SEVENTH FORAY: WHITLOCKITE-RICH LITHOLOGIES, A DIOPSIDE-BEARING TROCTOLITIC ANORTHOSITE, FERROAN ANORTHOSITES, AND KREEP. Paul H. Warren, G. Jeffrey Taylor and Klaus Keil, Dept. of Geology and Institute of Meteoritics, University of New Mexico, Albuquerque, NM 87131, Gregory W. Kallemeyn and John T. Wasson, Dept. of Earth & Space Sciences, University of California, Los Angeles, CA 90024.

Our project aimed at finding and characterizing pristine nonmare rocks continues to be focused mainly on clasts in breccias from the westernmost sample-return sites, Apollo 12 and 14. Pristine rocks from the west are distinctive in several ways [1, 2]: they generally have Sc/Sm <1.0 and Ti/Sm <200 (the opposites are true for virtually all eastern rocks); they frequently have Eu contents >4 μg/g (not true of any eastern rock); western anorthosites are generally alkali-rich (all known eastern anorthosites are ferroan). We assess pristinity on the basis of the standard diagnostics [3]. Siderophile element data are not yet available, however (they are due soon). This year's two most extraordinary discoveries are whitlockite-rich lithologies from Apollo 14.

Whitlockite-rich Apollo 14 Clasts

14305c2 A pristine anorthositic troctolite clast was discovered earlier from 14305 [1], so the new one is designated c2. It is about 6 x 5 mm and the thin section we studied (14305,301) has 7.4 sq. mm of clast. It is an anorthosite, with about 95 vol.% plagioclase. The remaining 5% consists of approximately equal amounts of whitlockite and pyroxene, of which about 2/3 is pigeonite (En46Wo10), 1/3 is augite (En44Wo38). The pyroxenes are quite uniform in composition, but plag is frequently zoned and ranges from An68 to An90. Pigeonite contains exsolution lamellae of submicron width. Average silicate compositions (Fig. 1) suggest that 14305c2 is akin to the alkali anorthosites. Texturally, it is a slightly annealed, but probably monomict breccia, reminiscent of some ferroan anorthosites such as 15415 [4]. Unbroken plag crystals are up to 1.7 mm across. Pyroxenes are typically anhedral, weaving in and out of the plane of the section in optical continuity up to 1.0 mm apart. The one grain of Fe-metal large enough for analysis has low Ni/Co (3.4), corroborating the textural indications that this clast is very probably pristine. Moreover, it would be impossible to produce this clast's bulk composition by mixing together any of the common lunar rock types.

Whitlockite occurs as six equant, anhedral crystals, 0.1 to 0.4 mm across. Sampling errors are potentially very large, but the high whitlockite content is probably not a fluke, because (a) the crystals are scattered fairly evenly throughout the section; and (b) it may be assumed that practically all the REE in this clast occur in the whitlockite, and comparison (Fig. 2) between our bulk analysis of a separate 38 mg aliquot and electron probe data for the whitlockite content is probably not a fluke, because (a) the crystals are scattered fairly evenly throughout the section; and (b) it may be assumed that practically all the REE in this clast occur in the whitlockite, and comparison (Fig. 2) between our bulk analysis of a separate 38 mg aliquot and electron probe data for the whitlockite indicates that the bulk rock contains ~36 x less REE than the whitlockite, which implies that this aliquot also had 1/36 = 2.8 wt.% whitlockite.

14313c A bulk analysis of this clast for REE was performed by Haskin et al. [5]. It is far richer in REE than any other lunar lithology, yet its petrographic nature was hitherto unknown. The clast is very small, and the thin section we studied (14313,70, produced from only 6 mg of material) is only ~0.9 sq. mm, of which ~50% is matrix. There is no evidence that this clast is pristine, except that its bulk composition would be impossible to derive by mixing together any of the common lunar rock types. It probably is pristine, but even if it is not, it is still reflects an extraordinary petrogenetic process.

