Mare Basalt Petrogenesis

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Mare basalt petrogenesis

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Melting experiments in vacuum at Fe-saturation for high-Ti basalt compositions 70215 and 15318 Red Glass, and low-Ti basalt composition 15555–15016, have defined equilibrium crystallization sequences and the liquid-lines-of-descent, and show that much of the chemical variety in the natural samples is due to near-surface fractionation processes. However, the various groups within the high-Ti suite (Apollo 11 low-K, Apollo 11 high-K and Apollo 17 basalts; Apollo 17 Orange Glass) cannot be interrelated by such processes, nor can the high-Ti suite be a near-surface derivative of a low-Ti parent magma. Likewise, the low-Ti Apollo 12 basalts and Apollo 15 basalts and Green Glass cannot be interrelated by simple fractionation, although much of the chemical variety within each group is explained by olivine fractionation.

On the basis of high-pressure studies, low-Ti basalts are believed to originate as a spectrum of partial melts from a previously differentiated olivine-pyroxenite lunar mantle, at depths ranging from approximately 200–500 km. High-Ti basalts are interpreted as hybrid liquids resulting from the assimilation of subcrustal Ti-rich material by a parental magma of low-Ti type.

INTRODUCTION

The mare basalt samples returned by the Apollo missions show considerable mineralogical and textural diversity, but in general belong to one of two major chemical groups: (*a*) the *high-titanium* suite, typically with 10–12 % TiO_2, or (*b*) the *low-titanium* suite, characterized by TiO_2 contents typically 2–4 %. The crystallization ages of the mare basalts correlate well with this bimodal bulk chemistry; high-Ti basalts, collected at Apollo 11 and 17 have approximately 3.8 Ga ages, whereas low-Ti basalts from Apollo 12 and 15, have markedly younger 3.3 Ga ages.

The two major chemical groups can be conveniently subdivided on the basis of their chemistry and mineralogy, as follows:

High-Ti suite. Apollo 11 high-K basalts, Apollo 11 low-K basalts, Apollo 17 basalts, Apollo 17 Orange Glass.

Low-Ti suite. Apollo 12 olivine-pigeonite basalts, Apollo 12 ilmenite basalts, Apollo 12 felspathic basalts; Apollo 15 olivine-normative basalts, Apollo 15 quartz-normative basalts, Apollo 15 Green Glass.

The origins and petrogenesis of the various mare basalt types remain controversial topics, but the techniques of experimental petrology can be usefully employed to answer some of these questions. This paper summarizes the results of melting experiments in vacuum by Kesson (1975), which have defined crystallization sequences and the equilibrium liquid-line-of-descent, and can thereby establish fractionation trends in the low-Ti and high-Ti suites. The results of her high-pressure studies provide some limited information on the mineralogy, depth,

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and thermal regime of mare basalt source regions in the lunar mantle. These high-pressure results, in combination with isotopic, geochemical and geophysical constraints, are used to construct a scenario for mare basalt petrogenesis.

EXPERIMENTAL TECHNIQUES

Complete details of the various experimental techniques, and the justification for their use, are given by Kesson (1975).

COMPOSITIONS INVESTIGATED

Synthetic analogues of high-Ti basalts 70215 and 15318 Red Glass, and low-Ti basalt 15555–15016 were used in the experimental study. Table 1 contains chemical analyses of the natural rock compositions.

TABLE 1. MARE BASALT COMPOSITIONS.

	high-ti basalts		low-ti basalts	
	70215[2]	15318 Red Glass[3]	15555[1]	15016[1]
SiO_3	37.70	34.88	44.49	44.65
TiO_2	13.34	14.25	2.27	2.35
Al_2O_3	8.79	7.07	8.53	8.56
FeO	19.89	22.20	22.60	22.93
MnO	0.28	0.29	0.29	0.34
MgO	8.65	12.18	11.26	11.31
CaO	10.57	7.96	9.51	9.55
Na_2O	0.32	0.39	0.24	0.21
K_2O	0.04	0.15	0.03	0.03
Cr_2O_3	0.43	0.62	0.66	0.67
total	100.00	100.00	100.00	100.00
Fe/(Fe+Mg)	0.56	0.50	0.53	0.53

Analyses of natural samples recalculated to 100%.

