and ascended to higher levels to produce the House Mountain dikes. Turbulence and shear during ascent may have caused disaggregation along the margins of the larger felsic bodies, producing globules that were stirred into the nephelinite. The low viscosity of the nephelinitic liquid will promote turbulent flow (Huppert & Sparks 1985). Ocelli are found principally along the margins of the largest felsic dike, where shearing would have been most pronounced. In addition, the fluid-rich ijolitic magma may have undergone boiling due to pressure release, promoting further disaggregation. Ferguson & Currie (1971) questioned how a residual liquid could produce ocelli with sharp boundaries, since it should wet mineral boundaries and conform to spaces between pre-existing crystals, but existence of a previously segregated late-stage liquid within a low-viscosity host would obviate this problem. Because the globules represent melt, they were drawn into ocelli by surface tension in the less viscous mafic magma.

The felsic magma spread as a sheet when it lost buoyancy at the top of the dike. The sheet underwent additional fractional crystallization as it cooled, resulting in banding (relatively clinopyroxene-rich and clinopyroxene-poor layers) and marked Fe-enrichment in olivine and clinopyroxene. The intergrowth textures, and possibly the poikilitic textures, indicate generally simultaneous (cotectic) growth of the principal early phases. Shallow emplacement of the magma and exsolution of volatiles may have led to considerable undercooling, which would tend to result in cotectic crystallization. A differentiated liquid will be volatile-rich relative to its host, and subsequent fractionation will enhance this characteristic. The intergrowth, skeletal, and poikilitic textures, and the large size of the crystals, may be due to low rates of nucleation and relatively rapid rates of growth in a volatile-rich, low-viscosity magma. Vugs up to several centimeters in diameter and miarolitic cavities with zeolites are evidence of a high content of fluid in the magma. Fluid movement within the bodies of phaneritic rock produced an abundance of hydrothermal zeolites and carbonate. As the host nephelinite cooled, it underwent differentiation, producing wispy patches and schlieren where the residual liquid collected interstitially and was drawn into tension gashes in the solidifying dike. In addition, larger segregations of differentiated felsic magma were injected as small dikes into the nephelinite, or formed as apophyses off the larger felsic bodies.

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