Tholeiitic Basalt Magmatism of Mount Etna and Its Relations With the Alkaline Series

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Abstract. Mount Etna is composed for the most part of intermediate alkaline products, most of them porphyritic – the "etnaïtes" –, that may be defined as sodic trachybasalts or trachyandesites. The strato-volcanio itself overlies tholeiitic basalts (usually aphyric, except for olivine) belonging to three major types: *olivine tholeiites* (normative Ol + Hy; modal olivine and augite, titanomagnetite and ilmenite), *pigeonite tholeiites* (normative Hy + minor Ol or Qz; modal pigeonite and augite with minor olivine, ilmenite and titanomagnetite), *transitional tholeiites*, i.e. transitional between pigeonite tholeiites (aphyric) and alkali basaltic etnaïtes (porphyritic, with normative Ol + Ne or minor Hy; modal augite and olivine, titanomagnetite alone). An "analcite basalt", chemically close to alkali basaltic etnaïtes, forms the small Cyclopean Islands, SE of Etna, and an alkali olivine basalt composes a neck at Paterno, SW foot of Etna.

Both pigeonite tholeiites and alkali basaltic etnaïtes may be derived from a primitive olivine tholeiite magma by subtraction or addition of phases crystallized at moderate and low pressure (kaersutite ± olivine, calcic plagioclase and clinopyroxene). The differentiation process implies crystal fractionation of the primitive olivine tholeiite magma at varying levels of the crust. The speed of ascent of the magma is thought to be the factor controlling the level at which differentiation may take place: in low velocity regimes, fractionation takes place at deeper levels of the crust. Slow ascent speeds would be the consequence of a developing crustal extension episode, induced by mantle diapirism that generated the olivine tholeiite magma below the Mount Etna area.

I. Introduction

Most of the rocks that compose the complex Etna strato-volcano correspond to intermediate members of an alkaline suite, close – but not identical – to ha-waiites and mugearites as defined by Muir and Tilley (1961) or Macdonald and Katsura (1964). Their chemical composition is distinctly higher in Ca and Al (with lower Ti), leading mineralogically to abundant calcic plagioclase. Moreover, they are typically porphyritic, having conpicuous phenocrysts of plagioclase (An 90-40), slightly titaniferous augite and minor amounts of olivine and titanomagnetite. The same minerals are present in the groundmass, together with a highly alkalic residuum made of sodic sanidine and, frequently, nepheline ± sodalite (Tanguy, 1966). These particular lavas were called "etnaïtes" by Rittmann (1960): for those who are working on Mount Etna, the term "etnaïte" is indeed a very convenient one, as clearly defining a peculiar porphyritic texture associated with a chemical composition varying from that of a sodic trachybasalt to a sodic trachyandesite.

It has long been known that the building of Mount Etna itself had been preceded by sparse eruptions generally referred to a "pre-etnean" period. The petrochemistry of the products of this early volcanism had been greatly neglected and only some ten years ago it was found independently by two authors (Atzori, 1966; Tanguy, 1966, 1967) that these rocks were basalts with tholeiitic affinities. The few outcrops studied at that time appeared quite surprising as they were negligible in size with respect to the huge alkalic edifice of Etna. The present writer, however, had presented the chemical analysis of subcalcic augite that left little doubt about the actual tholeiitic character of these basalts. This fact stimulated a more detailed study and other outcrops of tholeiitic basalts were found. Although a continuous evolution was suspected from olivine tholeiites, through alkali basalts, to etnaïtes, there were not enough data to establish the relationships between these lavas. New investigations in the field, including largely lavas of Mount Etna itself, and more than 150 new analyses selected from about 2000 samples now permit the magmatic evolution of Etna to be described with a certain degree of accuracy.

Table 1. Analyses[a] and C.I.P.W. norms of pre-etnean basalts

	Olivine tholeiites								Pigeonite tholeiites								
	413	*414*	*205*	*‡[b]*	*311*	*5725*	*434*	*466*	*516*	*643*	*432*	*739*	*734*	*601*	*481*	*1593*	*1594*
SiO_2	47.07	47.52	47.25	48.55	49.08	49.53	49.74	50.33	49.53	51.45	52.30	51.76	52.35	51.57	51.73	53.08	51.61
TiO_2	1.54	1.54	1.76	1.65	1.52	1.53	1.53	1.53	1.66	1.47	1.50	1.51	1.55	1.53	1.61	1.19	1.12
Al_2O_3	13.82	14.36	14.23	14.52	14.66	14.51	14.50	15.48	15.63	15.20	15.17	15.02	14.66	14.76	14.51	15.74	12.44
Fe_2O_3	3.45	2.97	4.22	—	2.18	1.68	1.40	4.68	3.87	1.46	2.89	2.05	1.77	1.20	2.28	2.06	3.32
FeO	7.76	8.04	5.89	10.70	8.75	8.94	9.19	5.75	6.63	9.37	8.12	9.12	9.39	9.79	8.20	6.91	6.85
MgO	11.68	10.50	10.06	11.04	9.84	9.80	9.93	7.76	6.80	7.35	7.10	7.45	7.24	7.45	7.83	7.76	10.93
CaO	9.30	9.84	9.74	9.89	9.99	9.78	9.31	10.59	10.76	9.37	9.33	9.27	9.54	9.61	9.39	9.44	10.16
Na_2O	2.58	2.70	2.83	2.77	2.96	2.94	3.06	3.23	3.31	3.22	3.29	3.25	3.21	3.17	3.35	3.28	2.65
K_2O	0.36	0.38	0.34	0.37	0.36	0.38	0.37	0.35	0.39	0.26	0.33	0.22	0.20	0.20	0.35	0.30	0.22
CO_2	0.35	0.52	0.45	—	—	—	—	—	—	—	—	—	—	—	—	—	—
H_2O^+	1.67	1.21	1.86	—	0.36	0.36	0.26	0.38	1.34	0.38	0.16	0.46	0.23	0.38	0.50	0.29	0.26
H_2O^-	0.53	0.57	1.04	—	0.13	0.23	0.03	0.22	0.60	0.10	0.14	0.06	0.06	0.11	0.16	tr.	0.07
MnO	0.13	0.15	0.15	0.15	0.16	0.15	0.18	0.18	0.15	0.15	0.15	0.15	0.18	0.17	0.14	0.15	0.16
P_2O_5	0.28	0.28	0.52	0.36	0.24	0.21	0.32	0.34	0.28	0.27	0.19	0.12	0.22	0.18	0.25	0.29	0.25
	100.52	100.58	100.34	100.00	100.23	100.04	99.82	100.82	100.95	100.05	100.67	100.44	100.60	100.12	100.30	100.49	100.04
$\dfrac{Mg^b}{Mg+Fe^{2+}}$	0.69	0.67	0.68	—	0.66	0.66	0.66	0.62	0.59	0.58	0.58	0.59	0.58	0.57	0.61	0.65	0.70
Qz	—	—	—	—	—	—	—	—	—	—	1.35	—	0.64	—	—	1.44	0.13
Ne	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Or	2.13	2.25	2.01	2.19	2.13	2.25	2.19	2.07	2.30	1.54	1.95	1.30	1.18	1.18	2.07	1.77	1.30
Ab	21.83	22.85	23.95	23.44	25.05	24.88	25.89	27.33	28.01	27.25	27.84	27.50	27.16	26.82	28.35	27.76	22.42
An	25.07	25.94	25.12	26.09	25.65	25.27	24.74	26.71	26.64	26.25	25.65	25.75	25.00	25.46	23.52	27.34	21.40
Di	13.63	14.28	13.44	16.66	18.08	17.74	15.72	18.78	20.03	15.14	15.77	15.91	17.12	17.28	17.40	14.24	21.89
Hy	12.63	11.77	15.88	6.99	7.57	10.04	11.26	14.73	9.50	21.49	20.33	22.64	23.19	21.06	20.13	21.74	25.04
Ol	13.67	12.65	5.35	18.24	14.66	13.46	14.06	0.12	3.11	2.37	—	0.71	—	2.76	1.23	—	—
Mt	5.00	4.31	6.12	2.60	3.16	2.44	2.03	6.79	5.61	2.12	4.19	2.97	2.57	1.74	3.31	2.99	4.81
Ilm	2.92	2.92	3.34	3.13	2.89	2.91	2.91	2.91	3.15	2.79	2.85	2.87	2.94	2.91	3.06	2.26	2.13
Ap	0.65	0.65	1.20	0.83	0.56	0.49	0.74	0.79	0.65	0.63	0.44	0.28	0.51	0.42	0.58	0.67	0.58

[a]   Analyses by Ms. M. Lenoble (Pétrographie, Univ. de Paris 6); combination of XRF and wet chemistry methods (Velde and Lenoble, 1972)

[b]   with $Fe_2O_3 \leqq 0.85$ Fe as FeO

413/414   Two different outcrops 200 m apart in Sicilian clays, base of Mt Vamboleri, W of Aci-Trezza (Etna SE). Norms include 0.80 and 1.18 calcite, respectively

205   Center of pillow-lava, platform around Aci-Castello Rock. Norm includes 1.02 calcite

‡   Average of samples 413-414-205, recalculated on anhydrous basis

311   Thick lava flow, base of the cliff under Biancavilla, SW of Etna

5725   Pillow-lavas below Adrano, South of the churchyard

434   Thick lava flow, middle of the Costa Mendola cliff, between Adrano and Biancavilla

466   Oxidized flow, summit of the cliff North of Adrano

516   Large spheroid of radiating columns, Timpa Ignazio, above Aci-Castello railway station

643   Flow from the lower part of the cliff under Santa Maria di Licodia (Etna SW)

432   Ibid., upper part of the cliff

739   Prominent outcrop at 281 m, about 2 km SE of Paterno (Etna SW)

734   Poggio Guardia near Valcorrente, about 2 km distant from 739

601   Erratic block near Valcorrente

481   Small outcrop (breccia?) at Ficarazzi, above Aci-Castello

1593/1594   Pyroxene phenocrysts poor and rich samples from contrada Perazzo, W of Macali (Etna E)

1536/1535   Boulders in Terre Forti, SW of Catania (Etna S)