[1] Apollo 15 LSPET (1972). [2] Apollo 17 LSPET (1973). [3] Hlava *et al.* (1973), analysis 15318 (1).

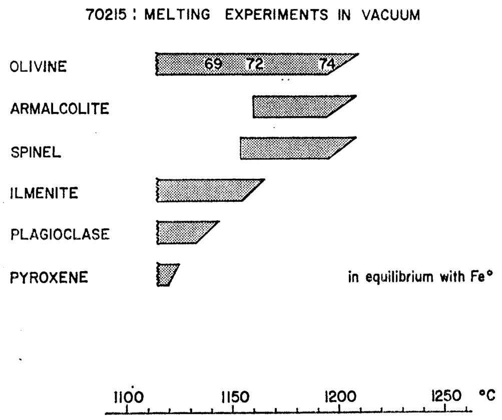
70215 (described by Longhi *et al.* 1974; Green *et al.* 1974), contains microphenocrysts of armalcolite (Mg/(Mg+Fe) = 0.48 max) and olivine (Fo_{74} max) with inclusions of Ti–Cr spinel, set a quenched, vitrophyric groundmass of zoned olivine, zoned calcic pyroxene, ilmenite and plagioclase.

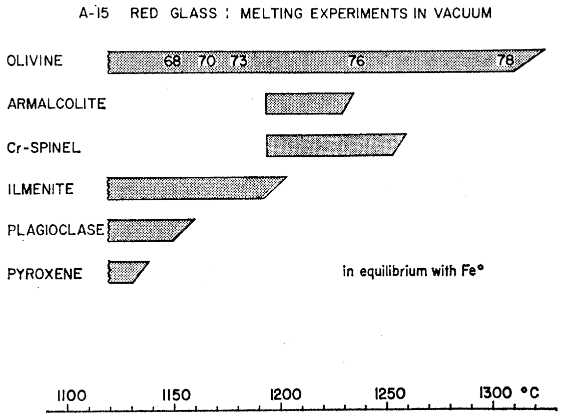
15318 Red Glass: Hlava *et al.* (1973) present data which show that the abundant glass spherules in the Apollo 15 rake samples include a high-Ti mare basalt component, which is compositionally quite distinct from highlands ejecta and regolith impact melts. The orange-red glass composition, 15318 Red Glass, has one of the highest TiO_2 contents and lowest Fe/Mg ratios reported for the high-Ti suite. Volcanic fire-fountaining (Heiken & McKay 1974) is a possible explanation for the origin of these mare glasses, but their stratigraphic location (on a crater ray from Aristullus or Autolycus) suggests that impact processes may be a more likely explanation.

15555 and 15016 (described by LSPET 1972; Kushiro 1972; Longhi *et al.* 1972) are compositionally equivalent. 15555 is coarser-grained with olivine (Fo 71 max), plagioclase, pyroxene (pigeonite cores zoned to augite rims), minor Ti–Cr spinel and groundmass ilmenite and cristobalite. The finer-grained, vesicular 15016 has olivine (Fo_{72} max) in a subophitic to intergranular matrix of plagioclase, pyroxene, minor spinel and ilmenite.

Melting experiments in vacuum

The equilibrium crystallization sequences and liquid-line-of-descent of 70215, 15318 Red Glass and 15555–15016, in vacuum at Fe-saturation, are summarized by figures 1–6. A full description of the method is given by Kesson (1975). The phase-entry temperature ranges given in the following discussion refer to the temperature intervals for reversals.





