ON THE HISTORY AND ORIGIN OF LKFM. Randy L. Korotev, Department of Earth and Planetary Sciences, Washington University, St. Louis, MO 63130 (rlk@levee.wustl.edu)

Fra Mauro is the name of a geologic formation surrounding of the Imbrium basin of the Moon as well as the name of the region of the Apollo 14 lunar landing site [1]. The formation was named for a 16th century Italian geographer and cartographer (e.g., [2]).

Etymology and Evolution of LKFM: In its original invocation in 1971 by the Apollo Soil Survey (ASS), *Fra Mauro basalt* was not a crystalline basalt, but the designation of a "compositional group" of impact glasses found in the Apollo 14 soil that was basaltic in composition [3]. The ASS noted the similarity between the Fra Mauro basalt glass composition and sample 14310, an unbrecciated, crystalline Apollo 14 rock that would now be designated an *impact melt rock* [4]. In 1972 the term *Fra Mauro basalt* was first applied to a rock, sample 14310 [5], although in related papers, Fra Mauro basaltic glass was equated with KREEP [6,7].

In 1973 the ASS noted that a wide range of K concentrations occurred among glasses of Fra Mauro basaltic composition in the Apollo 15 regolith [7]. The terms high-K, moderate-K and *low-K Fra Mauro* first occurred in that context, but always as an adjective. Low-K Fra Mauro glasses were those with 0.12± 0.07% K_2O (± = standard deviation?), compared with 0.47±0.17% and 1.1± 0.4% for moderate and high-K Fra Mauro glasses and 0.6% for Apollo 15 KREEP basalt. An important evolutionary step in the concept of low-K Fra Mauro basalt occurred in 1973 when the composition was first used as a component in a mass-balance (mixing) model for Apollo 16 soils [8,9] and later average highlands crust [10] despite that the term had not yet been applied to an actual rock sample.

The first use of the acronym *LKFM* occurred in a 1973 paper describing glass compositions in Apollo 16 soil [11]. That paper made a distinction between the LKFM composition and medium- (alternately, *moderate-K* [7] and *intermediate-K* [12]) and high-K Fra Mauro basaltic glass compositions, which were still equated with KREEP. Again, *LKFM* was used as an adjective. The practice of using *LKFM* as a noun was well established by 1977, however [13–17]. At that time the first reports of detection of Fra Mauro basalt from orbit by remote sensing techniques occurred, based on Fe [17] and Th [18].

Ryder and Wood made another important advance in the LKFM concept when they reasoned that the LKFM composition was that of the lower crust because rocks of LKFM composition were impact-melt breccias they believed to have formed in very large impacts, those forming the Imbrium and Serenitatis basins [14]. The hypothesis that the average composition of the lower crust is that of LKFM is now largely accepted [19,20], although we question it below.

In their classic paper "In search of LKFM," Reid et al. [13] reviewed the significance of the LKFM composition. They recognized that there was no igneous LKFM, only impact melt breccias, glasses, and soils. All of the rock samples they listed and identified with LKFM were impact-melt breccias from Apollos 15, 16, and 17. Curiously, the average K_2O concentration of the listed rocks is 0.24%, approximately twice that of the original LKFM glasses, and for some of the rocks (60315, 62235, 77135), K_2O concentrations fall instead in the range of the medium-K Fra Mauro glasses (≥0.3%). Reid et al. reviewed the arguments about whether the LKFM composition is that of a mixture or an igneous rock. It was clearly a mixture in that all samples were either glasses or breccias, but the composition is very similar to that of an equilibrium liquid in the silica-anorthite-olivine system [15].

By 1980, LKFM had become synonymous with mafic impact-melt rocks and breccias, although the K_2O concentration of samples used to represent LKFM had continued to 'kreep' up to values as high as 0.49% [12,19]. Recently, the LKFM concept has been extended based on results of the Clementine mission: "…the Fe abundance of the interior of [the] South Pole Aitken [basin] lies within the LKFM field…. Thus, the lower crust in this part of the Moon is also LKFM in composition" [20]. The implication is that LKFM is moonwide in occurrence, not a special product or component of the Fra Mauro formation and that LKFM can now be identified without knowledge of the concentration of K or other incompatible elements.