118   Inner (columnar) part of Motta Sant'Anastasia neck (Etna S)

1612   Flow from the base of Timpa Santa Caterina cliff below Aci-Reale (Etna SE)

104/623   Alkali olivine basalt, average of two samples from Paterno neck, SSW base of Etna

213/709   "Analcite basalt", from two Cyclopean Islands, near Aci-Trezza

II. Geological Setting

Magmas have been erupted discontinuously, but over a large period of time in eastern Sicily along a SSW–NNE zone of faulting which seems to be a persistent tensional line leading to distensive volcanism (Rittmann, 1963; Barberi et al., 1973). Triassic and Cre-taceous lavas are known in the SE part of the island and were found by drilling at 2000 m depth under Ragusa; these lavas are strongly alkaline in character (Cristofolini, 1966). Progressively, eruptive centers migrated northward as the time went. During the Tertiary and early Quaternary an important basaltic volcanism occurred in Monti Iblei (about 60 km SSW of Etna), as indicated

Table 1 (continued)

	Transitional tholeiites			Paterno basalt	Cyclopean islands	
1536	*1535*	*118*	*1612*	*104/623*	*213*	*709*
51.12	50.80	50.82	49.86	48.55	47.28	46.49
1.79	1.70	1.68	1.63	1.55	1.45	1.51
16.13	16.39	15.80	15.62	14.88	16.58	15.38
1.66	2.53	2.09	4.27	2.93	3.63	3.64
8.63	7.58	7.40	6.08	7.48	6.20	6.70
7.02	6.72	7.22	8.41	10.20	5.91	7.12
9.34	9.39	9.83	9.92	9.54	10.29	10.56
3.37	3.45	3.34	3.28	3.62	4.17	3.77
0.35	0.50	0.69	0.57	0.70	0.70	0.98
—	—	—	—	—	—	—
0.55	0.73	0.44	0.35	0.21	2.60	2.89
0.13	0.40	0.45	0.07	0.08	0.45	0.46
0.17	0.16	0.15	0.17	0.16	0.17	0.15
0.33	0.34	0.40	0.32	0.40	0.70	0.53
100.59	100.69	100.30	100.55	100.30	100.13	100.18
0.59	0.59	0.62	0.64	0.68	0.57	0.60
—	—	—	—		—	—
—	—	—	—	2.16	3.78	5.15
2.07	2.95	4.08	3.37	4.14	4.14	5.79
28.52	29.19	28.26	27.76	26.81	28.31	22.40
27.85	27.76	26.08	26.22	22.23	24.46	22.15
13.34	13.49	16.27	16.66	18.06	17.76	21.55
18.23	15.78	12.62	10.65	—	—	—
3.33	2.71	4.96	5.45	18.55	9.00	10.41
2.41	3.67	3.03	6.19	4.24	5.26	5.28
3.40	3.23	3.19	3.10	2.94	2.75	2.87
0.76	0.79	0.93	0.74	0.92	1.62	1.23

by numerous intrusions and large flows, which often exhibit submarine morphology (pillow-lavas, hyaloclastites). Both alkaline and tholeiitic basalts coexist, without apparent gradation between them (Carapezza and Morandi, 1966; Romano and Villari, 1973).

In middle Quaternary times, the first basalts were erupted in the Mount Etna zone. Some of them appear contemporaneous with Sicilian clays and their normal magnetic polarity (Tanguy, unpublished data) suggests that they may be younger than 700,000 years. The Paterno neck, one of the pre-etnean basalts, has been dated to 210,000 years B.P. (Condomines and Tanguy, 1976). This result is in agreement with careful stratigraphic investigations by Kieffer (1971), showing that many of these basalts are pre-Tyrrhenian and were emitted before the building of Etna itself.

The latter has had a complex evolution (Rittmann, 1963; Klerkx, 1968; Kieffer, 1973, 1974, 1975): Primordial Etna, Trifoglietto cone, Elliptical Crater, Mongibello (=actual Etna) (see map in Tanguy and Kieffer, 1976–77, Fig. 1). Many recurrent eruptive cycles emitted large quantities of porphyritic trachybasalts to trachyandesites (etnaïtes), associated with a few aphanitic lavas of the same composition or eventually reaching trachytes (Tanguy, 1973 b).

Although it is difficult to estimate the volume of pre-etnean basalts with respect to the whole mass of Etna, it seems rather evident that they represent a small portion of the edifice. The necks of Paterno and Motta Sant'Anastasia, which are outside the volcano itself, contain numerous blocks belonging to the sedimentary basement (volcanosedimentary breccia) and can be considered as little independent volcanoes resulting from a single eruption. Other pre-etnean basalts were probably emitted by narrow fissures without direct relations between them (eccentric volcanism) and disseminated over an area south of the present Etna axis (Tanguy and Kieffer, 1976–77, Fig. 1).

III. Pre-Etnean Basalts

From mineralogical and chemical points of view (Yoder and Tilley, 1962; Poldervaart, 1964), the pre-etnean basalts can be subdivided into four groups, although several types display transitional characters between them, or are transitional towards alkali basaltic etnaïtes ("transitional tholeiites") (Tables 1 and 2, and Fig. 1):

Table 2. Modal analyses of Pre-etnean Basalts

		Olivine tholeiites					Pigeonite tholeiites							Transitional tholeiites		Paterno alkali basalt
		413	*414*	*311*	*434*	*466*	*432*	*739*	*734*	*601*	*481*	*1593*	*1594*	*118*	*1536*	*104*
Olivine	ph.	16.2	11.5	9.3	10.6	6.7	3.7	2.5	3.1	2.6	8.0	1.0	1.2	4.9	7.1	12.3
	g.	2.2	3.3	2.8	1.2	1.6	0.1	0.3	0.5	0.4	1.2	6.0	3.9	2.3	2.3	1.4
Plagioclase	ph.	—	—	0.7	0.6	2.1	0.3	—	tr.	0.9	9.7	12.7	16.7	—	15.2	4.5
	g.	30.7	33.8	43.8	44.8	45.4	50.4	48.8	47.8	45.6	39.7	29.6	20.0	45.8	37.2	36.3
Clinopyroxene	ph.	—	—	—	—	—	—	—	—	—	tr.	4.5	18.3	0.6	0.1	0.7
	g.	23.4	25.5	31.7	29.7	30.4	36.1	37.0	38.1	38.3	30.3	29.0	25.0	26.4	25.8	28.9
Orthopyroxene	ph.	—	—	—	—	—	—	—	—	—	—	0.9	7.2	—	—	—
Oxides	g.	4.1	5.2	3.3	3.1	5.8	2.6	2.8	2.8	2.2	4.7	3.9	1.3	2.9	2.7	4.7
Glass, alterations		23.5	20.3	8.3	10.0	8.0	6.8	8.6	7.6	10.0	6.4	12.4	6.4	17.0	9.6	11.2

(Caption as in Table 1); *ph*: phenocrysts; *g*: groundmass

— Olivine tholeiite: normative hypersthene + olivine. Modal olivine (> 5%) and augite; titanomagnetite + (minor) ilmenite.

— Pigeonite tholeiite: normative hypersthene + minor olivine (Hy ≫ Ol) or quartz. Modal pigeonite and augite with minor olivine (< 5%); ilmenite + (minor) titanomagnetite.

— Transitional tholeiite, i.e. transitional between pigeonite tholeiite and alkali basaltic etnaïte (the latter being itself transitional towards etnaïte proper, with normative Ol + Ne or minor Hy; modal augite and usually minor olivine and nepheline, titanomagnetite and no ilmenite).

— Alkali olivine basalt (one example known): normative olivine + nepheline. Modal olivine (> 5%) and augite, titanomagnetite and no ilmenite.

A general feature of pre-etnean basalts is their low phenocryst content, usually of forsteritic olivine. The basaltic character ot the rocks is indicated by the presence of numerous grains of spinel (chromite, Table 3), generally enclosed in olivine phenocrysts; in pigeonite and transitional tholeiites, however, chromite is almost lacking. The pre-etnean chromites are quite similar to those found in Hawaiian basalts (Evans and Wright, 1972).

Fig. 1a and b. Alkali silica diagrams of Mount Etna lavas. 1: primitive olivine tholeiites; 2: pigeonite tholeiites; 3: transitional tholeiites; 4: alkali basaltic, transitional etnaïtes; 5: etnaïtes (dots) and associated aphanitic lavas, including trachytes (circles). Full squares indicate the primitive (?) alkali-olivine basalt from the Paterno neck. Asterisk represents the average of 5 samples of aphyric trachybasalt that erupted in early 1974 on the W slope of Etna (see Tanguy and Kieffer, 1976–77)

Olivine Tholeiites

Basalts that form small outcrops, sometimes with columnar jointing, in Sicilian clays west of Aci-Trezza (Mt Vamboleri) and pillow-lavas at Aci-Castello, are probably the earliest lavas to have been erupted in the Mount Etna area (samples 413, 414, 205). They show numerous olivines (Table 4) with chromite inclusions and rarely (205) a few diopside-augite phenocrysts in a dense, aphanitic groundmass. The latter appears essentially composed of brownish,

Table 3. Representative analyses of chromites

	Olivine tholeiites		Pigeonite tholeiite	Paterno alkali olivine basalt			
	Cr 413	Cr 311	Cr 432	Cr 104$_a$	Cr 104$_b$	Cr 104$_c$	Cr 104$_d$
Cr_2O_3	34.08	36.88	35.70	45.88	39.28	34.01	28.95
Al_2O_3	24.38	18.76	18.20	17.37	19.72	13.62	6.22
FeO^a	23.72	29.22	30.73	20.98	26.62	35.34	39.93
MnO	0.30	0.36	0.31	0.38	0.42	0.48	0.63
MgO	14.70	11.64	11.11	14.29	11.37	10.12	7.80
NiO	0.01	0.16	0.19	0.10	0.11	0.11	0.14
TiO_2	1.12	1.79	1.79	0.87	0.95	4.37	13.59
	98.31	98.81	98.02	99.87	98.47	98.05	97.27

[a]   Total Fe as FeO. All electron microprobe analyses with Cameca MS 46 electron microprobe, B.R.G.M., Orléans (1968–1976)

