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PETROGRAPHY AND PETROLOGY OF APOLLO 12 ILMENITE BASALTS 12005 AND

12045. M. A. Dungan, NRC-Resident Research Associate, NASA-Johnson Space Center, Houston, TX 77058; R. W. Brown and R. M. Myers, Lockheed Electronics Co., Inc. Houston, TX 77058

The paper presents preliminary results of one aspect of a collaborative reexamination of the Apollo 12 mare basalts (1,2,3). The Apollo 12 ilmenite basalts are a unique suite among the returned mare basalts and are receiving special attention in our investigations. New data generated by (1,2) has confirmed chemical and isotopic distinctions between the ilmenite suite and the olivine-pigeonite suite and has shown that extensive olivine fractionation has occurred in both groups resulting in highly fractionated compositions and olivine cumulates.

12005 - Coarse-grained Apollo 12 olivine basalts (e.g., 12040, 12035) are partial cumulates which have been enriched in olivine to varying degrees by near-surface crystal fractionation (4). New chemical analyses of Apollo 12 basalts (1) have allowed the identification of two coarse-grained quasi-ultramafic rocks (12036 and 12005) which are related to the ilmenite suite by olivine accumulation. On the basis of REE and Sr 87/86 initial ratio (2) concurs that 12005 is an ilmenite suite basalt. 12005 has the highest MgO and FeO as well as the lowest CaO, Al_2O_3, SiO_2 and magmaphile elements of any Apollo 12 basalt (1) and, therefore, may be the most olivine-enriched mare basalt studied thus far. The unique chemical composition of 12005 is reflected in its modal mineralogy: olivine = 30%, low-Ca pyroxene = 35.5%, high-Ca pyroxene = 21% plagioclase = 11%, ilmenite = 1.9%, spinel, etc. <1%.

Petrography and Mineral Chemistry - The petrography and mineral chemistry (particularly of the pyroxenes) are also distinct from any of the fine-grained A-12 mare basalts and are compatible with a cumulus origin. 12005 is heterogeneous, consisting of two distinct types of mineralogical-textural domains. Large poikilitic pyroxenes (2-6 mm) enclose an early crystallizing assemblage of rounded olivine grains (Fo_{66-63}), single grains and clusters of euhedral spinel, and minor associated metal. The pyroxene oikocrysts are generally composite in that they typically consist of weakly zoned augite cores of an unusually magnesian composition ($Wo_{37-35}En_{47-46}Fs_{15-17}$). The cores are rimmed by both high-calcium and low-calcium compositions which are only slightly enriched in iron relative to the cores ($Wo_{35-30}En_{46-43}Fs_{35-31}$ and $Wo_{13-10}En_{62-53}Fs_{25-35}$). The core of the largest grain in the thin section studied is low-calcium pyroxene, raising the possibility that both pyroxenes formed simultaneously. If this inference is correct, an approach to an equilibrium solvus may be recorded in the 12005 pyroxene crystallization trend. Pyroxene cores have higher Ti, Al and Cr and lower Ti/Al compared to the rims (0.30-0.35 vs. 0.45-0.50) apparently reflecting the late incoming of plagioclase and Ti-rich oxide phases.

The pyroxene oikocrysts are in turn surrounded by narrow bands comprised of euhedral olivine grains (<1 mm; Fo_{63-57}) poikilitically enclosed in plagioclase (An_{92-80}) or more rarely by irregular branching poikilitic ilmenite grains. Additional phases in the interstitial assemblage are high-calcium and low-calcium pyroxenes (similar in composition to the rims of the poikilitic grains), Cr-ulvöspinel, euhedral ilmenite, troilite, metal, and minor patches of a multi-phase crystalline mesostasis consisting of plagioclase ($An_{73}Ab_{21}Or_6$)

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K-feldspar and phosphate.