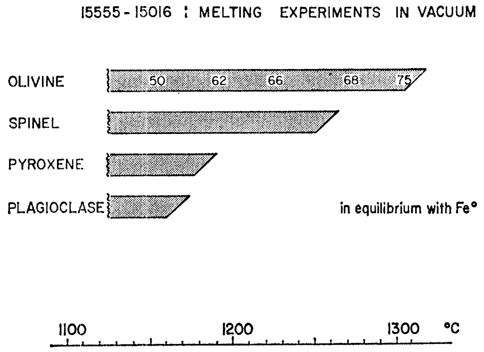


Figure 1. Equilibrium crystallization sequence for 70215 in vacuum. Numbers in olivine field refer to mol % Fo. Tapered regions of phase fields correspond to temperature intervals for phase-entry reversal.

Figure 2. Equilibrium crystallization sequence for 15555–15016 in vacuum. Numbers in olivine field refer to mol % Fo. Notation as in figure 1.

Figure 3. Equilibrium crystallization sequence for 15555–15016 in vacuum. Numbers in olivine field refer to mol % Fo. Notation as in figure 1.

High-Ti basalts

70215 is simultaneously saturated with three phases at its liquidus (1206–1196 °C); olivine Fo_{74}, armalcolite $Mg/(Mg+Fe) = 0.54$, and a Ti–Cr spinel. At 1161 °C armalcolite $Mg/(Mg+Fe) = 0.50$ reacts out with the liquid to produce ilmenite $Mg/(Mg+Fe) = 0.32$, and spinel reacts out by 1142 °C. Plagioclase crystallizes at 1143–1135 °C and pyroxene at 1126–

1121 °C. The equilibrium crystallization of plagioclase before pyroxene is the reverse of the sequence observed in the quickly-chilled natural rock, and implies that rapid cooling effectively delays plagioclase nucleation.

15318 Red Glass has olivine Fo_{78} on its liquidus at 1300–1290 °C, followed by a Ti–Cr spinel at 1261–1253 °C. Armalcolite crystallizes at 1245–1235 °C but reacts with the liquid to produce ilmenite in the temperature interval from 1199 to 1196 °C, and spinel reacts with the liquid by 1196 °C. Plagioclase appears at 1158–1150 °C and pyroxene at 1139–1130 °C.

With decreasing temperature, as crystallization proceeds in the high-Ti compositions, Fe/(Fe + Mg) ratios in the residual liquids increase, and provide a useful fractionation index. Kesson (1975) found that Cr_2O_3 and MgO abundances decrease rapidly with fractionation, reflecting the early crystallization of olivine and spinel, while alkalis, SiO_2 and MnO are concentrated in the residual liquids. TiO_2 abundances gradually drop, since Ti-rich oxide phases are present throughout the crystallization interval. CaO and Al_2O_3 abundances build up until plagioclase-saturation is reached.

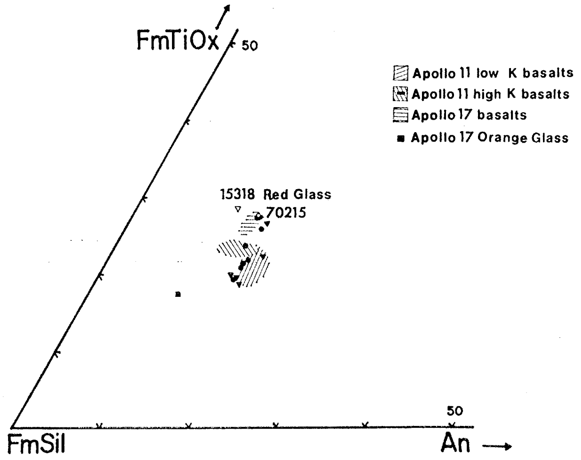


FIGURE 4

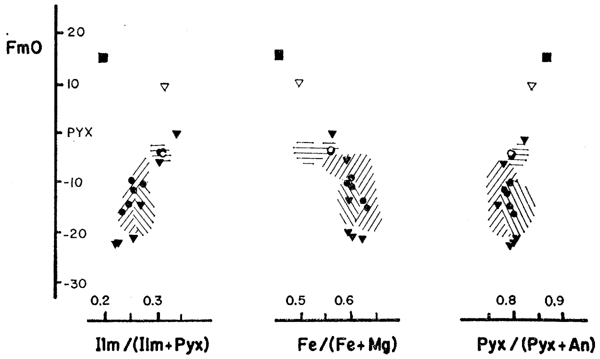


FIGURE 5

FIGURE 4. Equilibrium liquid-line-of-descent for 70215 (circles) and 15318 Red Glass (triangles). Open symbols represent corresponding bulk rock compositions. Pseudoquaternary projection scheme for high-Ti basalts from Longhi *et al.* (1974).

