EXPERIMENTAL PETROLOGY OF HIGH TITANIUM BASALT

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Table 1 contains experimental results for 28 synthetic compositions related to high Ti-basalt run in molybdenum capsules at the fO_2 of the Fe/FeO equilibrium. Primary liquidus fields of olivine, pigeonite, augite, anorthite, ilmenite and armalcolite are found, and the six fields must come close to conjuction in a cotectic liquid whose composition lies intermediate between 528 and 89, all six phases appearing almost simultaneously at the liquidus in such a liquid, at a temperature of close to 1145°C. Phase equilibria data for some Apollo 17 soils in table 2 show early crystallization of anorthite after olivine and iron-titanium oxides. The orange soil 74220 has a very high liquidus temperature, and extensive early olivine crystallization before the entry of other phases. Apollo 17 high TiO_2 rock compositions (table 2) show early crystallization of iron-titanium oxides and ferromagnesian silicates before anorthite appearance. The compositions of Apollo 17 rocks and soils resemble those of Apollo 11 materials, but are poorer in silica, and higher in Mg/Mg + Fe. The average rock composition erupted at the Apollo 11 site was that of a liquid in simulataneous equilibrium with many crystalline phases (including anorthite). Phenocrysts of anorthite, olivine, ilmenite, spinel and pyroxene were all present in small amounts in evidently rapidly quenched matrix among the lithic fragments in soils and breccias (O'Hara et al. in press EPSL).

The chemical characteristics of the high titanium basalts and soils are best accounted for if the original magma was derived from the residual liquid in a high level magma chamber in which there was well advanced extreme fractional crystallization of anorthite-bearing cumulates. Eruption was followed by enrichment of the flow base in olivine and iron-titanium oxides relative to the upper parts. If such a model is adopted for Apollo 17 the orange soil must be regarded as an impact melt, an interpretation supported by the liquidus temperature which is exceptionally high for a magma of internal origin.

Figure 1A shows variation of liquidus phase in 24 of the 26 synthetic network samples studied as a function of SiO_2 and TiO_2 content. Fields in which pigeonite (PIG), anorthite (AN), olivine (OL), or titanium-rich oxide (TI-OXIDE) are the liquidus phases are indicated. Anorthite does not appear as a liqidus phase at this low oxygen fugacity in the compositions 1-9, 23, 56, 59, 69, 89 but its liquidus field lies very close to the surface defined by those compositions. Samples 28 and 38 both display anorthite liquidus as do samples 838, 538 and 528 which are intermediate between 8 and 38, 5 and 38 and 5 and 28 respectively. The narrow anorthite field indicated between the olivine and pigeonite fields thus expresses the composition region in which anorthite will most readily crystallize from TiO_2-rich magmas in the presence of olivine and pigeonite. Figure 2A shows the variation of liquidus phase in the same range of synthetic compositions as a function of SiO_2 and $CaO+Al_2O_3$ content.

TABLE 1

Compn.	1	2	23	3	4	5	56	6	58	59	69	7	9
	ol, an >1164 aug, pig, ilm 1148 ± 15	ol>1205 an, aug, ilm 1170	ol>1205 aug(1180) an 1165	ol>1205 an, ilm 1165	ol>1215 an 1193 ± 20 aug, pig 1153 ± 20 ilm 1121±10	ol>1220 an 1210 aug 1160 ilm 1145	ol>1190 an 1172 ilm 1161 cpx 1150	ol>1200 arm, an, ilm 1170 aug 1155	ol>1180 an 1165 aug 1155 pig 1150 ilm 1145	ol 1170 an 1160 pig, arm 1155 ilm 1145	arm, ol 1165 an, ilm, pig 1150	pig 1205±8 aug 1185±12 an 1167±5	pig 1195 ol 1170 aug 1160 an 1155 ilm 1135
SiO_2	43.5	40.5	39.2	37.9	44.9	41.3	40.3	38.3	43.0	41.5	40.0	48.5	44.8
TiO_2	3.8	7.2	8.7	10.1	4.6	6.5	10.1	11.7	8.2	9.8	11.4	4.3	7.9
Al_2O_3	9.8	9.2	8.8	8.5	11.7	10.8	10.4	10.0	10.6	10.1	9.7	11.0	10.2
FeO	19.8	21.7	22.5	23.4	16.6	19.0	20.0	21.1	18.5	19.5	20.6	15.5	17.9
MgO	12.2	11.4	11.0	10.6	9.3	8.5	8.2	7.9	8.3	7.9	7.6	8.7	8.0
CaO	10.8	10.1	9.8	9.4	12.9	11.9	11.5	11.0	11.5	11.2	10.7	12.1	11.2