Table 4. Representative analyses of olivine phenocrysts[a]

	Olivine tholeiites				Pigeonite tholeiites				Transitional tholeiites		Paterno alkali basalt	
	$Ol413_a$	$Ol414_1$	$Ol311_a$	$Ol311_1$	$Ol432_a$	$Ol481_a$	$Ol481_1$	$Ol1594_a$	$Ol118_a$	$Ol1535_a$	$Ol104_a$	$Ol104_1$
SiO_2	39.5	39.40	39.9	—	38.4	38.4	36.86	38.8	37.3	38.5	40.1	39.25
TiO_2	0.01	—	0.00	—	0.00	0.03	—	0.04	—	0.02	—	—
Al_2O_3	0.08	—	0.01	—	0.07	0.02	—	0.01	—	0.06	0.02	0.05
Cr_2O_3	0.04	—	0.06	—	0.02	0.00	—	0.02	—	0.04	0.07	—
Fe_2O_3	—	1.42	—	0.74	—	—	1.23	—	—	—	—	1.58
FeO	13.4	15.75	13.3	17.27	17.2	18.4	23.30	18.4	24.6	20.7	12.4	11.63
CaO	0.25	—	0.23	—	0.24	0.27	—	0.30	0.28	0.30	0.24	0.14
MgO	46.4	42.27	45.7	43.35	43.3	41.4	37.02	41.9	36.7	40.5	47.0	46.67
MnO	0.22	0.23	0.22	0.26	0.25	0.26	0.36	0.29	0.33	0.26	0.23	0.18
NiO	0.30	—	0.29	—	0.19	0.17	—	—	—	0.16	0.24	0.28
	100.20	99.07	99.71	—	99.67	98.95	98.77	99.76	99.21	100.54	100.30	99.78
Si	0.986	1.006	0.998		0.981	0.993	0.983	0.994	0.992	0.990	0.994	0.979
Ti	0.000	—	0.000		0.000	0.001	—	0.001	—	0.000	—	—
Al	0.002	—	0.000		0.002	0.001	—	0.000	—	0.002	0.001	0.001
Cr	0.001	—	0.001		0.000	0.000	—	0.000	—	0.001	0.001	—
Fe^{3+}	—	0.027	—		—	—	0.025	—	—	—	—	0.031
Fe^{2+}	0.279	0.336	0.278		0.368	0.398	0.519	0.394	0.547	0.445	0.257	0.243
Ca	0.007	—	0.006		0.007	0.007	—	0.008	0.008	0.008	0.006	0.004
Mg	1.724	1.607	1.704		1.648	1.595	1.470	1.600	1.454	1.551	1.735	1.734
Mn	0.005	0.005	0.005		0.005	0.006	0.008	0.006	0.007	0.006	0.005	0.004
Ni	0.006	—	0.005		0.004	0.003	—	—	—	0.003	0.004	0.005
	3.010	2.981	2.998		3.015	3.004	3.005	3.004	3.008	3.007	3.003	3.002
$Mg/Mg+Fe$	*0.86*	0.82	*0.86*	0.81	*0.82*	*0.80*	0.73	*0.80*	*0.73*	*0.78*	*0.87*	0.86

[a]   Key to Table 4: Ol n... = number of whole-rock sample (see Table 1); n...$_a$, most Mg crystal analysed (core phenocryst) by electron microprobe (B.R.G.M., see Table 3); n...$_1$, average phenocrysts on separate 80-50 µm, wet chemical analysis

strongly zoned augites and smaller laths of plagioclase (Figs. 2 and 3). Despite their tholeiitic parentage, the ferriferous zones of groundmass augites often display extensive replacement of Si by Al and Ti (Table 5), these features being probably related to the conditions of cooling (Mevel and Velde, 1976). Titanomagnetite occurs as tiny crystals and subordinate ilmenite forms very small, acicular prisms usually less than a few microns in width (Table 6).

The most conspicuous olivine tholeiites are found between Adrano and Biancavilla, SW of Etna, where thick pahoehoe lava flows form a cliff about 60 m high. Samples taken in this zone have a practically constant composition (311, 434, 5725). They show numerous olivine phenocrysts with usual chromite inclusions and sometimes traces of glomerophyric plagioclase. The coarse grained groundmass exhibits a typical doleritic texture with numerous laths of plagioclase and grains of augite strongly zoned towards ferroaugite. Ilmenite seems as abundant as titanomagnetite and there is a small amount (< 10%) of a rhyodacitic residual glass (Table 7, V 311_2).

Samples 466 and 516 are of particular interest because they appear transitional to pigeonite tholeiites. They differ from the olivine tholeiites described above by lower MgO content and slightly higher SiO_2. However, the mineralogy is almost the same, substantially higher CaO content possibly preventing any trend towards pigeonitic pyroxene (a similar relationship is postulated for the presence/absence of hypersthene in Hawaiian lavas: Tilley and Scoon, 1961).
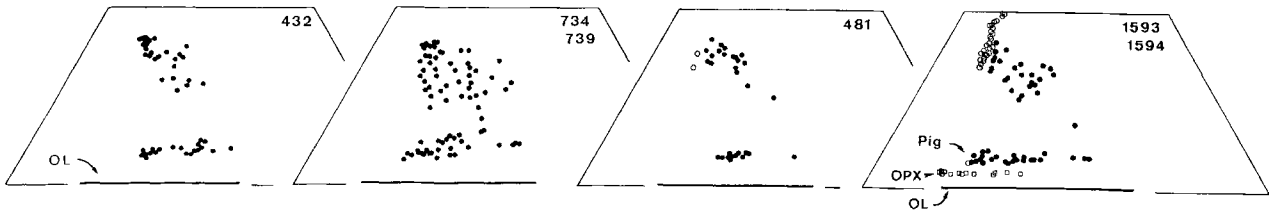
Pigeonite Tholeiites

Pigeonite tholeiites, namely SE of Biancavilla (432, 643) and Paterno (734, 739, 601) display a doleritic texture similar to that of Adrano olivine tholeiites. However, they are chemically and mineralogically different. They have essentially higher SiO_2 (around 52%) and lower MgO content, leading to little or no normative olivine. The olivine phenocrysts represent a few percent of the modal composition; they are less magnesian than those of the olivine tholeiites (Table 4) and are rounded, corroded and almost without chromite inclusions. Pyroxenes are confined to the groundmass and are of two varieties: augite, zoned towards subcalcic ferroaugite, and pigeonite, zoned to ferropigeonite. From mineral separates and electron microprobe investigations, the pigeonite/augite ratio can be roughly estimated to 1/4 or 1/3, but sometimes pigeonite appears as abundant as augite. Ilmenite occurs as well developed prisms and there is scarce titanomagnetite.

Another common feature of pigeonite tholeiites is the presence of a highly acid glassy residuum approaching a rhyolitic composition. The glass appears inhomogeneous and electron microprobe analyses performed on the most potassic areas differ in their alkali content from results obtained by wet chemistry on fractions separated from the rock ($K_2O = 6.2$, $Na_2O = 2.8$, $SiO_2 = 72.3$, $Al_2O_3 = 14.0$, $FeO = 1.30$, $CaO = 1.00$, $TiO_2 = 0.18$, compare to V 432_2, Table 7).

Olivine Tholeiites
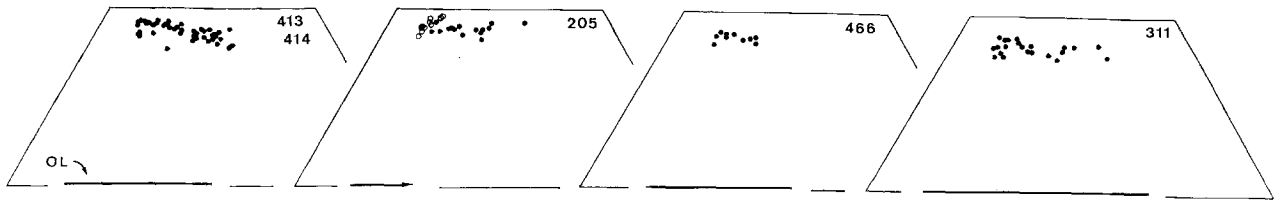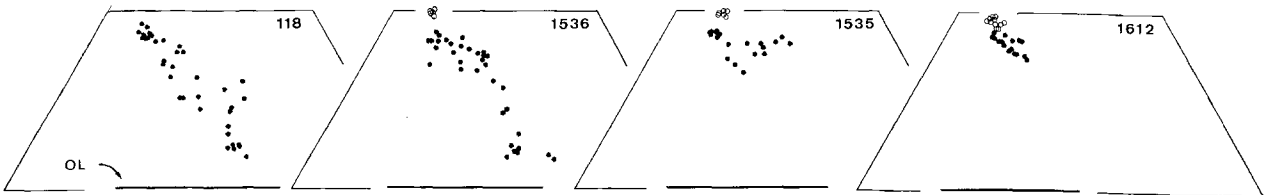

Pigeonite Tholeiites

Transitional Tholeiites

Fig. 2. Major element variation in pyroxenes and olivines of tholeiitic basalts. Open symbols: phenocrysts; full: groundmass. Mol.-%