FIGURE 5. Sub-projection in pseudoquaternary system of Longhi *et al.* (1974) illustrating experimentally determined liquid-line-of-descent for high-Ti basalts 70215 and 15318 Red Glass. Notation as in figure 4.

The vitrophyric texture of 70215 has been interpreted as evidence that the magma was erupted in an entirely liquid state on the lunar surface (Longhi *et al.* 1974; Green *et al.* 1975). O'Hara & Humphries (1975) and O'Hara *et al.* (1974) have challenged this interpretation, arguing that the hand specimens are not representative of true liquid compositions, but have a more complex history involving post-eruptive cumulus enrichment of microphenocryst phases in a cotectic (= multiply saturated) liquid. In other words, they propose that a hand specimen composition is equivalent to that of a cotectic liquid plus microphenocrysts. But any such composition, brought to its liquidus in laboratory melting experiments, will no longer be simultaneously saturated with several phases. The simultaneous saturation of the liquidus of 70215 with three phases does not substantiate the interpretation of O'Hara *et al.* (1974), and strongly suggests that the 70215 magma was entirely liquid at eruption. This peculiarity of the phase equilibria also indicates a prior fractionation history, and shows that the liquid which was erupted at the surface was derivative in character and not a true primary magma from the lunar interior.

15318 Red Glass is highly olivine-normative, and its composition could be explained by impact-remelting of an olivine-rich accumulate. But Red Glass does not have the disproportionately high Cr_2O_3 content which would be expected to characterize an early cumulate of olivine, spinel and armalcolite (Kesson 1975), so it is either a representative sample of a picritic high-Ti liquid, or an impact melt of a magma which had undergone only very limited cumulus enrichment.

The equilibrium liquid-line-of-descent for high-Ti basalts is summarized by Kesson (1975) and is illustrated in figures 4 and 5 by projection into a model system. 'FmO–Ilm–Pyx–An' (see Longhi *et al.* 1974). The similarity with the distribution of the natural samples strongly suggests that near-surface fractionation processes play an important role in determining the chemical variety in the high-Ti suite. But geochemical and trace-element arguments can be used to show that near-surface fractionation processes cannot be called upon to interrelate the low-K and high-K Apollo 11 groups, nor can they provide a genetic link between Orange Glass and any other high-Ti group (Walker *et al.* 1975; Green *et al.* 1975).

