GEOCHEMICAL ANOMALIES IN THE LUNAR HIGHLANDS. B. R. Hawke[1], D. T. Blewett[2], D. B. J. Bussey[3], T. A. Giguere[4], D. J. Lawrence[5], P. G. Lucey[1], G. A. Smith[1], P. D. Spudis[3], and G. J. Taylor[1], [1]Hawaii Institute of Geophysics and Planetology, University of Hawaii, 2525 Correa Rd., Honolulu, HI 96822, [2]NovaSol, 1100 Alakea Street, 23rd floor, Honolulu, HI 96813, [3]John Hopkins University Applied Physics Laboratory, Laurel, MD 20723, [4]Intergraph Corporation, 2828 Pa`a St., Honolulu, HI 96819, [5]Los Alamos National Laboratory, MS D466, Los Alamos, NM 87545.

Introduction: Analyses of orbital geochemistry data have shown that some lunar regions exhibit unusual abundances of certain elements relative to surrounding or adjacent areas, or have a surface chemistry unlike that which would be expected from the examination of local geological relationships. Investigation of the formation of these geochemical anomalies can provide important clues to understanding the impact and volcanic processes operative during the early phases of lunar evolution [e.g., 1, 2, 3, 4]. A wide variety of elemental abundance data was obtained by the Lunar Prospector (LP) neutron and gamma ray spectrometers. We have used selected LP elemental abundance data to identify mafic chemical anomalies on the lunar surface. The purpose of this study was to investigate the nature and origin of geochemical anomalies in the lunar highlands. Since some of the mafic anomalies are clearly related to cryptomare deposits, we used LP data to better understand the composition and origin of these buried ancient basalts.

Method: Three LP elemental abundance data sets were used. The half degree iron abundance data product contains data from the LP gamma ray spectrometer (GRS) [5] acquired during the low-altitude portion of the mission. A description of the reduction of this data set is given by Lawrence *et al*. [6, 7]. The 2 degree titanium abundance values were derived from LP-GRS measurements acquired during the high- and low-altitude portions of the mission. The reduction of the data is described by Prettyman *et al*. [8]. The 2 degree thorium data were described by Lawrence *et al*. [9]. A variety of other remote sensing data was used to investigate the anomalies identified in the LP data. These include FeO, TiO_2, and optical maturity maps produced from Clementine UV-VIS images, Earth-based near-IR reflectance spectra, and spacecraft imagery.

Results and Discussion:

Lomonosov-Fleming Region. A major mafic anomaly is associated with the Lomonosov-Fleming (L-F) basin on the east side of the Moon. This 620 km, pre-Nectarian basin is just out of view from Earth at 19°N, 105°E and is positioned northeast of Mare Marginis. The LP-GRS FeO values range from 7 to 10% in the L-F region while the adjacent highlands exhibit FeO abundances of 4–5%. No anomalies were identified in the LP TiO_2 or Th data for the L-F region. TiO_2 abundances are generally <1.7%.

Schultz and Spudis [4, 10] identified dark-haloed impact craters in the L-F region and suggested that the basin was the site of ancient mare volcanism. We have used Clementine 750-nm images to identify numerous dark-haloed craters (DHCs) in the region and 17 well-developed DHCs were selected for detailed analysis. Five point spectra were extracted from Clementine UV-VIS image cubes for DHCs in the L-F region. These spectra have moderately strong “1-µm” bands centered near 0.95 µm. The portions of the dark halos for which these spectra were obtained are dominated by mare basalts. FeO and TiO_2 maps produced from Clementine UV-VIS images were used to determine the compositions of DHCs in the L-F region. The FeO and TiO_2 values range between 10.1% and 16.3% FeO and from 0.4% to 4.0% TiO_2. Clearly, a major expanse of cryptomare exists in and around the L-F basin. A variety of mare compositions were exposed by DHCs in the region. The compositions range from VLT basalts to intermediate TiO_2 mare basalts.

We have used the location of dark-haloed impact craters as well as Clementine FeO and TiO_2 maps to determine the distribution of cryptomare in the L-F region. Cryptomare deposits occur in all portions of the L-F region but are most extensive within the Lomonosov-Fleming basin. At least 1/3 of the basin interior is mapped as cryptomare. Most of the cryptomare on the interior of the L-F basin are associated with light plains and other deposits of Nectarian and Imbrian age [11, 12].

Cryptomare in the L-F region were formed by covering ancient mare surfaces with varying thicknesses of highlands debris. While both impact basins and craters played a role by transporting highlands material to mare surfaces, a variety of evidence indicates that most of the cryptomare units inside the L-F basin are of the Distal Basin Ejecta-type. These cryptomare deposits are located near the outer boundaries of the distal ejecta deposits of the Nectarian-aged Crisium and Humbodtianum basins.

The cryptomare surfaces in the L-F region exhibit LP-GRS FeO values that range from 7 to 10%. These values are in good agreement with those measured using Clementine FeO images (7–10%). These FeO values are greater than the average values (4–5%) determined for the background highlands material. Clearly, major amounts of mare material were incorporated into the surface of the cryptomare during the emplacement of the highlands material that obscures the ancient mare basalts. The enhanced FeO abundances exhibited by the cryptomare surfaces indicate that ballistic erosion and sedimentation played an important role in their formation.