Crystallization History - On the basis of textural relationships and mineral chemistry, a multi-stage crystallization history characterized by relatively slow cooling is inferred for 12005. The initial phase of crystallization involved the accumulation of olivine phenocrysts and minor inclusions of Cr-spinel and metal. This is consistent with low pressure phase-equilibria experiments performed on ilmenite basalt 12022 (5). The 12005 olivines are more iron-rich (Fo_{66-57}) than the 12022 liquidus olivine (Fo_{77} - in experiments and in the rock) which may be the result of subsolidus equilibration or continuous reaction with evolving melt. Subsequently, spinel crystallization continued, but olivine growth was interrupted and the early olivine grains were in large part resorbed, probably due to a peritectic reaction-relationship with the liquid which resulted in the formation of the large pyroxene oikocrysts. Pyroxene crystallized continuously throughout the remaining supersolidus interval. The euhedral olivine grains in the interstitial assemblage apparently represent resumption of olivine crystallization prior to precipitation of the interstitial plagioclase and ilmenite as these phases are not included in olivine except as components of the assemblages in melt inclusions. Metal, troilite, and the mesostasis phases are the final crystallization products.

The unusually limited degree of iron-enrichment in the pyroxenes, their regular zoning patterns for Ti, Al, Cr, etc. and the separation of high-calcium and low-calcium compositions in the absence of subcalcic augites all contrast with pyroxene crystallization trends in rapidly cooled mare basalts and are compatible with much slower crystallization rates. Spinels included in the cores of pyroxene oikocrysts and in early-formed olivine grains are TiCr-spinel. While those within the pyroxene rims, interstitial pyroxene or the late-stage olivines are Cr-ulvospinel. In contrast to spinels in rapidly cooled low-Ti mare basalts which are resorbed and rimmed by Cr-ulvospinel, the spinel composition in 12005 changed gradually with progressive crystallization. This is indicated by the lack of abrupt zoning relationships and the strong correlation between spinel chemistry and the relative position of the enclosing silicate phase in the crystallization sequence.

Evidence for subsolidus equilibration is found in sub-micron sized exsolution lamellae in pyroxenes, the extensive development of reduction assemblages in ilmenite (Cr-spinel-rutile-metal) and ulvospinel (ilmenite-metal) and the compositions of adjacent mafic silicate-FeTi oxide mineral pairs. Spinels enclosed in olivine are characterized by higher Fe/(Fe+Mg) at any Cr/Al or Cr/Ti and higher Cr/(Cr+Al) at any Cr/Ti compared to those in pyroxene. Olivine grains within the interstitial assemblage which are in contact with poikilitic ilmenites have rims which are more magnesian and Ti-rich than their cores (Fo_{60} and $\approx 0.50\%$ TiO_2 vs. Fo_{57} and 0.10% TiO_2).

12045 - 12045 is an olivine porphyritic basalt that belongs to the ilmenite basalt group and is similar in textures, mineralogy and bulk chemistry to 12008 and 12022. These three samples represent the most rapidly quenched and least fractionated members of the A-12 ilmenite suite although they may have accumulated up to 5-10% olivine phenocrysts relative to a true liquid composition. A comparison of grain size and textures in these three samples indicates that 12008 is a vitrophyre and is the most rapidly cooled of the group. Textural relationships in 12022 and 12045 are virtually identical but the grain

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size of all the phases and particularly those in the ground mass are more coarse-grained in 12022 indicating that it is the least rapidly cooled of the three samples.