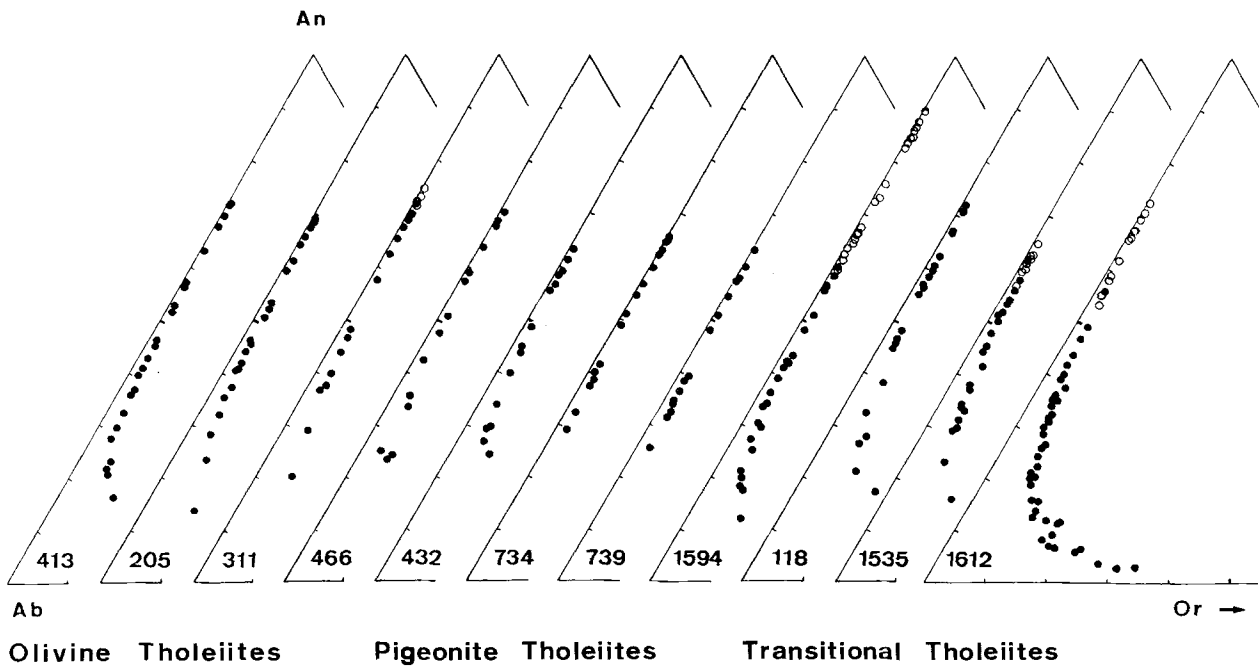**Olivine Tholeiites**   **Pigeonite Tholeiites**   **Transitional Tholeiites**

Fig. 3. Feldspar composition of tholeiitic basalts. Weight percent

Exceptional pigeonite tholeiites (1593, 1594) having conspicuous greenish pyroxene, plagioclase and olivine phenocrysts were recently found (Kieffer and Tanguy, 1976). The pyroxene phenocrysts are either orthopyroxene or diopside-salite, rimmed by augite, and pigeonite is abundant in the groundmass. The plagioclase phenocrysts are abundant and unusually calcic, up to An 90. Olivine with an iddingsite rim is more abundant as small rounded grains than as phenocrysts. Ilmenite and titanomagnetite often show signs of oxidation.

The modal abundance of pyroxene phenocrysts is variable from one sample to another, and the calculations indicate evident crystal fractionation. The two analyses 1593 and 1594 adequately represent the least and the most femic varieties.

Transitional Tholeiites

In some samples the tholeiitic characters become less apparent, the lavas showing a continuous transition toward porphyritic alkali basalts (transitional etnaïtes, see part IV). Most of these tholeiites are found stratigraphically just below the lavas of Etna proper and probably belong to an earlier stage of the strato-volcano itself. They may be considered as transitional tholeiites, i.e. transitional towards more evolved alkaline products (Fig. 1). Although the texture is still generally doleritic, it is often less typical than in samples described above and phenocrysts other than olivine are frequent.

The lava forming the Motta Sant'Anastasia neck (118) has a bulk chemical composition close to that of a typical pigeonite tholeiite. However the alkali content, especially K_2O, is higher, with slightly lower SiO_2. Pigeonite occurs as very few and tiny crystals of an unusually ferrous variety, whereas magnesian and intermediate pigeonite are lacking. Another particularity of this lava is the relative abundance and more ferrous composition of olivine phenocrysts.

Boulders found a few kilometers southwards are chemically much alike, but they exhibit conspicuous plagioclase and fewer aluminous diopside-salite phenocrysts. As at Motta, pigeonite is very scarce in the groundmass and more ferriferous (1536) or may be lacking altogether (1535). In this latter case, the groundmass augite is zoned towards titanian ferroaugite (Table 5).

A similar lava forms one of the lowest flows of Timpa Santa Caterina, below Aci-Reale (1612), this flow being overlain without anconformity by a femic etnaïte (1611, Table 8). As above, the rock shows many plagioclase and a few pyroxene phenocrysts, together with olivine. The texture is more fluidal than doleritic, and alkali feldspar is evident between the microlites. As in alkaline types (see below), the groundmass augite is slightly zoned and pigeonite is absent.

Table 5. Representative electron microprobe analyses of pyroxenes

	Olivine tholeiites					Pigeonite tholeiites								
	Mg Aug 311	Al DiSal[a] 205	TiFe Aug 205	Fe Aug 413	Fe Aug 311	Al DiSal[a] 1593	Mg Aug 432	Fe Aug 739	Mg OPX[a] 1594	Fe OPX[a] 1594	Mg Pig 739	Mg Pig 432	Fe Pig 432	Fe Pig 739
SiO_2	52.91	50.74	46.84	48.62	48.94	49.36	52.95	50.55	54.74	52.62	54.51	52.97	50.91	49.44
Al_2O_3	1.63	4.48	4.39	1.49	0.99	6.32	1.73	1.32	1.58	0.46	0.52	0.49	0.39	0.86
TiO_2	0.66	0.80	3.93	1.53	1.28	1.26	0.51	1.08	0.42	0.48	0.25	0.34	0.49	0.74
Cr_2O_3	0.21	1.14	—	—	—	0.23	0.75	—	0.25	0.02	—	—	—	—
FeO	7.14	5.13	13.59	20.41	22.77	5.56	7.35	22.46	11.81	22.61	14.95	18.81	27.45	29.06
MnO	0.09	0.12	0.30	0.51	0.51	0.10	0.19	0.53	0.26	0.40	0.37	0.44	0.64	0.69
MgO	17.37	15.31	10.45	8.62	7.28	13.36	16.42	11.22	29.04	20.12	25.17	22.08	15.17	12.87
CaO	18.73	21.05	19.58	17.94	17.64	22.70	19.73	12.38	2.19	2.15	3.46	4.03	4.43	5.40
Na_2O	0.31	0.51	0.86	0.60	0.62	0.50	0.33	0.38	0.08	0.12	0.06	0.07	0.21	0.32
K_2O	0.01	0.01	0.01	0.02	0.02	0.00	0.02	—	0.01	0.00	0.00	0.01	0.02	0.01
	99.07	99.28	99.94	99.74	100.05	99.41	99.99	99.92	100.39	99.00	99.30	99.25	99.72	99.39
Si	1.957	1.877	1.797	1.915	1.939	1.834	1.951	1.961	1.944	1.992	1.989	1.977	1.979	1.955
Al^{IV}	0.043	0.123	0.199	0.069	0.046	0.166	0.049	0.039	0.056	0.008	0.011	0.022	0.018	0.040
Al^{VI}	0.028	0.072	0.000	0.000	0.000	0.111	0.026	0.022	0.010	0.013	0.011	0.000	0.000	0.000
Ti	0.018	0.022	0.113	0.045	0.038	0.035	0.014	0.032	0.011	0.014	0.007	0.010	0.014	0.022
Cr	0.006	0.033	—	—	—	0.007	0.022	—	0.007	0.001	—	—	—	—
Fe^{2+}	0.221	0.159	0.436	0.672	0.755	0.173	0.226	0.729	0.351	0.716	0.456	0.587	0.892	0.961
Mn	0.003	0.004	0.010	0.017	0.017	0.003	0.006	0.017	0.008	0.013	0.012	0.014	0.021	0.023
Mg	0.957	0.844	0.598	0.506	0.430	0.739	0.901	0.649	1.536	1.135	1.369	1.229	0.879	0.759
Ca	0.742	0.834	0.805	0.757	0.749	0.903	0.779	0.515	0.083	0.087	0.135	0.161	0.184	0.229
Na	0.022	0.037	0.064	0.046	0.048	0.036	0.024	0.028	0.006	0.009	0.005	0.005	0.016	0.025
K	0.000	0.000	0.001	0.001	0.001	0.000	0.001	—	0.000	0.000	0.000	0.001	0.001	0.001
	3.998	4.005	4.022	4.028	4.023	4.007	3.999	3.991	4.012	3.988	3.995	4.005	4.006	4.015
Ca	38.6	45.4	43.8	39.1	38.7	49.8	40.8	27.2	4.2	4.5	6.5	8.2	9.4	11.7
Mg	49.9	45.9	32.5	26.1	22.2	40.7	47.3	34.3	78.0	58.5	69.8	62.1	44.9	38.9
Fe	11.5	8.6	23.7	34.8	39.0	9.5	11.9	38.5	17.8	37.0	23.3	29.7	45.6	49.3

[a] Phenocrysts; others: groundmass

Table 5 (continued)

Transitional tholeiites						Alkali basaltic etnaïtes		
Al DiSal[a] 1536	Al DiSal[a] 1612	Al DiSal[a] 1535	TiFe Aug 1535	Fe Pig 118	Fe Pig 1536	Al DiSal[a] 1611	Al Sal[a] 1618[b]	Fe Sal 1611
50.95	50.96	49.13	47.44	49.76	49.43	49.73	46.24	50.81
4.76	4.66	5.88	2.52	0.85	0.20	6.62	9.22	2.35
1.07	0.95	1.41	3.42	0.92	0.40	1.06	2.31	1.90
–	–	0.13	–	–	–	0.55	0.19	0.00
5.36	5.57	6.26	17.09	30.23	35.02	6.86	8.12	10.07
0.10	0.12	0.15	0.38	0.73	0.98	0.08	0.12	0.32
14.27	14.89	13.03	8.87	12.15	10.15	14.64	12.35	12.81
22.88	22.83	22.70	19.14	5.42	3.72	20.84	21.19	21.35
0.38	0.45	0.56	0.68	–	0.11	0.52	0.66	0.69
–	–	0.00	0.03	–	–	0.00	0.00	0.00
99.77	100.42	99.25	99.57	100.06	100.01	100.88	100.39	100.30
1.879	1.871	1.835	1.854	1.955	1.988	1.821	1.722	1.905
0.121	0.129	0.165	0.116	0.039	0.009	0.179	0.278	0.095
0.086	0.072	0.094	0.000	0.000	0.000	0.107	0.126	0.009
0.030	0.026	0.039	0.100	0.027	0.012	0.029	0.065	0.054
–	–	0.004	–	–	–	0.016	0.006	0.000
0.165	0.171	0.195	0.559	0.993	1.178	0.210	0.254	0.316
0.003	0.004	0.005	0.012	0.024	0.033	0.002	0.004	0.010
0.784	0.815	0.725	0.517	0.712	0.609	0.799	0.685	0.716
0.904	0.898	0.909	0.802	0.228	0.160	0.817	0.845	0.858
0.028	0.032	0.040	0.051	–	0.009	0.037	0.048	0.050
–	–	0.000	0.002	–	–	0.000	0.000	0.000
4.001	4.018	4.012	4.014	3.978	3.999	4.017	4.031	4.013
48.8	47.7	49.6	42.7	11.8	8.2	44.8	47.4	45.4
42.3	43.2	39.7	27.5	36.8	31.3	43.7	38.4	37.9
8.9	9.1	10.7	29.8	51.4	60.5	11.5	14.2	16.7

[b] 1618 = gabbroïc inclusion in 1611

Alkali Olivine Basalt From the Paterno Neck (Fig. 4)

This rock (104, 623, Tables 1 and 2) is rather exceptional as it represents the only alkali basalt to have some "primitive" characters (e.g. chromite in olivine). Chemically, it resembles olivine tholeiites, but with a higher alkali content – and also P_2O_5 –, leading to a few normative nepheline.