Throw it out: In this observer's opinion, the term LKFM has outlived it's usefulness and should be abandoned because of its ambiguity. It has been used interchangeably to refer to a composition, a chemical component, a rock type, and the lower crust. The composition associated with LKFM has evolved to cover such a wide range (Al/[Fe+Mg], Fe/Mg, K_2O, etc.) that most mafic polymict rocks from the highlands are included. The term is nondescriptive and misleading in the literal sense and, like *KREEP*, is jargon that justifiably offends nonlunaphiles. Rocks identified as LKFM are usually better designated as *impact-melt breccias*. As detailed below and elsewhere [21,22], it is likely that all of the Apollo Fra Mauro basalts (i.e., KREEP basalt and Th-rich mafic impact-melt breccias) are related and that those on the low-K end of the range have no special significance. If the Fe-rich material of the interior of the SPA basin is, in fact, impact melt and the concentration of Th is as low as preliminary results of the Lunar Prospector mission imply [23], and if the Th-rich impact-melt breccias of the Apollo missions all derive from an anomalous geochemical province [21,22], then there is little genetic link between the SPA material and those materials that have been historically identified with LKFM.

A Model: In an extension of previous work [24], I can demonstrate that to a good first-order approximation, the composition (31 elements) of all Apollo Th-rich, mafic melt breccias, i.e., the low- and medium-K Fra Mauro basalts and VHA basalts of Apollo 16, can be modeled as a mixture of three major components: (1) a material with a composition very similar to Apollo 15 KREEP basalt, (2) highly magnesian olivine (Fo_{90-95}), and (3) typical feldspathic upper crust. In this model the crustal component is represented by the average composition of the feldspathic lunar meteorites [e.g., 25]. The olivine component is required to account for the wide range of Mg/Fe ratios in the breccias and the high normative (and modal) abundance of high-Mg/Fe olivine in some specific breccias (Fig. 1). In order to account for concentrations of incompatible elements (IEs), the KREEP component of some melt breccias must have IE concentrations up to 2× lower or higher than the average of Apollo 15 KREEP basalt. Some minor components are also required. In order to account for Ti, ilmenite must be included as a distinct component, although its abundance in best-fit solutions remains in the narrow range of –0.6% to 1.1%. A component of alkali anorthosite (or albite) is required to account for variation in Na, Sr, and Eu, and this component varies between –7% and 10%. Two meteoritic components are required to account for siderophile elements: FeNi metal (up to 1.9% in Apollo 16 breccias) which derives from the impactor [22,25] and CI chondrite (up to 0.6% in Apollo 17 poikilitic breccias) which derives from clasts [26].

Interpretation: The abundance of KREEP component in the Fra-Mauro-type impact-melt breccias is so high (mean: 51%, Fig. 1) that such material must have been the dominant material of the target area. This observation, plus other lines of evidence now suggest that KREEP (or *ur*KREEP [27]) was not necessarily a material distributed moonwide in a narrow zone at the base of the crust but instead was concentrated massively in the Imbrium-Procellarum area prior to the Imbrium impact [21,22,28]. The LKFM melt breccias are precisely the types of products to be expected from an impact into a region dominated by KREEP magma by a bolide large enough to encounter the upper mantle and provide some olivine component to the melt (0 to ~20%, Fig. 1). The wide compositional range of the breccias reflects (1) minor regional variation in the extent of differentiation of the KREEP magma (variable IE abundance and variable alkali anorthosite and ilmenite subcomponents of the KREEP model component) and (2) variable incorporation of material of the mantle and the feldspathic upper crust into breccias formed in different parts of the basin. Such variation is to be expected from a large impact into a partially molten, heterogeneous target [22]. Much of the feldspathic component occurs as clasts. The virtual absence of lithic clasts of LKFM or KREEP composition in the melt breccias [29] argues that this component was largely at or near the liquidus at the time of the impact(s).

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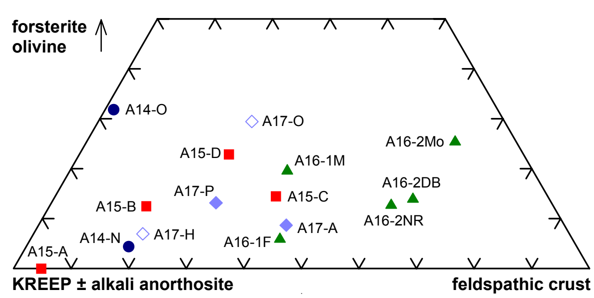

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Figure 1. Preliminary model results. Most of the points represent averages of many samples of recognized compositional groups; some points represent unique samples with anomalously high Mg concentrations: A14-O (the Apollo 14 olivine vitrophyres of [30], A17-O (sample 76055), and A16-2Mo (sample 62295).