Petrography and Mineral Chemistry - 12045 contains ≈20% olivine phenocrysts (0.2 - 0.5 mm - rarely 1.0 mm) which vary in shape from equant-subhedral to skeletal and in composition from Fo_{74} to Fo_{51}. The olivine phenocrysts occur in clusters of 5 - 20 grains and contain inclusions of spinel and minor Femetal. Relatively small, sparse euhedral spinel grains within olivine cores are weakly zoned Ti-Cr spinels, while the larger and more abundant euhedral to anhedral grains partially included within phenocryst margins are assymetrically zoned towards the groundmass to Cr-ulvöspinel. Spinel grains entirely within the groundmass are either Cr-spinel rimmed by Cr-ulvöspinel or euhedral to skeletal grains which are composed entirely of Cr-ulvöspinel. As in 12022 (6) there are two distinct textural varieties of calcic pyroxene. Early elongate phenocrysts are set in a fan-spherulitic matrix formed by the coprecipitation of acicular pyroxene and plagioclase ($An_{93-84}Or_{0.4-1.7}$), skeletal platy ilmenite and an acicular silica-phase. Olivine crystallization terminated with the incoming of pyroxene which mantles the phenocrysts. The compositions of the early pyroxenes in 12045 are similar in character to those in 12022 but differ in detail, apparently as a function of cooling rate. The compositions of the phenocryst cores cluster around $Wo_{45}En_{30}Fs_{25}$ as do those in 12022. However, these early grains are enriched in Ti and Al by ≈50% relative to those in 12022 (12045: Al_2O_3 = 7-10%, TiO_2 = 5-7%). The rims of the 12045 phenocrysts and the fan-spherulitic groundmass pyroxene are similar in composition. Relative to the cores, they exhibit progressive depletion in Ca, Cr, Ti and Al with increasing iron-enrichment ($Wo_{35-20}En_{30-25}Fs_{30-55}$) but extreme compositions near the Hd-Fs join (such as those in 12022) have not been recognized. Metal, troilite, and a trace of a K-bearing phase are also present.

Although pyroxene crystallization trends in 12022 and 12045 are fundamentally similar, the higher Ti and Al and the lack of iron-enrichment in the 1204 groundmass pyroxene relative to 12022 are indicative of the dependence of mare basalt pyroxene compositions on cooling rate (7). The marked contrast between pyroxene chemistry in 12005 and 12022-12045 is only one manifestation of the drastically different crystallization histories and resultant bulk compositions of these rocks. Currently, we are examining many aspects of the textural-chemical relationships among these and other samples (12016 and 12056) within the Apollo 12 ilmenite suite which differ as a function of cooling rate and degree of olivine fractionation.

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CHEMISTRY, CLASSIFICATION AND PETROGENESIS OF APOLLO 12 MARE BASALTS.

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This paper is concerned with the bulk composition of Apollo 12 mare basalts, and is part of a collaborative re-examination of these rocks. Companion papers (1, 2, 3) discuss the petrology and mineralogy, Sr-isotope geochemistry and sulfur abundances for the same samples. Major and trace element data have been obtained by a combination of XRF and INAA techniques for 20 texturally and compositionally diverse samples, doubling the number of samples from this site for which compositional data are available.

The new data confirm earlier classifications of these basalts into four compositionally-defined basalt types; these are, the olivine, pigeonite, ilmenite and feldspathic basalts (4, 5, 6). An important consequence of this study is that the abundance and compositional range of the ilmenite basalts has been extended (Fig. 1), permitting a clearer understanding of their petrogenesis and relationship to the other basalt types. In view of their abundance, it appears likely that they are indigenous to the landing site rather than exotic as has recently been suggested(7). The variation observed for the pigeonite basalts is also greater, whereas that of the olivine basalts remains within previous limits. An additional sample of fedlspathic basalt (12031) has been identified. The table below assigns all currently analyzed samples to the appropriate basalt type, subdividing them further into two broad cooling-rate categories, based on textural criteria.