Compn.	89	9	838	538	38	28	528	548	48	848	828	818	18
	pig 1170 arm 1165 an, ilm 1145	arm, pig 1177 ilm 1156 an 1145	an>1190 cpx 1165 ilm 1136	an>1190 ol (1180) aug 1165 pig 1148 ilm 1136	an>1190 cpx 1177 ol 1173 ilm 1136	an 1185 pig 1151 aug 1148 ilm 1135	an, ol, aug 1170 ilm, pig 1135	aug, ol 1195 an 1156 pig 1145	aug 1197 an 1154 pig 1145 ilm(1120)	pig(1175) an 1150 ilm 1130	pig 1160 aug, an 1154 ilm 1136	pig, ol >1195 an 1146 ilm 1136	pig, ol >1218 an 1146 ilm 1140
SiO_2	43.3	41.7	44.6	42.9	44.5	43.8	42.5	43.8	46.2	45.5	44.3	45.2	45.6
TiO_2	9.5	11.1	7.1	7.5	6.2	9.0	8.8	7.5	6.5	7.2	8.4	7.5	7.1
Al_2O_3	9.8	9.4	13.0	13.4	15.9	11.4	11.1	9.5	8.3	9.3	10.8	9.7	9.1
FeO	19.0	20.0	16.0	16.5	14.0	16.7	17.8	18.1	17.1	17.5	17.3	18.4	18.8
MgO	7.7	7.4	7.1	7.4	6.3	6.5	7.5	8.4	8.4	8.2	7.2	8.6	9.2
CaO	10.8	10.4	12.2	12.5	13.1	12.6	12.2	12.8	13.6	12.4	11.9	10.6	10.0

Temperatures of appearance of phases are probably ± 5°C. Those in brackets (1195) are ± 10°C. In many samples armalcolite reacts out after the appearance of ilmenite and olivine reacts out after the appearance of pigeonite.

TABLE 2. Preliminary atmospheric pressure, Fe/FeO oxygen fugacity data for Apollo 17 samples

Temp °C	70017	70181	71501	74220	74241	74261	75061	75081
1279	g	g	g	ad 2g's	g	(d)g	g	(d)g
1207	acdg	adg	adg	ad(e)g	adg	adg	adg	acdg
1177	acdg	abdg	adeg	adeg				
1163	acdeg	abdg	abcdefg	adeg	abdfg	abdg	abcdg	abcdg
1140	abeg	abefg	abefg	adefg	abefg	abeg	abeg	abdefg
1129	abefg	abefg	abefg	abefg	abef	abefg	abefg	abefg

a=olivine; b= plagioclase; c=armalcolite; d=spinel; e=ilmenite; f=clinopyroxene; g=glass

Other results 74220 1352=a,2g's; 1325=a,d,2g's; 1152=adeg; 74261 1325=g

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Figures 1B, 2B compare natural high-titanium basalt data (attached key) with the phase boundaries deduced from figs. 1A, 2A. Figures 1C, 2C compare Apollo 17 rock and soil compositions with the same phase boundaries. The other important aspect of the chemistry variation of these rocks, Mg/Fe ratio as a function of silica-saturation level, is displayed in the MgO-FeO-SiO_2 plots (figs. 3A-D). Figure 3A shows the synthetic net (table 1) and the deduced region of anorthite-saturated multiphase cotectic liquid composition (large circle). Figure 3B shows the relationships of various natural Apollo 11 high titanium basalts to that composition, while figure 3C follows the trends of liquid evolution in the experimental <u>equilibrium</u> crystallization of some of the samples at an fO_2 slightly but significantly higher than in the natural rocks. Figure 3D shows the compositions of Apollo 17 soils and rocks in relation to the synthetic nets and Apollo 11 rock data.