Balmer Basin Region. A mafic anomaly was identified in Balmer basin region. Balmer basin is a pre-Nectarian impact basin located just east of Mare Fecunditatis [12, 13]. This impact structure exhibits two rings, approximately 210 and 450 km in diameter. The LP-GRS FeO values range from 7 to 11%. No anomaly was identified in the LP TiO_2 data for the Balmer region. TiO_2 abundances are generally < 1.7%. A slight Th enhancement was noted in the LP Th data. Maximum values of 3–4 ppm are exhibited by portions of the region.

Previous studies have identified a variety of geochemical anomalies in the Balmer region [1, 2, 3, 13, 14, 15], and the association of DHCs with light plains deposits that exhibit chemical anomalies has been cited as evidence of ancient volcanism in the region [e.g., 1, 2, 3, 10, 15]. We have identified and investigated ten well-developed dark-haloed impact craters in the Balmer region.

The DHCs in the Balmer region exhibit FeO abundances which range between 11% and 16%. While the TiO_2 values of these craters range between 1% and 3%, most DHCs in the region expose low TiO_2 (<2%) mare basalts. The evidence clearly indicates that a major expanse of cryptomare exists in the Balmer basin region.

Schiller-Schickard Region. The Schiller-Schickard (S-S) region is the site of an extensive mafic anomaly. The LP-GRS FeO values range from 7 to 11%. No TiO_2 or Th anomalies were identified in the region. The S-S region has been intensively studied by a number of investigators and a major expanse (3–4 × 10^5 km^2) of cryptomare has been identified in the region [4, 10, 15–20]. The LP FeO anomaly closely corresponds to the S-S cryptomare as mapped by Head *et al.* [19] and Blewett *et al.* [16]. Spectral studies have demonstrated that DHCs in the region excavated mare basalts from beneath light plains deposits emplaced as a result of the Orientale impact event [16–19]. We used Clementine FeO and TiO_2 maps to determine the composition of the basalts exposed by DHCs in the region. The FeO values generally range from 13% to 16%. All DHCs in the region excavated basalts that have TiO_2 abundances of <2%. Some expose basalts with <1% TiO_2. Spectral mixing analyses have suggested that major amounts of mare material were incorporated into the light plains units by local mixing during the emplacement of Orientale basin ejecta in the region [16, 18, 19]. The LP FeO values (7–11%) exhibited by the S-S region are consistent with a highlands-mare mixture as suggested by Head *et al*. [19] and Blewett *et al*. [16]. No LP TiO_2 anomaly is exhibited by the S-S region because the cryptomare are VLT or low TiO_2 mare basalts.

Mendel-Rydberg Region. A mafic anomaly was identified in the Mendel-Rydberg (M-R) region (50°S, 95°W) which is located south of the Orientale basin on the west side of the Moon. The LP-GRS FeO values for the region range from 7 to 9%. No TiO_2 or Th anomalies were identified. The iron anomaly is centered on the interior of the M-R basin, a pre-Orientale, multiringed impact structure. Head *et al*. [19] described a spectral anomaly on the interior of the M-R basin. Based on the results of a spectral mixing analysis, Head *et al*. [19] determined that the surfaces in the M-R region contained up to 40% mare debris and suggested that a cryptomare was present in the M-R basin. At least one DHC has been identified in the region [4]. The enhanced LP FeO values (7–9%) provide independent confirmation of the presence of major amounts of mare basalt in the regolith in the M-R region.

References: [1] Haines E. L. *et al*. (1978) *PLPSC 9*, 2985. [2] Hawke B. and Spudis P. (1980) *PCLHC*, 467. [3] Hawke B. *et al*. (1985) *E. M. P. 32*, 257. [4] Schultz P. and Spudis P. (1979) *PLPSC 10*, 2899. [5] Feldman W. *et al*. (1999) *Nuclear Instruments and Methods in Physics Research A, 422*, 562. [6] Lawrence D. J. *et al*. (2001) *LPS XXXII*, #1830. [7] Lawrence D. J. *et al*. (2002) *JGR, 107* (E12). [8] Prettyman T. *et al*. (2002) *LPS XXXIII*, #2012. [9] Lawrence D. J. *et al*. (2000) *JGR, 105* (E8), 20, 307. [10] Schultz P. and Spudis P. (1983) *Nature, 302*, 233. [11] Wilhelms D. and El-Baz (1977) U. S. G. S. Map I-948. [12] Wilhelms D. (1987) U. S. G. S. Prof. Pap., 1348. [13] Maxwell T. and Andre C. (1981) *PLPSC 12*, 715. [14] Clark P. and Hawke B. (1987) *E. M. P. 38*, 97. [15] Antonenko I. *et al*. (1995) *E. M. P. 69*, 141. [16] Blewett D. *et al*. (1995) *JGR, 100* (E8), 16, 959. [17] Hawke B. and Bell J. (1981) *PLPSC 12*, 665. [18] Mustard J. *et al*. (1992) *LPS XXIII*, 957. [19] Head J. *et al*. (1993) *JGR, 98* (E9), 17, 149. [20] Antonenko I. and Yingst R. A. (2002) *LPS XXXIII*, #1438.