The texture is decidedly porphyritic, with conspicuous phenocrysts of olivine (abundant), plagioclase and pyroxene (scarce). The olivine crystals show less iron enrichment on their rims than the tholeiitic ones, and the bulk composition of a separate is practically identical to the most magnesian electron microprobe analysis (Table 4). Pyroxene, on the border between diopside-augite and salite, is almost unzoned. The labradorite phenocrysts have a nearly constant composition (An 63), except on their rims that are rounded and slightly more calcic.

Flow texture is evident in the groundmass, the thin, elongated plagioclase microlites being surrounded by alkali feldspar. Both X-ray diffraction pattern and electron microprobe analyses show a continuous zoning towards calcic anorthoclase. Numerous grains of pyroxene (salite with about 3.6 Al_2O_3, 1.8 TiO_2) have a constant $Ca - Mg - Fe$ content, close to that of phenocrysts. Chromite crystals are exceptionally well developed and, when not trapped in olivine, act as nuclei for microphenocrysts of titanomagnetite (Table 3, Cr 104 b, c, d). Titanomagnetite itself is abundant as small octaedra in the groundmass. There is no ilmenite.

The mineralogy of this basalt is quite similar to that of alkali olivine basalts from Hawaii (Keil et al., 1972; Fodor et al., 1975).

"Analcite Basalt" From the Cyclopean Islands

The small Cyclopean islets, near Aci-Trezza, are the remnants of an old submarine intrusion (213, 709). From the texture, the rock is more a dolerite than a basalt. It is holocrystalline and exhibits stout microlites or microphenocrysts of zoned plagioclase often poikilitically contained in large diopside-salite crystals. Analcite occurs as anhedral phenocrysts that contain abundant inclusions of potassic feldspar composition. Exceptionally large titanomagnetites show, in one sample (213), beautiful exsolution lamellae of ilmenite, but the latter does not occur as separate crystals. There are also a few altered olivine and various alterations products, including calcite and zeolites.

Although generally considered as pre-etnean, the Cyclopean Islands basalt is unlike any of the other pre-etnean lavas. Its composition is rather similar to that of transitional etnaïtes (part IV), which often contain small amounts of interstitial nepheline. The analcite obviously formed during the latest stage of crystallization: perhaps
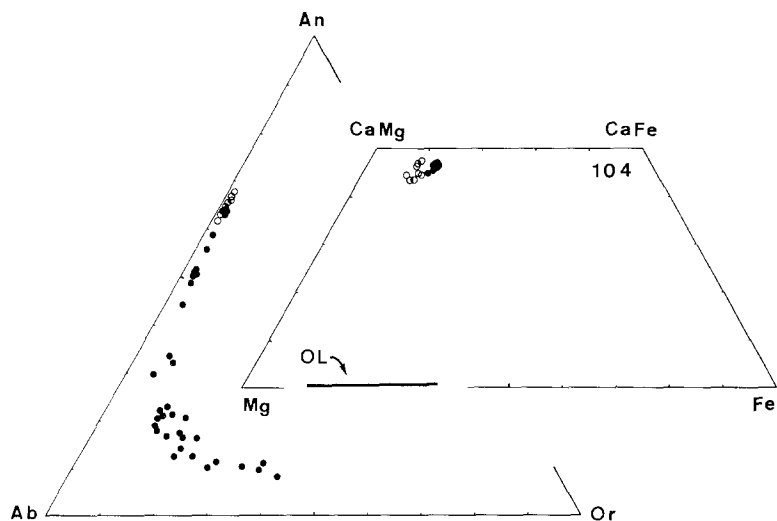
Fig. 4. Electron microprobe data on Paterno alkali olivine basalt. Feldspars, weight-%; pyroxenes and olivines, mole-%

Table 6. Analyses of titanomagnetites and ilmenites[a]

	Olivine tholeiites				Pigeonite tholeiites					Transitional tholeiite		Alkali basalts			
	Mt 414	Ilm 414	Mt 311	Ilm 311	Ilm 432	Mt 739	Ilm 739	Mt 481	Ilm 481	Mt 118	Ilm 118	Mt 104	Mt[b] 709	Mt[b] 1443$_1$	Mt 1443$_2$
TiO_2	24.05	49.35	23.83	48.45	49.84[c]	22.80	50.47	22.90	50.26	20.65	46.80	20.92	19.26	15.86	17.40
SiO_2	–	–	–	–	–	–	–	–	–	–	–	–	2.06	3.80	3.84
Fe_2O_3	25.48	–	30.24	7.65	4.14	36.44	4.41	28.84	4.38	38.75	4.89	39.85	28.88	34.92	38.81
Al_2O_3	1.22	0.14	0.72	0.19[c]	0.15[c]	0.82	0.13[c]	0.82	0.15[c]	2.13	0.13[c]	1.88	4.62	5.90	5.04
FeO	47.70	48.06	42.42	42.46	42.23	36.85	43.39	44.36	41.68	35.29	46.81	32.80	42.78	34.20	31.22
MnO	0.66	0.66	0.56	0.72	0.42[c]	0.43	0.33	0.54	0.73	0.76	0.38	0.66	–	–	–
MgO	0.65	0.58	0.45	0.47	1.67[c]	0.42	1.19	0.88	2.55	1.62	0.98	3.11	1.30	3.52	2.42
CaO	–	–	–	0.06	–	–	0.08	–	0.25	–	0.01	–	0.32	0.94	1.04
	99.76	98.80[c]	98.22	100.00[d]	98.45	97.76	100.00[d]	98.34	100.00[d]	99.20	100.00[d]	99.22	99.22	99.14	99.77

[a] Analyses of ilmenite concentrates through the courtesy of Professor E.A. Vincent, Oxford (an. Ms. Pamela Shreeve)
[b] Phenocrysts; others: groundmass
[c] Electron microprobe analyse
[d] Corrected for small amounts (< 10%) silicate impurities

Table 7. Analyses of residual glasses

	Olivine tholeiite	Pigeonite tholeiites			Transitional tholeiite
	V 311$_2$	V 481$_3$	V 432$_2$	V 739$_2$	V 118$_1$
SiO_2	64.08	63.93	71.76	72.87	63.40
TiO_2	0.60	0.64	0.34	0.32	0.48
Al_2O_3	11.38	11.60	14.18	13.85	12.30
Fe_2O_3	5.55	5.73	1.14	1.22	0.88
FeO	1.98	1.35	0.54	0.72	6.19
MgO	1.13	1.18	0.46	0.14	1.55
CaO	2.36	1.52	2.22	2.64	2.00
Na_2O	3.59	4.13	4.92	5.20	3.45
K_2O	4.30	3.78	2.52	1.72	4.72
MnO	–	–	–	–	0.04
P_2O_5	–	–	–	–	1.14
H_2O^+	3.59	3.87	0.45	0.78	2.45
H_2O^-	0.67	1.51	0.59	0.30	0.66
	99.23	99.24	99.12	99.76	99.26

around 400° C from its measured cell parameter ($a_0 = 13.716$ Å, see Liou, 1971). The replacement of the common nepheline by analcite (with minor potassic feldspar) could be the consequence of a peculiar cooling history in subvolcanic conditions near the bottom of the sea.

Concluding Remarks on the Mineralogy of Pre-Etnean Basalts

A major feature that distinguishes the tholeiitic pre-etnean basalts is the strong zoning of ferromagnesian silicates, especially pyroxenes. This is in great contrast with the practically constant Ca — Mg — Fe content in pyroxenes from the alkaline lavas of Paterno or Etna itself (Figs. 4 and 5). Differences in the bulk composition of Ca-rich pyroxene phases are less evident indi-

cators. Although most of our tholeiitic basalts have pyroxenes quite similar to those of tholeiitic Hawaiian basalts (Evans and Moore, 1968; Fodor et al., 1975) and of other tholeiitic provinces (Brown, 1957; Carmichael et al., 1974), some of them display unusual pyroxene composition for tholeiitic rocks: titan ferroaugites in the groundmass, or salite phenocrysts with extensive replacement of Si by Al. These characters could be thought as transitional towards alkaline types, however, the tholeiite from Contrada Perazzo (1593), that has the highest SiO_2 content, also shows a high Al diopside-salite as primary pyroxene. Such a composition most likely reflects a moderately high pressure origin for these phenocrysts, whatever the nature of the parent magma (Aoki, 1968, 1970; Brooks and Rucklidge, 1973, p. 206).