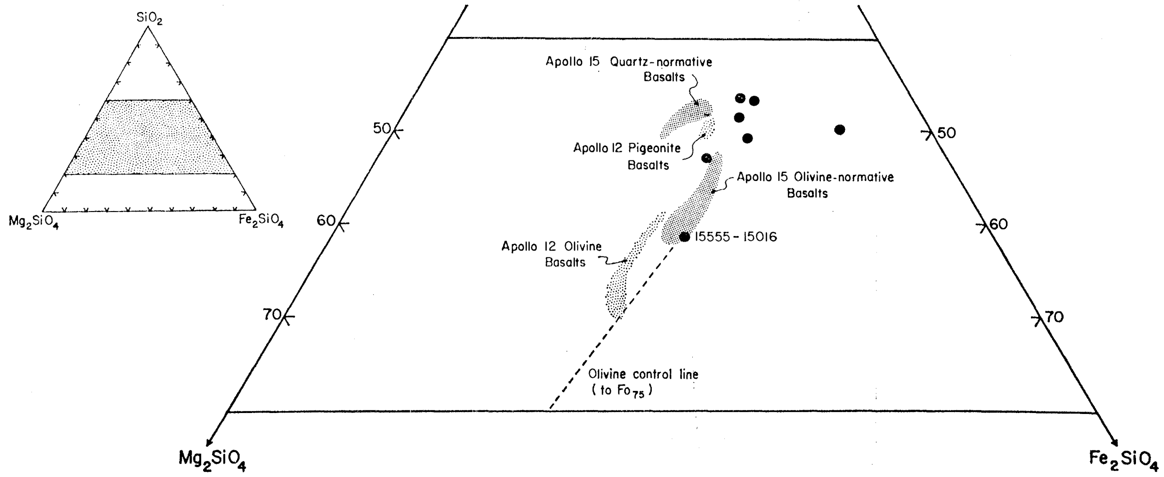


FIGURE 6. Experimentally determined equilibrium liquid-line-of-descent for low-Ti basalt 15555–15016, projected into the system Mg_2SiO_4–Fe_2SiO_4–SiO_2.

Low-Ti basalts

15555–15016, a typical example of the Apollo 16 olivine-normative basalts, has olivine Fo_{75} as its liquidus phase at 1300–1283 °C. Ti–Cr spinel crystallizes at 1237–1227 °C, pyroxene at 1162–1156 °C and plagioclase at 1147–1138 °C. Neither armalcolite nor ilmenite occur in the equilibrium crystallization sequence. The analytical data presented by Kesson (1975) show that the liquid-line-of-descent is characterized by decreasing MgO and Cr_2O_3 abundances, reflecting the early crystallization of olivine and spinel. FeO and SiO_2 do not show any dramatic increase until the very late stages of fractionation. CaO and Al_2O_3 abundances build up until plagioclase-saturation is reached and TiO_2 abundances increase steadily, despite the continued crystallization of Ti–Cr spinel.

The chemical evolution of 15555–15016 derivative liquids is illustrated in figure 6 by means of projection into the system Mg_2SiO_4–Fe_2SiO_4–SiO_2. The distribution of the natural low-Ti basalts in general follows an olivine control-line and the 15555–15016 derivative liquids lie on the same general trend. This suggests that crystal fractionation or accumulation processes, involving olivine (and minor spinel) are mainly responsible for the chemical diversity among the various groups in the low-Ti suite. However, geochemical and trace-element constraints prove that most of the various groups within the low-Ti suite, e.g. Apollo 15 quartz-normative,