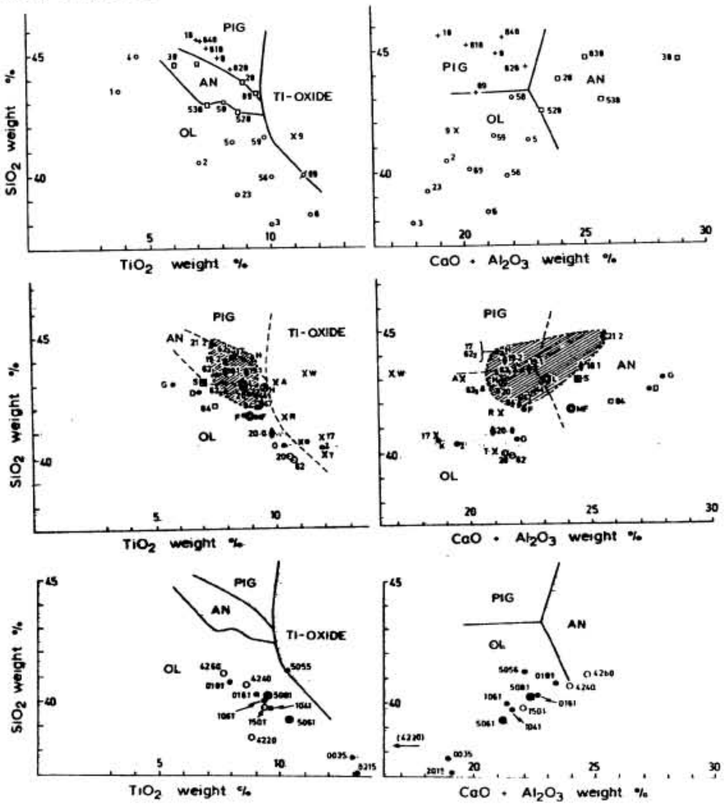

Fig 1A — Fig 2A

Fig 1B — Fig 2B

Fig 1C — Fig 2C

<u>Key to figures 1-3</u>

(1) Points in figures 1A-2A & 3A are identified by the numbers in table 1, and symbolised in 1A, 2A, by liquidus phase in atmospheric pressure experiments as listed in (2).

(2) <u>Figures 1B,2B,3B and 3C</u>

Liquidus phase (excluding spinel) is:- O = olivine; + = pigeonite; □ = anorthite; X = titanium-rich oxide, in the following compositions (groups C-F). • indicates a composition for which no phase equilibria data are available.

A. <u>Liquids produced in experiments from natural rocks, soil or synthetics made up to natural rock compositions, which are in or close to equilibrium with olivine, plagioclase, pyroxene(s) and titanium-rich oxide.</u>

▲17 = from 10017, 1133°C; ▲62_1 = from 10062, 1142°C

▲20 = from 10020, 1133°C; ▲62_2 = from 10062, 1133°C

▲84 = from 10084, 1160°C; ▲62_3 = from 10062, 1120°C

▲H = from lithic fragment average, high potassium group.

(Data from Biggar <u>et al</u> 1971, O'Hara <u>et al</u> 1974)

B. Natural rock, groundmass or glass compositions beleived, from petrographic evidence, to represent liquids close to saturates with olivine, anorthite pyroxene and iron-titanium oxide.

♦19.1 = groundmass to anorthite phenocrysts in 10019/15; fragment one

♦19.2 = groundmass to anorthite phenocrysts in 10019/15; fragment two

♦21.2 = groundmass to anorthite phenocrysts in 10021/26; fragment two

♦18.1 = groundmass to olivine, spinel, ilmenite phenocrysts in 10018/20; fragment one

♦20.0 = trapped liquid in olivine phenocryst, 10020

(Data from Roeder and Weiblen 1970; O'Hara <u>et al</u> 1974)

C. Average compositions of rock types.

O L = average low K_2O lithic fragments in soil (Prinz <u>et al</u> 1971);

⊗ H = average high K_2O lithic fragments (see A above)(Prinz et al 1971);

• F = average of hand-picked microgabbro fragments in soil (Frondel <u>et al</u> 1970)

• K = average of hand picked vesicular basalt in soil (Fondel <u>et al</u> 1970)

• O = average of hand specimens of low K_2O (ophitic group) basalts, (Compston <u>et al</u> 1970) referred to precipitate anorthite when less than 10% crystalline (from James and Jackson 1971).