In the same way, the behaviour of olivine in the pre-etnean basalts is not clear. All types, including tholeiitic ones, contain a discrete amount of olivine in the groundmass. Thus, the presence of olivine in the groundmass cannot be considered as an index of alkalinity. Moreover, it is often difficult to distinguish between true microlitic olivine and the small grains of this mineral that are actually the remnants of corroded phenocrysts: this is probably the case in tholeiites from Perazzo where, despite the silica oversaturation of the rocks, the "microlitic" olivine exceeds 5 or 6 times the amount of phenocrystic one (Table 2).

Within the tholeiitic types, olivine and pigeonite tholeiites differ by the crystallization trends of augites: while in olivine tholeiites Fe replaces almost uniquely Mg (Ca being nearly constant), both Ca and Mg are substituted by Fe in pigeonite tholeiites. For this reason, the gap that usually exists between magnesian augite and pigeonite is greatly reduced or even suppressed with iron enrichment of these minerals, thus permitting the crystallization of subcalcic ferroaugites (a similar trend has been found in the Tawhiroko dolerite, Nakamura and Coombs, 1973).

The iron titanium oxides of the pre-etnean basalts are very sensitive to the composition of the melts and provide another criterion for distinguishing them. In pigeonite tholeiites, ilmenite predominates over titanomagnetite, the latter being very rare and probably the last mineral to crystallize. In olivine tholeiites, the amount of titanomagnetite usually equals the amount of ilmenite and the two oxides tend to form euhedral crystals. In alkali basalts (including lavas of Etna itself), there is no primary ilmenite, but a considerable amount of titanomagnetite, partly as microphenocrysts, with significant Al and Mg content (Table 6). Similar observations have been made elsewhere (Smith and Carmichael, 1969). The disappearance of ilmenite with increasing amounts of early

crystallized titanomagnetite indicates a higher oxygen fugacity in alkaline types (Osborn, 1959).

IV. Lavas of Mount Etna

The study of Mount Etna lavas is still in progress and only some general features will be given here (Fig. 1 and Table 8).

Alkali Basaltic, Transitional Etnaïtes (= Porphyritic Alkali Basalts)

Some of the lavas that compose Mount Etna itself are still relatively low in alkalies, especially K_2O (K_2O/Na_2O between 0.2 and 0.3). Out of their context, they could be called alkali basalts. However, they are generally lower in MgO and higher in Al_2O_3 than most of the pre-etnean basalts (see also Table 9, col. 5) and, over all, they show the characteristic porphyritic texture of etnaïtes. Therefore, they are defined as "transitional etnaïtes", i.e. transitional between true basalts ($K_2O/Na_2O < 0.2$) and etnaïtes s.s. ($K_2O/Na_2O > 0.3$) (Fig. 1 b)[1].

Most of the transitional etnaïtes from the beginning of Etna show evidence of intensive crystal fractionation, either as phenocryst enriched rocks (1443) or nearly residual liquids (1606, 1607). The phenocrysts are olivine, clinopyroxene, plagioclase and titanomagnetite. These minerals may compose gabbroïc inclusions, sometimes abundant (e.g. 1611). In some specimens there is also kaersutite (Table 9, col. 2), often more or less resorbed, but occasionally reaching several centimeters in length.

The abundance of phenocrysts in rocks that are clearly transitional between tholeiitic and alkaline types has been observed elsewhere (Macdonald and Katsura, 1964; Engel et al., 1965; Snavely et al., 1968) and must be pointed out.

Etnaïtes s.s. (= Porphyritic Trachybasalts)

This is the most frequent type, a detailed description of which has been given in a previous work (Tanguy, 1966). It composes almost all the historic flows, but it is also abundant in many earlier lavas. The chemical composition corresponds to that of a sodic trachybasalt (in the sense of Le Maître, 1962), with often a tephritic tendancy because of small amounts of modal feldspathoïds (nepheline, sodalite) in the groundmass. Interstitial alkali feldspar (sodic sanidine) makes up to 10–15% of the rock (Fig. 5). Kaersutite is rare.

Light Etnaïtes (= Porphyritic Trachyandesites)

More fractionated etnaïtes have a trachyandesitic composition, being characterized by a regular decrease of CaO, MgO, total Fe, and an increase of SiO_2, K_2O, Na_2O and often Al_2O_3. Mineralogically, there is more plagioclase and alkali feldspar (the latter as usual in the groundmass) and less ferromagnesian minerals. More frequently than in etnaïtes s.s., a kaersutitic amphibole may be present, associated with typical microphenocrysts of apatite containing numerous submicroscopic oxide inclusions.

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[1]   The Paterno alkali olivine basalt, having an older age and primitive characters (see below), is regarded as different from these alkali basaltic etnaïtes
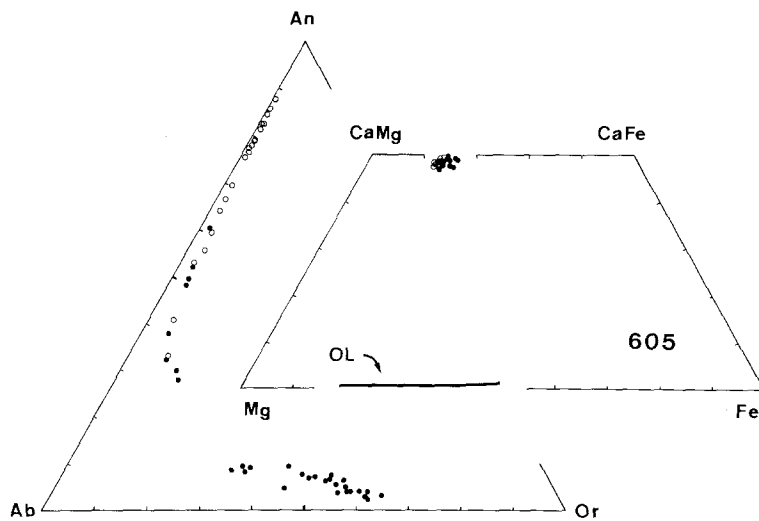
Fig. 5. Electron microprobe data on etnaïte (1950 lava flow at Milo, see Tanguy, 1966)

Table 8. Selected analyses and C.I.P.W. norms of Mount Etna lavas

	Alkali basaltic etnaïtes					Etnaïtes			Light etnaïtes			Aphanitic lavas			
	1443	*1611*	*624*	*1606*	*1607*	*1047*	*1268*	*1262*	*966*	*1032*	*1019*	*1090*	*1101*	*1358*	*1002*
SiO$_2$	46.96	49.12	49.90	50.85	51.93	48.59	50.04	51.43	52.31	55.72	56.89	51.09	54.06	60.30	62.31
TiO$_2$	1.95	1.47	1.45	1.42	1.35	1.74	1.43	1.42	1.49	0.79	0.78	1.82	1.59	0.54	1.10
Al$_2$O$_3$	14.58	15.17	16.70	18.92	19.88	17.40	19.28	18.67	18.14	18.87	20.53	17.40	18.09	18.53	17.28
Fe$_2$O$_3$	4.61	2.22	4.27	3.37	3.23	3.96	4.53	3.48	2.43	4.85	3.04	2.08	1.90	2.73	1.78
FeO	7.40	7.78	5.75	5.51	5.17	6.12	4.37	5.10	5.52	1.52	1.30	7.49	6.36	1.79	2.76
MgO	8.52	9.43	6.08	5.01	3.40	5.90	4.12	3.36	3.25	2.66	1.15	3.58	2.87	1.17	1.42
CaO	12.29	10.55	9.95	9.34	8.56	10.20	9.36	8.56	7.08	6.27	5.24	7.27	6.50	3.38	2.76
Na$_2$O	2.79	3.06	3.84	4.33	4.81	4.03	4.12	4.73	5.66	5.39	5.77	5.50	5.57	6.76	6.41
K$_2$O	0.74	0.61	0.90	1.01	1.14	1.41	1.55	1.97	2.49	2.43	3.27	2.62	2.36	3.90	3.29
H$_2$O$^+$	0.23	0.26	0.27	0.07	0.23	0.27	0.36	0.53	0.07	0.52	1.19	0.40	0.30	0.50	0.20
H$_2$O$^-$	0.06	0.20	0.10	0.13	0.23	0.07	0.13	0.08	0.07	0.35	0.36	0.09	0.03	0.23	0.17
MnO	0.17	0.16	0.18	0.16	0.15	0.18	0.15	0.17	0.17	0.11	0.10	0.21	0.23	0.18	0.15
P$_2$O$_5$	0.44	0.37	0.51	0.45	0.46	0.72	0.55	0.68	0.77	0.36	0.40	0.98	0.86	0.24	0.34
	100.74	100.40	99.90	100.57	100.54	100.59	99.99	100.18	99.45	99.84	100.02	100.53	100.72	100.25	99.97
Qz	—	—	—	—	—	—	—	—	—	0.55	—	—	—	—	5.02
Ne	1.83	—	—	0.42	0.01	4.11	0.59	2.42	6.49	—	—	8.25	2.15	0.94	—
Or	4.37	3.60	5.32	5.97	6.74	8.33	9.16	11.64	14.72	14.36	19.32	15.48	13.95	23.05	19.44
Ab	20.23	25.89	32.49	35.87	40.69	26.51	33.77	35.56	35.92	45.61	48.83	31.31	43.16	55.47	54.24
An	25.08	25.86	25.67	29.21	29.29	25.23	29.54	23.89	16.74	20.12	20.46	15.05	17.39	8.70	8.66
Di	26.45	19.42	16.31	11.14	8.27	16.61	10.57	11.47	10.95	6.72	2.28	12.12	7.68	5.14	2.29
Hy	—	2.31	2.73	—	—	—	—	—	—	3.51	0.56	—	—	—	4.48
Ol	11.09	15.99	6.88	8.84	6.77	8.74	5.31	5.27	6.37	—	0.88	9.09	8.30	0.68	—
Mt	6.68	3.22	6.19	4.89	4.68	5.74	6.57	5.05	3.52	2.97	2.26	3.02	2.75	3.96	2.58
Ilm	3.70	2.79	2.75	2.70	2.56	3.30	2.72	2.70	2.83	1.50	1.48	3.46	3.02	1.03	2.09
Ap	1.02	0.86	1.18	1.04	1.07	1.67	1.27	1.58	1.78	0.83	0.93	2.27	1.99	0.56	0.79

1443 Pyroxene rich etnaïte, M$^+$ Nardello (Etna E)
1611 Pyroxene and olivine rich flow above tholeiite 1612, base of Timpa S. Caterina
624 Recent flow near Valcorrente (Etna S)
1606 Fine-grained flow with pyroxene phenocrysts, above tuffs overlying 1611
1607 Upper part of flow 1606, without pyroxene phenocrysts
1047 Typical etnaïte flow 18,000 years old (Kieffer, 1975), Valle del Simeto, Ponte Maccarone (Etna SW)
1268 Plagioclase rich flow, Valle dell'Alcantara, North of Castiglione (Etna N)
1262 Dyke in Serra Giannicola Grande, 1,850 m a.s.l. (Etna E)
966 Flow near Villaggio Valentino, 1,460 m a.s.l. (Etna SW)
1032 Amphibole flow from Trifoglietto Vocano, South wall of Valle del Bove caldera (1,660 m a.s.l.). Norm includes 2.80 hematite
1019 Ibid., large dyke. Norm includes 1.48 hem
1090 Basaltic trachyandesite, flow in W wall of Valle del Bove (2,620 m a.s.l.)
1101 Fine-grained flow above Rifugio Citelli, 1,880 m a.s.l. (Etna NE)
1358 Alkali trachyte, 1 km South of Serra Giannicola Grande (2,400 m a.s.l.)
1002 Trachytic flow, SW wall of Valle del Bove (2,130 m a.s.l.)