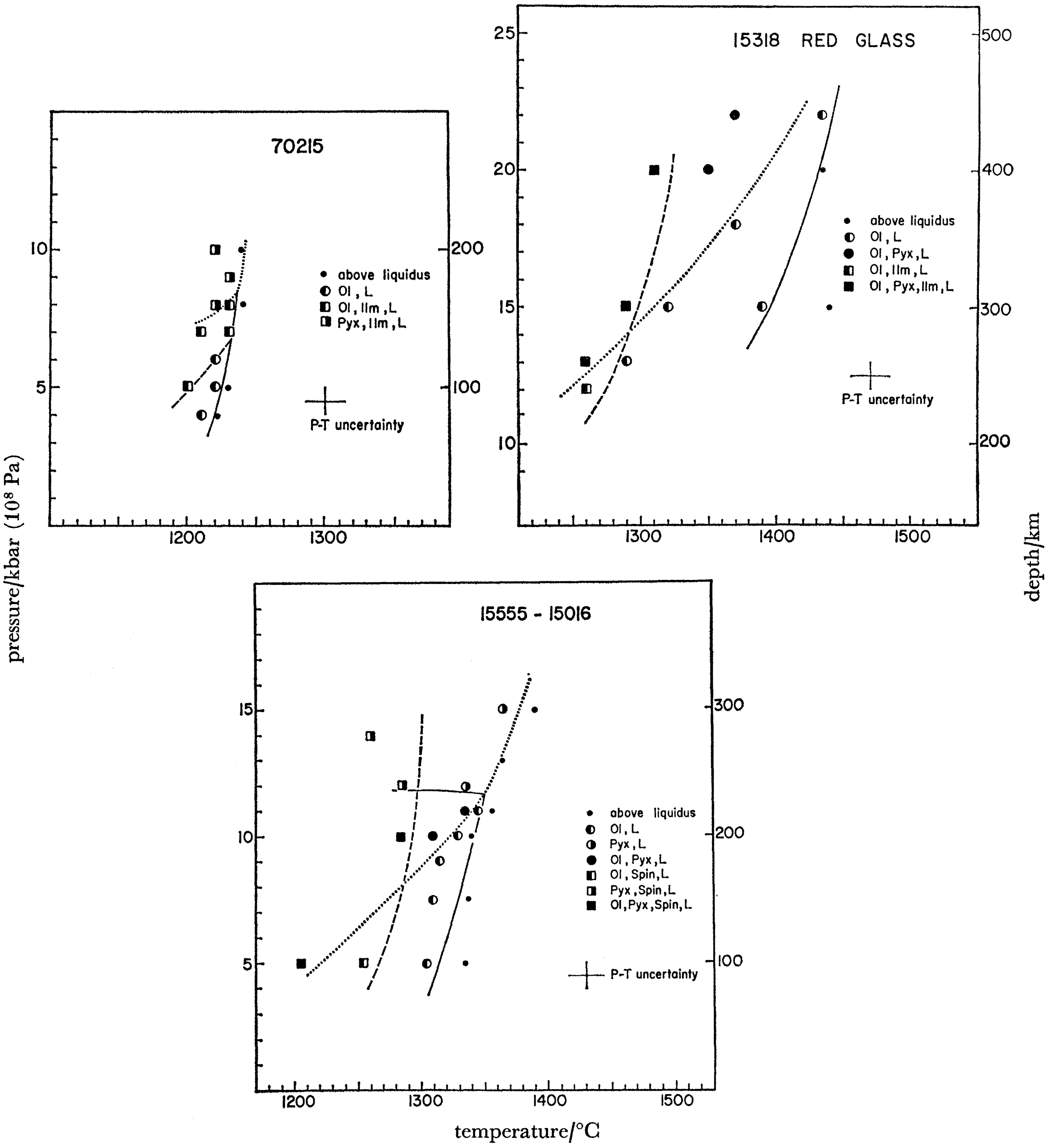


Figure 7. High-pressure near-liquidus phase equilibria for 70215 at Fe-saturation. Olivine entry is bounded by solid curve, pyroxene entry by dotted curve, ilmenite entry by dashed curve.

Figure 8. High-pressure equilibria for 15318 Red Glass. Notation as in figure 7.

Figure 9. High-pressure equilibria for 15555–15016. Spinel entry shown by dashed curve. Other notation as in figure 7.

Apollo 15 olivine-normative, Green Glass – cannot be interrelated by crystal fractionation processes (e.g. Rhodes 1972; Chappell & Green 1973).

The low-Ti suite cannot be parental to the high-Ti suite, since there is no stage at which low-Ti residual liquids even remotely resemble high-Ti compositions (Kesson 1975). Furthermore, neither armalcolite nor ilmenite – the characteristic near-liquidus oxide phases of the high-Ti suite – appear in the crystallization sequence of low-Ti basalts.

High-pressure experiments

Ideally, the purpose of high-pressure melting experiments is to define the phase chemistry, mineralogy, pressure (= depth) and thermal regime of mare basalt source regions in the lunar interior. However, this is only possible if the samples investigated represent true primary magmas, i.e. unfractionated, uncontaminated partial melts, from the lunar mantle. Since melting experiments in vacuum indicate a prior fractionation history for many mare basalts, high-pressure experiments will provide at best only a limited amount of information on mare basalt source regions, and can generally only indicate the residual mineralogy, and a *minimum* depth for partial melting. (High-pressure equilibria are illustrated in figures 7, 8 and 9.)

High-Ti basalts

70215 has olivine Fo_{73} on its liquidus to approximately 6.5 kbar (650 MPa) olivine plus ilmenite $Mg/(Mg+Fe) = 0.32$ from 6.5 to approximately 8.5 kbar (850 MPa) and pyroxene plus ilmenite at higher pressures. Thus at 8.5 kbar and 1230 °C, the liquidus is simultaneously saturated with olivine, pyroxene and ilmenite, implying an olivine–pyroxene–ilmenite residual mineralogy at 170 km or deeper.

