LUNAR MARE BASALT EVOLUTION OVER 1.5 BILLION YEARS. Carlton Allen[1], Benjamin Greenhagen[2], Paul Lucey[3], Harald Hiesinger[4], and David Paige[5] [1]NASA JSC (Emeritus), Houston, TX carlton.c.allen.@nasa.gov, [2]JHU/APL, Laurel, MD benjamin.greenhagen@jhuapl.edu, [3]University of Hawaii at Manoa, Honolulu, HI lucey@higp.hawaii.edu, [4]Westfälische Wilhelms Universität, Münster, Germany hiesinger@uni-muenster.de, [5]UCLA, Los Angeles, CA dap@moon.ucla.edu.

Introduction: Lunar impact basins are filled with massive amounts of basaltic lava, erupted over extremely long periods of time. Recent orbital datasets, internally consistent across the lunar surface, allow studies of "big picture" questions such as the compositional range and temporal evolution of mare basalts. This study addresses the Imbrium basin lavas. Imbrium is compared to the Columbia River Basalt group (CRB), a massive flood basalt province on Earth.

The Imbrium basin, over 1,000 km in diameter, was formed approximately 3.9 Ga ago by an impact that likely penetrated into the lunar mantle [1,2]. The basin was subsequently filled by multiple flows of tholeiitic basalt. Hiesinger et al. [3,4] mapped 30 mare lava units within the basin, each covering thousands of km^2, based on multispectral Galileo Earth/Moon encounter images.

Data Sets: *Crater Ages.* Hiesinger et al. [3,4] derived ages for each of the 30 units within the Imbrium basin (Fig. 1), based on crater abundances in specific areas within each unit. The center point for each of these count areas was determined from shapefiles published online in *Lunaserv* at http://wms.lroc.asu.edu/lroc/view_rdr/SHAPEFILE_HIESINGER2011_MARE_CRATER_COUNT_AREAS. Each crater count area is at least 50 km across. Crater model ages for the 30 units range from 3.57 to 2.01 Ga. Of these units, 17 have ages older than 3.2 Ga, while 13 have younger ages [4].

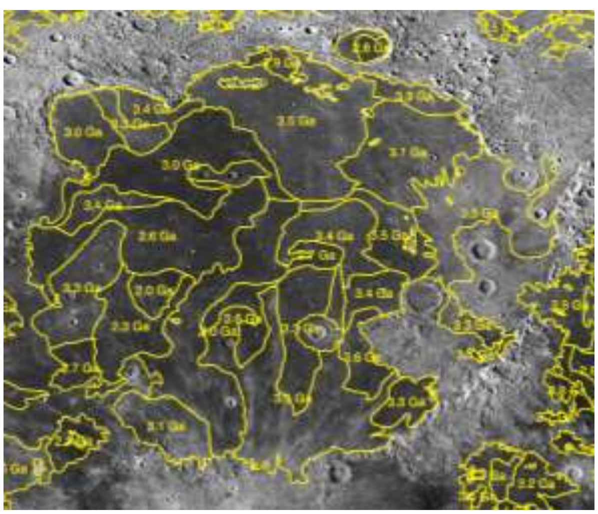

Fig. 1. Flow units and model ages in the Imbrium basin

FeO and TiO_2 Abundances. This study used FeO abundances derived from Lunar Prospector neutron spectrometer data [5], binned at 2 px/deg (~15 km) and presented on the USGS *Map-a-Planet* website at https://www.mapaplanet.org/data_local/Lunar_Prospector/lp_fe_hd.asc. TiO_2 abundances were derived from Lunar Reconnaissance Orbiter (LRO) Wide-Angle Camera (WAC) images [6], binned at 32 px/deg (~0.9 km). The FeO and TiO_2 abundances for the point nearest the center of each count area was determined.

Christainsen Feature. The Diviner instrument on LRO is a near/thermal-IR mapping radiometer. It includes three channels centered near a wavelength of 8 µm specifically designed to estimate the emissivity maximum known as the Christiansen feature (CF) [7]. The location of this feature is particularly sensitive to silica polymerization in minerals including plagioclase, pyroxene, and olivine – the major crystalline components of lunar rocks and soils. The CF position is directly correlated with FeO abundance [8]. This study used CF data binned at 32 px/deg (~0.9 km). CF values in a 10 x 10 pixel box around the center of each crater age count area were averaged, and the results corrected for space weathering [9].

Results: *FeO Abundances.* The FeO abundances at the 30 crater age count areas in the Imbrium basin range from 12.4 to 21.9 wt.% (Fig. 2). The measured counting rate uncertainty, limited by Poisson statistics, is ~2% relative [5]. The FeO abundances of units older than 3.2 Ga are tightly clustered, while those for younger units cover a distinctly wider range. The linear regression for all 30 count areas (Fig. 2) shows a slight decrease in FeO abundances with increasing unit age, but the correlation is weak ($r^2 = 0.02$).