Aphanitic Lavas and Trachytes

A much less common variety is represented by nearly aphanitic lavas, some of which are trachybasalts or trachyandesites of chemical composition similar to that of etnaïtes, but often with higher alkalies for a given SiO_2 content.

The most differentiated types are trachytes with a silica content up to about 62%. They contain very scarce and small phenocrysts of acid plagioclase (An 40), fewer augite and titanomagnetite. Olivine may be entirely lacking. An acicular amphibole is not frequent. The groundmass is fine grained with abundant cryptocrystalline alkali feldspar (anorthoclase to sodic sanidine); in silica oversaturated types, there are also tiny crystals of ferropigeonite and cristobalite. Alkali feldspar never forms phenocrysts.

On the whole, the lavas of Mount Etna define a rather continuous alkaline suite, the intermediate members of which are particularly abundant. Figure 1 summarizes the relations between the various products of the volcano, including pre-etnean basalts.

V. Discussion

A Primitive Olivine Tholeiite Magma

The olivine tholeiites described in this paper are postulated to represent the closest composition to a primary magma in the Etna volcanic province. Several features demonstrate that such magma is likely to have undergone a minimum of differentiation:

— small range of composition, with high Mg, Fe and Ca content;

— quasi absence of phenocrysts other than olivine;

— magnesian character of early crystallized olivine with high Ni content and its numerous chromite inclusions;

— with rare exception (s. 466 and 516, which have been shown transitional towards pigeonite tholeiites — see also Table 9, columns 1a, 3), all the olivine tholeiites have the highest magnesium content found in lavas of Mount Etna.

Particularly, their Mg numbers (0.66 to 0.69) are consistent with those of liquids in equilibrium with a peridotitic mantle (Green and Ringwood, 1967). As has been already suggested (Kay et al., 1970; Thompson, 1973), these lavas with high MgO content (> 8%) may be considered as "primitive" basalts.

From experimental work, there is some convergence between various authors to consider olivine tholeiite as the most common primary magma produced by partial melting of the upper mantle, provided the volatile content is not too high.

The latter point is important because of its implications for the generation of primary magmas and their further crystallization. If, as suggested by Moore

(1970), the volatiles present in a basaltic magma are correlated with its chemical composition, the primary water content of olivine tholeiites of Etna may be estimated to 0.3–0.5%. By assuming that most of the volatiles were concentrated in the melted part of a mantle of pyrolite composition, then the H_2O content of pyrolite source would be about 0.1%, yielding olivine tholeiite by 25–30% melting near 1350° C, 20 Kb (Green, 1972, p. 56). From other works of the same author (Green, 1970, 1973), it may be deduced that, more generally, similar olivine tholeiites are produced by 25–30% melting of pyrolite with a slight water content ($H_2O < 0.4\%$) at 1200–1400° C, 15–20 Kb (40–70 Km depth). This is in agreement with the probable temperature of extrusion of etnean olivine tholeiites (about 1200° C, see e.g. Tilley et al., 1965; Wright et al., 1968; Thompson, 1973) and the presumed thickness of the crust beneath Mount Etna (about 30 Km), as inferred from geophysical data (Morelli et al., 1975).

In this study, however, the most convincing argument for a primitive olivine tholeiite magma lies in the fact that it is capable of generating all the other magmas found at Mount Etna. Particularly, both pigeonite tholeiites (silica saturated) and transitional etnaïtes (= alkali basalts, silica undersaturated) can be shown to result from relatively simple processes of crystal fractionation affecting the olivine tholeiite parent magma.

Differentiation Model I:
Origin of Pigeonite Tholeiites, Transitional Tholeiites, Transitional (Alkali Basaltic) Etnaïtes

Although olivine is commonly the only phenocryst phase in olivine tholeiites, these rocks may also have a discrete amount of glomerophyric plagioclase near An 75, suggesting that the latter may have played a role in the differentiation of olivine tholeiite magma. When passing through transitional tholeiites towards alkaline products, i.e. transitional (alkali basaltic) etnaïtes, the proportion of plagioclase phenocrysts increases and they are joined by aluminous diopside-salite, the composition of which remains unchanged in the various magma types (Table 5, Al Di Sal). In some basaltic etnaïtes, there are also rare corroded megacrysts of kaersutitic amphibole or completely resorbed crystals of this same mineral.

It should be pointed out, also, that most pigeonite tholeiites are virtually aphyric, except for rare corroded olivines. The composition of these olivines is significantly less magnesian than that of the olivines

found in olivine tholeiites, in keeping with the lower MgO content of pigeonite tholeiites.

These (aphyric) pigeonite tholeiites are considered to be liquids obtained by subtracting 13% kaersutite, 7% olivine, 6% plagioclase, 1% aluminous diopside-salite, 0.35% apatite from the primitive olivine tholeiite (Table 9, col. 1 b, 4). The kaersutite used in the calculations is the average of two kaersutite megacrysts found in basaltic etnaïtes (col. 2). A small amount of apatite is used to balance P_2O_5 in both rocks, according to the fact that apatite is usually found as early microphenocrysts associated with amphibole. Other minerals are average compositions of phenocrysts observed in olivine and transitional tholeiites.

Kaersutite is generally considered as an early crystallizing phase at moderate pressure in presence of volatiles from alkaline magmas (e.g. Aoki, 1970; Wilkinson, 1974). In tholeiitic liquids, amphibole was believed to precipitate only with excess of H_2O in the latest stages of crystallization (Yoder and Tilley, 1962). However, T.H. Green and Ringwood (1968, p. 148) observed the crystallization of sub-silicic amphibole very close to etnean kaersutite from a quartz tholeiite composition with $P_{H_2O} < P_{Load}$, at 9 Kb, 1040° C. The crystallization of kaersutite from an olivine tholeiite magma was more recently obtained under controlled H_2O and CO_2 contents by Holloway and Burnham (1972): these authors observe as much as 31% kaersutitic amphibole at 8 Kb, 1060° C, and extrapolation of their curve (Fig. 3, p. 12) suggests that the kaersutite is the liquidus phase at 10 Kb. This is a confirmation of an earlier work (Nesbitt and Hamilton, 1970) showing that the temperature of appearance of amphibole is raised not only with increasing pressure, but also by lowering the H_2O content of the starting material. Finally, Holloway and Burnham conclude that "even at relatively low f_{H_2O} amphiboles may be important in differentiation processes at high temperatures" (see also Cawthorn and O'Hara, 1976 – Basalts of olivine tholeiite composition with conspicuous amphibole megacrysts have recently been reported by Sigurdsson and Shepherd, 1975).

Thus, it seems a reasonable assumption to consider that the H_2O poor olivine tholeiite magma of

Table 9. Derivation of the various magma types from primitive olivine tholeiite

P^a conditions	1	2	1_a LP	3	1_b MP (LP)	4	1_c MP	1_d MP+LP	5	1_e HP (LP)	1_f HP (LP)	6
SiO_2	49.15	40.12	50.16	50.34	51.84	51.99	47.61	50.27	49.66	49.85	48.95	47.56
TiO_2	1.60	3.95	1.76	1.62	1.49	1.53	1.66	1.67	1.66	1.63	1.73	1.68
Al_2O_3	14.58	13.55	16.03	15.68	14.90	14.93	14.40	17.29	17.39	17.26	16.63	17.45
FeO^b	10.65	9.95	9.93	10.13	10.91	10.78	10.50	9.64	9.78	10.18	11.43	10.56
MgO	10.48	14.59	7.29	7.34	7.47	7.42	12.20	6.00	5.90	6.01	5.45	5.52
CaO	9.82	12.15	10.77	10.76	9.48	9.45	10.01	10.15	10.29	10.25	10.80	10.77
Na_2O	2.88	2.96	3.17	3.29	3.20	3.26	2.70	3.71	3.78	3.74	3.87	4.00
K_2O	0.37	0.87	0.41	0.37	0.33	0.26	0.39	0.56	0.96	0.49	0.51	1.71
MnO	0.16	0.13	0.15	0.16	0.16	0.16	0.15	0.16	0.17	0.16	0.19	0.21
P_2O_5	0.31	—	0.34	0.31	0.21	0.21	0.37	0.54	0.40	0.41	0.43	0.54

[a] HP, MP, LP, respectively High Pressure, Moderate Pressure, Low Pressure crystal fractionation

[b] Total Fe as FeO

1 "Primitive" olivine tholeiite (average 6 analyses), recalculated to 100% free of water

2 Kaersutite, average of 2 megacrysts in basaltic etnaïtes (Tanguy and Kieffer, 1978)

1_a Composition 1 minus 9% olivine (Table 4, Ol $414_1 + 311_1/2$)

3 Olivine tholeiites 466–516, transitional to pigeonite tholeiites

1_b Composition 1 minus 13% kaersutite (col. 2), 7% olivine, 6% plagioclase An 75, 1% diopside-salite, 0,35% apatite

4 Aphyric pigeonite tholeiite (average 6 analyses)

1_c Composition 1 plus 13% kaersutite, 7% olivine, 6% plagioclase, 1% diopside, 0.35% apatite

1_d Composition 1_c minus 14.5% olivine, 9% diopside-salite, 6% plagioclase An 85, 2% titanomagnetite

5 Transitional (alkali-basaltic) etnaïte (average 13 analyses)

1_e Composition 1 minus 11% orthopyroxene, 7% diopside-salite, 3% olivine, 2% plagioclase An 85, 2% titanomagnetite

1_f Composition 1 minus 17% orthopyroxene, 4% diopside-salite, 1% olivine, 5% plagioclase An 85, 1,5% titanomagnetite

6 Typical etnaïte (1971 eruption, Tanguy, 1973a)

Etna underwent crystallization within the crust in conditions of slower velocity of ascent, yielding kaersutite near 10 Kb and increasing amounts of olivine, plagioclase and pyroxene at lower pressure. Then, the residual liquid erupting at the surface is of pigeonite tholeiite composition.