The mode of 14313,70 is roughly 40% plag, 35% whitlockite, and 25% low-Ca pyroxene. However, the potential for sampling error is far greater here than in the case of 14305c2. Indeed, comparison between the composition of the whitlockite and the 12.5 mg whole rock aliquot analyzed by [5] shows (Fig. 2) that the whitlockite content of the latter was probably only ~1/11 = 9 wt.%. The average silicate compositions (Fig. 1) suggest that the clast is also akin to the alkali anorthosites; and the sampling errors are potentially so great that the parent lithology could easily have been an anorthosite. The original igneous texture is obscured by brecciation, plus a moderate-high amount of annealing. Maximum dimensions of surviving crystal fragments are 0.18 mm for whitlockite, 0.12 mm for plag, and 0.08 mm for pyroxene. Pyroxenes contain exsolution lamellae of submicron width.

Petrogenesis and Significance of 14305c2 and 14313c Section 14305,301 contains about 16 x more area of 14305c2 than section 14313,70 has of 14313c; and our bulk analysis of 14305c2 is based on an aliquot 3 x more massive than the 14313c aliquot analyzed by [5] (which evidently contained much less whitlockite that 14313,70). Thus, 14305c2 is probably a much more representative sample of a phosphate-rich rock than is 14313c. The textures are ambiguous concerning wheteher the whitlockite originated from trappped liquid (TL), as opposed to cumulus (or heteradcumulus) crystals. The wide range in plag composition in 14305c2 implies that the TL content is probably at least 5%. On the other hand, the high plag content (95%) implies that the TL content is probably not ≫20%.

The P2O5 content of the whitlockite is 43 wt.%. The whitlockite content of the rock being roughly 2.5 %, the P2O5 content of the rock must be about 43 x 0.025 = 1.1 wt.%. If it is all of TL origin, the parent magma's P205 content must have been at least 2.8 wt.% (if the TL content is 40%; higher, if TL <40%). If it is not all of TL origin, the magma had to be saturated with whitlockite. This would require a P205 content for the magma of at least 2.5 wt.% (if T was 1050 C; higher, if T >1050 C) [6]. Thus, 2.5 wt.% is a conservative lower limit on the P2O5 content of the parent magma. This is at least 3.5 x higher than the P2O5 contents of pristine KREEPy rocks such as 15382, 15386 and 15405c [7] and 3.2 x that of the high-K KREEP component defined by [8]. Yet, the mafic silicates are only modestly Fe-rich. This paradox seems to require that some complex process such as assimilation or magma mixing was involved. At the very least, it shows that the nonmare crust is far too complex to be entirely a product of a single magma, or even a single magma type. It is still unclear how closely these samples are related to the alkali anorthosites, and less clear how the alkali anorthosites are related to the Mg-rich rocks.

Other Goodies

14305c3 Yet another pristine clast from 14305 was discovered, this one a small (7 x 6 mm), diopside-bearing troctolitic anorthosite. This clast has been severely brecciated, but is still almost certainly monomict (pristine). It consists of about 80% plag (An94.4), 15% olivine (Fo86), and 5% diopside (En48.5Wo46.3). Such an association of calcic plag, magnesian olivine, and high-Ca pyroxene (without any low-Ca pyroxene) is unprecedented among pristine rocks. For a western pristine lithology, 14305c3 has a high Sc/Sm ratio (1.2). This may be because it is a western counterpart of the gabbronorite [9] subset of the Mg-rich group. Two of the distinctive features of gabbronorites are high ratios of high-Ca/low-Ca pyroxene, and high Sc/Sm ratio. The 14305c3 Sc/Sm ratio is extremely low, for a gabbronorite.

14321c5 This is another unusual clast from "Big Bertha." We do not yet have a thin section. It contains only 1.0 wt.% FeO, yet its REE, including Eu, are very high (in µg/g, La = 112, Eu = 6.5, and Lu = 3.1). Its Sc/Sm ratio is extremely low (0.08); the nearest precedent is 14305c2 (0.10).