• I = average of hand speciments of high K_2O (intersertal group) basalts (Compston <u>et al</u> 1970)

• D)= inferred more feldspathic basalt component, required to be mixed

• G) with hand specimen averages to explain soil compositions (Duke <u>et al</u> 1970; Goles <u>et al</u> 1970)

D. <u>Individual hand specimen analyses</u>

X17 = 10017 intersertal, high K_2O group

O20 = 10020) ophitic, low K_2O group
O62 = 10062)

•44 = 10044 ophitic group rocks, judged to lie relatively close to

•47 = 10047 anorthite saturated compositions (Biggar <u>et al</u> 1971)

Chemical analyses from Agrell <u>et al</u> (1970); Compston <u>et al</u> (1970) Experimental data from O'Hara <u>et al</u> (1974).

E. <u>Synthetic mixtures made up to particular 'rock' compositions</u>

X A = Anderson <u>et al</u> (1970)

X R = Ringwood and Essene (1970)

X T = Tuthill and Sato (1970)

X W = Weill <u>et al</u> (1970)

+ S = Schairer and Muan (1971)

O MF = High titanium basalt glass (Reid <u>et al</u> 1971) from Mare Fecunditatis, experimental data in this paper.

F. <u>Soil samples, viewed here as representing average magma plus c 3.5% of highland derived anorthosites etc.</u>

□ 84 = soil sample 10084 (O'Hara <u>et al</u> 1970)

(3) <u>Figures 1C, 2C, 3D</u>. Apollo 17 rock and soil compositions are indicated by the final four digits of the specimen numbers, coded for liquidus phase as in previous figures.

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Figure 3. Projections from anorthite, albite, orthoclase, $CaSiO_3$, TiO_2, Cr_2O_3 etc. into MgO-FeO-SiO_2

Fig 3A
synthetic net

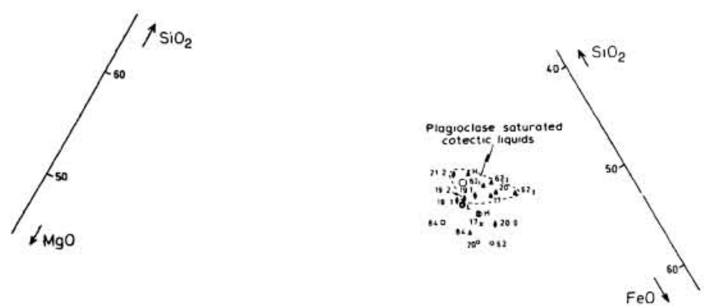

Fig 3B
Natural rock data
Apollo 11

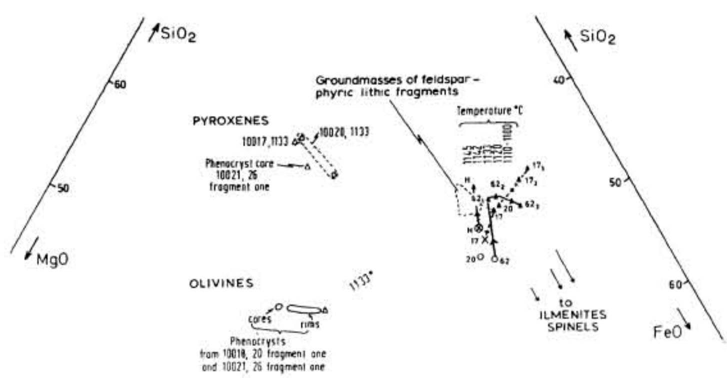

Fig 3C
Crystallization of Apollo 11

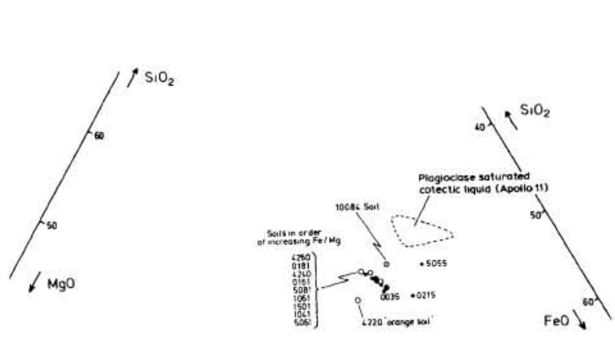

Fig 3D
Apollo 17 results