	Rapidly cooled	Slowly cooled
olivine basalts	12009, 12015, 12076, 12075, 12004	12002, 12018, 12020, 12012, 12014, 12006, 12035, 12040
Pigeonite basalts	12011, 12065, 12053, 12052, 12021, 12043	12055, 12017, 12007, 12039, 12064
Ilmenite basalts	12008, 12045, 12022	12063, 12047, 12051, 12016, 12056, 12054, 12030, 12005
Feldspathic basalts		12038, 12031

The rapidly cooled basalts (filled symbols in Fig. 1) include those that are porphyritic, with fine-grained or variolitic groundmass as well as vitrophyres. Those that have cooled more slowly (open symbols) have ophitic to sub-ophitic or gabbroic textures, and are medium- to coarse-grained. Within each category the samples have been ranked in decreasing cooling rate. Since almost all "hand specimen" basalts collected at the Apollo 12 site have now been analyzed, it is appropriate to consider the spatial distribution and stratigraphic sequence of these main basalt types. We concur with Warner(8) that the distribution may be depth-related, controlled mainly by ejecta from Middle Crescent Crater. If this is correct, then the olivine basalts, which are almost entirely restricted to the N.W of the sample site close to the rim of Middle

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Crescent Crater, are probably older and are overlain by younger ilmenite basalts largely confined to the S.E of the landing site, furthest away from the crater The pigeonite basalts are dispersed throughout the landing site, and if they are comagmatic with the olivine basalts, as is suggested below, they are probably "sandwiched" between the olivine and ilmenite basalts.

The compositional trend (Fig. 1) for the olivine basalts are dominated by near-surface fractionation of olivine and minor Cr-spinel, as has been widely recognized (e.g. 9, 7, 10, 4, 5, 11). Two compositional clusters are evident: one having lower Mg/(Mg+Fe) values of about 0.51 and high CaO and TiO_2, is composed entirely of fine-grained, rapidly cooled variants (12009-12004), the other is coarse-grained and characterized by high normative olivine content and lower CaO and TiO_2. The former are probably closest to a liquid composition and are the best candidates for the composition of the parental magma of the olivine basalts. The more mafic, coarser-grained basalts can be derived from this parental composition by partial accumulation, and re-equilibration of olivine. The pigeonite basalts are more evolved than the olivine basalts, with lower Mg/(Mg+Fe) values, Co and Cr abundances and correspondingly higher amounts of SiO_2, Al_2O_3, CaO TiO_2, Sc and magmaphile elements. They do, however, fall on the olivine fractionation trend of the olivine basalts and close to the experimentally determined liquid-line of descent for olivine basalt 12002(12) (Fig. 1). Our data are consistent with derivation from the olivine basalt parental liquid by moderate amounts of olivine fractionation. We believe that the compositional hiatus between the pigeonite basalts and the olivine basalts, coupled with wide textural diversity of essentially isochemical samples, indicate that they have evolved from the olivine basalt composition by shallow subsurface fractionation prior to eruption rather than by fractionation within a single cooling unit.

Several coarse-grained pigeonite basalts (e.g. 12007, 12039, 12064) depart from the olivine fractionation trend in response to the onset of co-precipitation of pyroxene and plagioclase. They are the most evolved in this group, and closely approach evolved members of the ilmenite basalt group in major element chemistry (Fig. 1). They can, however, be resolved from the ilmenite basalts by several trace element characteristics and by higher initial Sr isotope ratios(2).

Like the olivine-pigeonite basalts, the ilmenite basalts exhibit a wide range in composition which can largely be attributed to processes of near-surface crystal fractionation. They are readily distinguishable from the olivine-pigeonite basalts by higher TiO_2, Fe and Sc and lower SiO_2 for a given Mg/(Mg+Fe) value. They are also depleted in light REE relative to the olivine and pigeonite basalts, and have distinctly lower initial Sr isotope ratios(2). From this we conclude that they are derived from a distinctly different source than the other Apollo 12 basalts and, as noted earlier, we believe they are younger. Only three of the ilmenite basalts are fine-grained, and one, 12008, is a vitrophyre. These rapidly-cooled basalts have Mg/(Mg+Fe) values and Cr and Co abundances that compare closely with the inferred parental magmas for the olivine basalts, and are the best candidates for the parental magma composition of the ilmenite basalts. Most of the samples in this group have cooled slowly, and are more evolved, following an olivine ± ilmenite fractionation trend. The effects of ilmenite fractionation are most marked in the more

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evolved samples, resulting in a rapid decrease in TiO_2 and FeO abundances (Fig. 1). Three samples (12016, 12036, 12005) provide evidence of olivine accumulation, 12005 being the most extreme example of cumulative processes in the Apollo 12 suite.