Pristine KREEP Fragments from Apollo 15 Station 2 Station 2 is over 2 km from the nearest other collection site from which pristine KREEP had been described hitherto (Stations LM, 6, 7, 8 and 9a [10]). Nevertheless, several small fragments separated from Apollo 15 drill core 15007 are very similar, chemically as well as petrographically, to pristine KREEP lithologies described previously from Apollo 15 [8, 10, 11]. In all four cases, incompatible elements are uniformly enriched to 0.4-0.6 x their concentations in the high-K KREEP component defined by [8].

Apollo 15 Ferroan Anorthosite This is also a small fragment from 15007, which makes it unusual, because the vast majority of ferroan anorthosites are from Apollo 16. The mode of our 7 sq. mm thin section is 98% plag (An97) and 2% pyroxene (about half En70Wo2.5, half En44Wo46). This monomict breccia will plot slightly above and to the right of the previous ferroan anorthosite field (Fig. 1), thereby slightly narrowing the gap between the Mg-rich rocks and the ferroan anorthosites, and strengthening the case for a positive slope among the ferroan anorthosites [3].

Apollo 16 Ferroan Anorthosites Several Apollo 16 anorthosites are also under study. The most important of these is probably 62275. An earlier study [12] indicated that this 443 g rock's plag was exceptionally anorthitic (An97.1-99.0). However, we find (studying a different section) that the avg. plag is An 97.3. As a result, the maximum anorthite limit of the ferroan anorthosite field in Fig. 1 is 0.9% lower than in previous versions of this diagram [e.g., 1].

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References: [1] Warren P.H. and Wasson J.T. (1980) PLPSC 11, 431-470. [2] Warren P.H. et al. (1983) JGR, in press. [3] Warren P.H. and Wasson J.T. (1977) PLSC 8, 2215-2235. [4] James O.B. (1972) Science 175, 432-436. [5] Haskin L.A. et al. (1973) PLSC 4, 1275-1296. [6] Dickinson J.E. and Hess P.C. (1982) Lunar Planet. Sci. XIII, 172-173. [7] Ryder G. and Norman M.D. (1979) Catalog of Pristine Non-mare Materials, Part 1, Non-anorthosites, Revised, NASA JSC Pub. No. 14565. [8] Warren P.H. and Wasson J.T. (1979) Rev. Geoph. Space Ph. 17, 73-88. [9] James O.B. and Flohr M.K. (1983) JGR, in press. [10] Irving A.J. (1977) PLSC 8, 2433-2448. [11] Meyer C. (1977) Phys. Chem. Earth 10, 239-260. [12] Prinz M. et al. (1973) Science 179, 74-76

FIGURE 1.

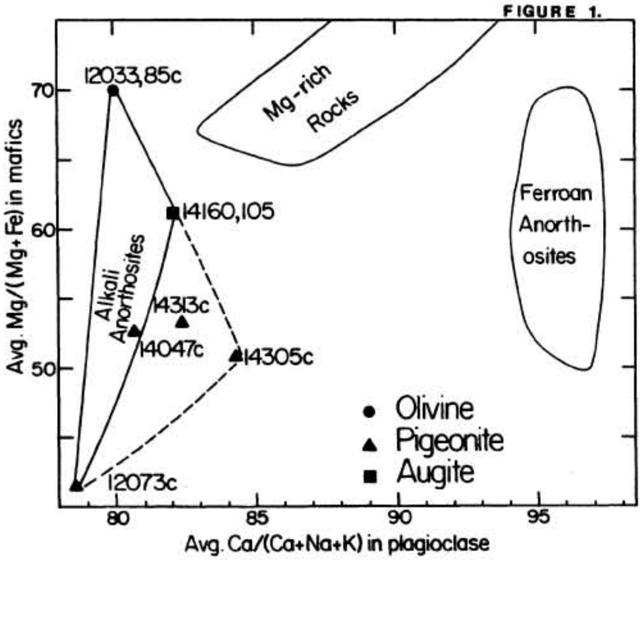

FIGURE 2.