Following this scheme, the entire spectrum of transitional tholeiites (namely their various phenocryst content) may be explained either by tapping at different levels or by rapid (short period) emissions from a differentiating olivine tholeiite body, owing to a general (long period) decrease in the velocity of ascent of the primary magma.

It is expected that the crystalline phases separated from the primitive olivine tholeiite magma tend to be remelted at deeper levels, a fact that may be also indicated by the rounded form of most of the phenocrysts found in transitional tholeiites. The composition of the remaining olivine tholeiite, therefore, is changed in the opposite direction of that of pigeonite tholeiites, i.e. towards more femic and silica undersaturated compositions (Table 9, col. 1c). Such a femic magma is unlikely to erupt without undergoing further differentiation. If 14% olivine, 9% diopside-salite, 6% plagioclase and 2% titanomagnetite are extracted from it, the composition obtained is close to the average composition of transitional etnaïte (Table 9, col. 1d and 5). The minerals used in the latter calculation are low pressure phenocrysts abundant in basaltic etnaïtes. A direct evidence for such a low pressure crystal fractionation is found in the phenocryst enriched or depleted transitional etnaïtes and in the presence of gabbroïc inclusions made of the same minerals in some of them (part IV).

There is some additional indication that such a process generated pigeonite tholeiites and, through transitional tholeiites, alkali basaltic etnaïtes. Thus, the very low f_{O_2} in pigeonite tholeiites would result from the retention of volatiles at depth in a hydrous crystalline phase (kaersutite). Conversely, the progressive increase in oxidation state towards alkaline rocks (leading to disappearance of ilmenite and increasing amounts of oxidized titanomagnetite — compare also the H_2O content of residual glasses, Table 7) may be explained — at least in part — by an increase in f_{O_2} owing to gradual remelting of kaersutite at deeper levels. This is due to the rapid sinking of kaersutite megacrysts, a phenomenon that is probably enhanced by the low viscosity of the melt at high pressure (Kushiro et al., 1976). This explains the scarcity of kaersutite in the products finally erupted, rather than the breakdown of this mineral at low pressure, that may also be involved.

This complete scheme of differentiation, from one unit of parental olivine tholeiite leads to approximately equal proportions of tholeiitic material and alkali basaltic etnaïte. Only about 16% extracted crystalline phases remain in the crust. Calculations show that a new batch of equal volume of primary olivine tholeiite is very slightly affected by even total remelting of these relicts — an indeed improbable eventuality. The process, therefore, is able to operate several times in the history of the volcano.

Differentiation Model II: Direct Production of Transitional Etnaïtes and Etnaïtes

Alternatively, transitional alkali basaltic etnaïtes may be directly derived from olivine tholeiite parent magma by essentially high pressure fractionation. In this case, however, we leave off most of the actually observed minerals to require hypothetical crystalline phases or phases in proportions that are not actually observed.

Experimental works cited above show that orthopyroxene may be a liquidus phase near 15-20 Kb (dry conditions) and its early appearance seems to be facilitated if a slight amount of water is present (Green and Hibberson, 1970). Removal of 11% orthopyroxene (=liquidus OPX at 13-18 Kb in Green and Ringwood, 1967), 7% clinopyroxene, 2% calcic plagioclase and 2% Titanomagnetite (low pressure phases) from primitive olivine tholeiite realizes, also, the composition of transitional etnaïte (Table 9, col. 1e). A similar conclusion is reached by using Ca poor clinopyroxene as a major high pressure phase (Thompson, 1974).

This latter process is plausible, an even slower rate of ascent of the magma from its source leading to crystallization at progressively deeper levels. It accounts for the absence of tholeiitic rocks in more recent products of Etna and the predominance of alkaline over tholeiitic ones. It is poorly substantiated, however, by petrological data. A small xenolith made of orthopyroxene, clinopyroxene and minor olivine found by Kieffer (personal communication) in a glassy etnaïte sample, or relicts of almost entirely resorbed diopside s.s. (total Fe — 3%, TiO_2 — 0.2, Al_2O_3 — 1.5) in the core pyroxene of some transitional etnaïtes are the only possible petrographic evidence.

Intensification of this fractionation (17% OPX extract) leads to a composition close to that of recent, typical etnaïtes.

The process, however, fails to adequately reproduce the trachybasaltic composition of the etnaïte: as noted for the proposed model I, the resulting K_2O content is too low (col. 1f and 6, Table 9), a discrepancy al-

ready evident in the computed transitional etnaïtes compositions (col. 5, 1 d, 1 e).

Thus, it appears that the characteristic feature of etnaïtes and their derivatives (i.e. the whole alkaline series of Etna) lies in an initial potassium enrichment that cannot be explained by a simple process of crystal fractionation. Removal of plagioclase as suggested by Aramaki and Moore (1969) or fractionation at depth of possibly high pressure andesine (Wright, 1968) are unable to change the K/Na ratio enough.

In the processes involved in alkali enrichment of magmas, the role of volatiles seems predominant (e.g. Kogarko, 1974). At Mount Etna, gaseous transfer and release of potassium in the melt when decreasing pressure, i.e. in the upper parts of eruptive channels, may explain the characteristic composition of etnaïtes.Such a mechanism is warranted by the persitent activity of the volcano and the actual observation that the K/Na ratio tends to increase when there is some evidence of stagnancy of the magma at shallow depth (Tanguy, 1966, p. 189–194; also, Tanguy and Kieffer, 1976–77). Other mechanisms such as wall rock reaction or zone refining are possible, but not evident.

A progressive change in the composition of the primary magma is difficult to consider because alkali basalts are generally believed to form by lower degrees of melting than tholeiitic ones—a fact that seems rather contradictory with the obvious increasing supply of alkaline magma at Mount Etna, particularly in the last 100,000 years period. One could imagine, however, that after rapid initial mantle diapirism beneath the area, the flattening of geotherms may produce on a larger scale larger quantities of magma available with a smaller degree of melting of the peridotite source, occurring at greater depth ($P > 30$ Kb). If so, alkaline components become relatively more important and the transition, at this pressure, of mantle subsolidus amphibole to phlogopite (Green, 1972, 1973) may explain a rapid increase of potassium in the magma generated. However, though this assumption is consistent with the general geotectonic model, it is not supported by any petrological data.

VI. Summary and Conclusions

The magmatic evolution of Etna may be summarized as follows: (1) Some 300,000 (?) years ago, mantle diapirism occurred beneath the Mount Etna area, producing rapidly increasing volumes (up to 25–30%) of partial melt (olivine tholeiite) from the peridotitic source. The rising diapir induced a beginning of distension in the crust overlying it, leading to sparse

effusions of almost undifferentiated primary magma (only possible loss of olivine by low pressure fractionation). (2) The crust suffered major extension, thus enlarging the fissures and lowering the velocity of ascent of the main magma body. Crystallization mostly occurred at some depth in the crust ($P \approx 10$ Kb), producing pigeonite tholeiites, transitional tholeiites and transitional alkali basaltic etnaïtes by extraction/addition of kaersutite ($\pm$ olivine, plagioclase and clinopyroxene at lower pressure) (differentiation model 1). (3) Continuation of this process may have led to crystallization at even greater depth, in the lower crust or the upper mantle ($P \approx 15$–20 Kb), where orthopyroxene or Ca-poor clinopyroxene are the dominant liquidus phases. Extraction of suitable amounts of these from primitive olivine tholeiite would produce directly transitional alkali basaltic etnaïtes and etnaïtes themselves (differentiation model II). To obtain the exact trachybasaltic composition of etnaïte, however, it is necessary to consider K_2O enrichment by additional mechanisms such as gaseous transfer, wall rock reaction or zone refining. A shifting of the composition of the primary magma toward more potassic alkaline type is possible, but almost entirely speculative.

This model is similar to those recently proposed in other provinces (e.g. Cox and Jamieson, 1974, particularly p. 298–299) and yields additional support for a deep crust or upper mantle origin of intermediate alkaline lavas (Macdonald, 1969; Green et al., 1974; Thompson, 1974).

Basalts of olivine tholeiite composition (normative $Ol + Hy$) have been recently reported from many localities, most of them being abyssal oceanic tholeiites. Among the olivine tholeiite compositions, however, a distinction must be made between "primitive" olivine tholeiites (i.e. little or no differentiated primary magma) and "transitional basalts" (Bass, 1972) which are obviously more evolved types, perhaps by a process similar to that of the pre-etnean "transitional tholeiites". At any rate, the term transitional basalt is ambiguous and it should be used only for convenience in specific studies where a precise definition is given (see above).

The tholeiitic basalts of Etna only differ from most oceanic tholeiites (Shido and Miyashiro, 1971) by somewhat lower Ca and Al contents. This similarity suggests a common origin for these magmas and particularly a similar process for their generation. A convergence of facts, therefore, seems to indicate that crustal extension in volcanic provinces such as Mount Etna would be the consequence—as in oceanic regions—of rising of the upper mantle at comparatively shallow depth.

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