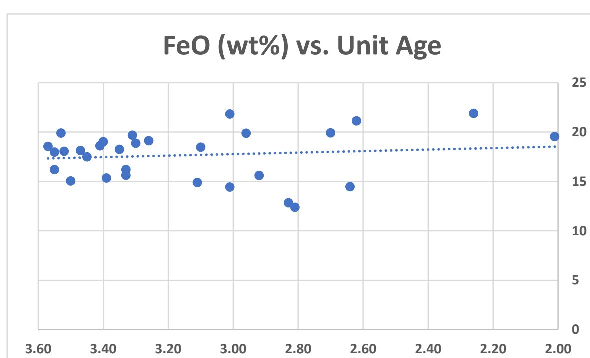

Fig. 2. FeO vs. unit age (slope = -1.73; $r^2 = 0.02$)

TiO_2 Abundances. The TiO_2 abundances at 25 of the crater age count areas range from 2.2 to 8.3 wt.%, with 5 areas having TiO_2 abundances below the 2 wt.% detection limit. The standard deviation around each value is ~5% relative [6]. The TiO_2 abundances decrease slightly with unit age, with weak correlation.

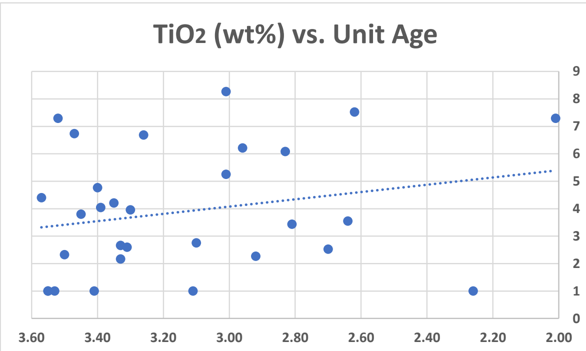

Fig. 3. TiO_2 vs. unit age (slope = -1.33; r^2 = 0.05)

The current study is restricted to the Imbrium basin. Previous studies of FeO and TiO_2 abundance vs. age across the entire Moon reached a variety of conclusions. Sato et al [6] observed that TiO_2 in mare basalts was more variable prior to 2.6 Ga than afterward, while Hiesinger et al [10] saw no systematic trend in TiO_2. These authors [10] also reported no systematic trend in FeO with age, but did observe that flow units older than ~3.3 Ga show a wider variety in FeO than younger units. A study of compositions and ages in Mare Australe found no correlation [11].

Christiansen Feature. Mean CF values (corrected for space weathering) in the 30 count areas range from 8.01 to 8.10 (Fig. 4). Within each 10 x 10 pixel box the standard deviation is ~0.01. Values for units older than 3.2 Ga cluster tightly, while values for younger units show more variation. Mean CF values decrease slightly with unit crater model age, with weak correlation. These results align with the direct correlation of CF values with FeO abundances [8].

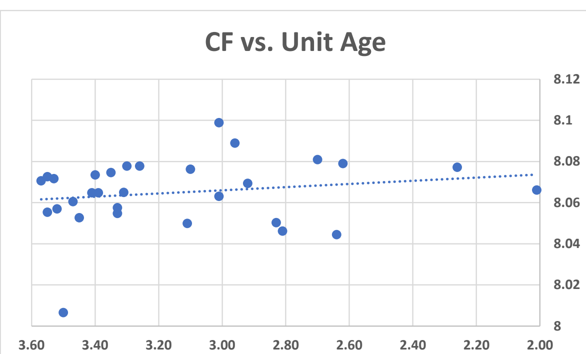

Fig. 4. Mean CF vs. unit age (slope = -0.01; r^2 = 0.03)

Discussion: *The Moon*. The oldest mare basalt units exposed in the Imbrium basin erupted ~300 million years after basin formation, and the youngest erupted >1.5 Ga later. Over this time FeO and TiO_2 abundances, as well as CF values, varied over significant ranges. Each of these three datasets exhibits slight decreases with increasing unit age, though the correlation in each case is weak. The FeO and CF ranges were more restricted prior to 3.2 Ga, and became more varied with later eruptions. The TiO_2 range did not change significantly with time.

The Earth. The Imbrium basin is comparable in size to large terrestrial flood basalt provinces. Of these, the most comprehensive age and elemental abundance data are from flows of the CRB [12]. The source of these basalts was likely a mantle plume. The CRB eruptions commenced ~17 Ma ago and continued until ~6 Ma ago. Over 300 flows, comprising ~ 25 members in 5 major formations, have been identified [12]. Major and minor element ratios are strikingly consistent throughout the lengths of individual flows [12].

The CRB flows are mainly tholeiitic, with iron abundances (as FeO) in the range of 12 to 17 wt.%. The TiO_2 abundances range from 2 to 4 wt.%. The FeO and TiO_2 values vary among members, but do not increase nor decrease systematically with age.

The variations in FeO and TiO_2 among CRB members are small compared to the ranges measured in other tholeiitic basalts. These small variations, coupled with the consistent compositions of individual flows, suggest that the mantle plume was large and remained nearly homogeneous for ~11 Ma.

Conclusions: These observations support a hypothesis that, unlike the CRB, the source region(s) for the Imbrium flows changed over time. The restricted range of FeO abundances and CF values in Imbrium units older than 3.2 Ga suggest that these basalts came from a common source, likely in the lunar mantle. The wider range of values in younger flow units might indicate multiple source regions. The slight decreases and weak correlations with increasing age for FeO, TiO_2, and CF suggest that source compositions evolved minimally with the eruptions of massive flows.

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