The important question of whether multiple parental magmas following similar liquid lines of descent are required to account for the total compositional variance of the Apollo 12 basalts(10) is obfuscated by inter-laboratory comparisons, and is beyond the space restrictions of this abstract. Our preference, based on our own data, is that no more than the three magma types discussed here (e.g. olivine-pigeonite, ilmenite, feldspathic) are required, and that these three are derived from distinctly different source materials.

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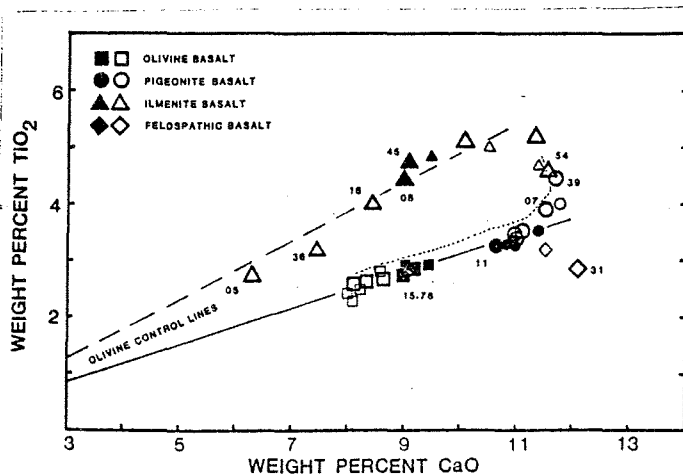(12) Walker D., Kirkpatrick R.J., Longhi J. and Hays J.F. (1976) Bull. Geol. Soc. Am. 87, 646-656

Fig. 1.- TiO_2 vs CaO for Apollo12 mare basalts. Data from this study in large symbols; data from the literature in small symbols. The liquid line of descent for 12002(12) is shown as a dotted line. For additional information see text.

ABSTRACT FORM

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MAGMA MIXING AT MID-OCEAN RIDGES: EVIDENCE FROM DSDP LEGS 45 AND 46
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Legs 45 and 46 of DSDP sampled 950 m of basalt in late Miocene oceanic crust on either side of the mid-Atlantic Ridge. At each drill site there are several compositionally distinct eruptive units, each having the characteristics of moderately evolved mid-ocean ridge tholeiite. These include both aphyric and highly phyric basalts, the latter containing abundant plagioclase and olivine phenocrysts of mixed parentage. The plagioclase phenocrysts exhibit a diversity of zoning patterns and evidence of resorption. One atmosphere melting experiments indicate that although some olivine and plagioclase phenocrysts were in equilibrium with melts corresponding to whole-rock compositions, others were not, and must have been derived from more "primitive" magmas. In addition, these phenocrysts contain Mg- and Ca-rich, Ti-poor melt inclusions which have compositional characteristics of more "primitive" magmas. Integration of these observations with major and trace element chemical data indicates that mixing of magmas and their attendant phenocrysts played an important role in the generation of these basalts. We suggest that mixing occurs as "primitive" picritic magmas are injected into zoned, fractionating magma chambers containing more evolved cogenetic magmas as well as zones of plagioclase accumulation. Ocean-floor basalts with chemical and petrographic characteristics similar to the above are widespread. Hence, we propose that magma-mixing processes are an important factor in controlling the compositions of magmas erupted at mid-ocean ridges. This model accounts for many enigmatic petrologic characteristics of ocean-floor basalts heretofore inadequately explained by partial melting and fractional crystallization processes.

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