15318 Red Glass has olivine Fo_{78} as its liquidus phase to at least 22 kbar; by extrapolation the liquidus is simultaneously saturated with olivine and pyroxene between 25 and 30 kbar (250 and 300 MPa). This implies an *ilmenite-free* olivine-pyroxenite residual mineralogy at approximately 500–600 km.

Green *et al.* (1975) have presented results indicating an ilmenite-free olivine–pyroxenite residual mineralogy at depths of 240 km or deeper, for one of the least-fractionated Apollo 17 basalts, 74275.

With such an extreme range of petrogenetic interpretations for the depth of origin and residual source region mineralogy for the high-Ti suite, one must seriously consider the possibility that the high-pressure equilibria have little or no bearing on reality. This could happen if the high-Ti suite were produced by hybridization or by assimilative processes, as suggested by Anderson (1971) and Hubbard & Minear (1975).

Low-Ti suite

15555–15016 has olivine Fo $\geqslant 73$ on its liquidus to approximately 12 kbar (1200 MPa), then pyroxene to higher pressures. Spinel remains sub-liquidus at all pressures. The simultaneous saturation of the liquidus with olivine and pyroxene at 12 kbar and 1350 °C (figure 9) implies an olivine–pyroxenite residuum at a minimum depth of 240 km.

These results are consistent with the following interpretation developed by Green & Ringwood (1973): the low-Ti suite is believed to be produced by partial melting of an olivine–pyroxenite lunar mantle, at depths ranging from approximately 200 to 500 km. A spectrum of primary magmas can be explained in this way, with the least olivine-normative liquids (Apollo 15 quartz-normative basalts) originating at the shallowest levels and the most olivine-normative (Apollo 15 Green Glass) at the deepest levels. Apollo 12 and 15 olivine basalts are believed to form at intermediate depths.

Petrogenesis of mare basalts

In the early geologic history of the Moon, just after accretion at about 4.5 Ga, the outer several hundred kilometres are believed to have melted and subsequently differentiated to form a thick, basal olivine–pyroxenite cumulate upper mantle and the complementary plagioclase-enriched highlands crust. The Ti-rich residual liquids of this differentiation event are thought to have been sandwiched between the crust and underlying mafic cumulate zone (e.g. Smith *et al.* 1970; Taylor & Jakes 1974).

A record of this early differentiation event is preserved in the isotope systematics of both low-Ti and high-Ti basalts (e.g. Compston *et al.* 1971; Tera & Wasserburg 1975; Lugmair *et al.* 1975). These isotopic characteristics imply that the source regions of mare basalts lie in the differentiated lunar upper mantle.

Alternatively, mare basalt source regions may lie in the primitive, undifferentiated, fertile lunar interior and the magmas may acquire their isotopic characteristics by some kind of complex interaction with the differentiated upper mantle. But the former explanation, being simpler, is preferred; furthermore, the characteristic r.e.e. abundance patterns of mare basalts are more easily explained in terms of a previously differentiated source region (Kesson 1975).

In summary, low-Ti mare basalts are interpreted as partial melts of a differentiated olivine–pyroxenite lunar mantle, at depths ranging from approximately 200 to 500 km. High-Ti basalts are interpreted as hybrid liquids resulting from the assimilation of the late-stage, subcrustal Ti-rich residuum by parental magmas of low-Ti type and origins.

Chemical differences *between* the various groups comprising the high-Ti suite are tentatively ascribed to compositional variety in the material assimilated by the parental magmas. Melting experiments in vacuum demonstrate that the chemical variety *within* the various groups is predominantly controlled by near-surface fractionation processes, but the high-Ti suite and low-Ti suite cannot be genetically linked by such mechanisms.

In the low-Ti suite, the chemical differences *between* the various groups, e.g. Apollo 15 quartz-normative basalts and Green Glass, are ascribed to different depth regimes for partial melting (Green & Ringwood 1973). The chemical variety *within* the various groups is attributed to fractionation (and accumulation) involving olivine and minor spinel.

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