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High resolution measurements of absolute thorium abundances on the lunar surface

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Abstract. The Lunar Prospector (LP) Gamma-Ray Spectrometer (GRS) has been used to map the global abundance of thorium on the lunar surface. A global map of absolute thorium abundances on a 2° by 2° equal-area pixel scale is presented using new detector modeling results and low altitude LP data. Because thorium is relatively abundant in KREEP-rich material, these data provide fundamental information regarding the locations and importance of terranes that are rich in KREEP bearing materials.

Introduction

The distribution of thorium (Th) bearing materials on the lunar surface provides detailed information regarding the Moon's formation and subsequent evolution. Radioactive ^{232}Th ($t_{1/2}$ = 4.1 x 10^{10} years) is relatively abundant in the lunar material called KREEP [potassium (K), rare earth elements (REE), and phosphorus (P)], which according to the most widely accepted model of lunar formation is thought to have formed between the lunar crust and mantle [e.g. *Warren and Wasson*, 1979; *Warren*, 1985]. It is thought that the early Moon was hot, being either totally molten [*Binder and Lange*, 1980; Binder, 1986] or having an outermost layer consisting of a thick magma ocean [*Warren*, 1985]. Upon cooling, dense minerals sank to form the mantle and light minerals floated to the surface to form the lunar crust. The last material to crystallize was rich in Th, K, and other elements associated with KREEP because these elements do not substitute readily into the crystal lattice of the major lunar rock-forming minerals.

Recent results from Lunar Prospector (LP) have conclusively demonstrated that the surface occurrence of KREEP (as mapped by Th, Gd, and Sm) is mostly confined to the nearside region in and around the Imbrium basin [*Lawrence et al*., 1998; *Elphic et al*., 1998]. Moderate levels of thorium are also observed in the farside South Pole-Aitken (SPA) basin. A possible implication of the LP results is that the distribution of KREEP was probably not uniform over the entire Moon just after the lunar magma solidified, but was mostly confined to a region on the nearside. This type of distribution is similar to the high-Th oval region described by *Haskin* [1998a]. If a KREEP layer was globally distributed as predicted by the simplest magma ocean models, then even with the crustal thickness differences of a 60 km thick crust on the nearside and a 68 km crust on the farside [*Zuber* et al., 1994], one would expect the distribution of KREEP abundances near the SPA basin to be at least similar to that seen on the nearside. Explaining the observed non-uniform KREEP distribution has become one of the major goals for the study of lunar formation and evolution [*Joliff and Ryder*, 1998]. Here we report new LP GRS results from the low altitude phase of the Lunar Prospector mission. The surface resolution of the GRS is about three times better for the low altitude data set (33±12 km) than for the high altitude data set (100±11 km). In addition, using recent detector modeling results, we are presenting our first estimates of absolute Th abundances on the lunar surface.

Deriving Absolute Thorium Abundances

The LP GRS measures γ-rays coming from the Moon having energies from 0.35 – 9 MeV [*Feldman et al*., 1999]. While most lunar γ-rays are produced from fast and thermal neutron reactions in the lunar regolith, the 2.6 MeV γ-ray is produced at the end of the radioactive decay chain from ^{232}Th [*Lederer and Shirley*, 1978]. This Th line is clearly resolved in the GRS energy spectra and shows large counting rate variations over the lunar surface [*Lawrence et al*., 1998]. A rigorous determination of the flux of 2.6 MeV γ-rays (and hence the Th abundance) requires a spectral fitting and deconvolution analysis that takes into account detector composition and geometry along with contributions from higher energy γ-ray lines which likely depend on spatial location on the Moon.

However, because the Th line has large variations over the lunar surface, has few competing γ-ray lines in the same energy range, and is produced by radioactive decay which does not depend on local neutron flux conditions, we can obtain an estimate of the absolute thorium abundance using the following relation:

$$C_{Th} = A_{Th} a \varepsilon F_{\gamma}. \tag{1}$$

Here, C_{Th} is the measured thorium counts per second above background within an energy band (2.5 – 2.7 MeV) around the 2.6 MeV full energy peak, A_{Th} is the average mass concentration of Th in μg/g, a = 54 cm^2 is the effective GRS detector area for γ-rays measured at the lunar equator [*Feldman et al*., 1999], ε is the GRS detector efficiency for γ-rays within the 2.5 – 2.7 MeV window, and F_{γ} is the expected flux of thorium γ-rays at the spacecraft per μg/g of thorium near the lunar surface.

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In using equation 1, we make two assumptions: 1) the background counts under the thorium line are assumed to be constant over the Moon; 2) the minimum counting rate in a given spatial resolution pixel is defined to have a thorium abundance of 0 μg/g. Assumption (1) is not strictly true because there are low fluxes of γ-rays with energies near 2.6 MeV that vary over the Moon. However, these variations are likely a second order effect and are ignored in this analysis. Assumption (2) probably holds quite well. Estimates of thorium abundances in meteorites thought to have originated in the lunar highlands are 0.4±0.2 μg/g [*Korotev*, 1999]. As an absolute offset, 0.4 μg/g contributes less than a 4% relative error at the highest Th abundances and is comparable to our largest measured uncertainties of 0.4 μg/g (see below). In regions with thorium abundances <2 μg/g, such an offset will contribute a larger fractional error, so our estimates for such regions should be treated with caution.

For this study, the GRS detector efficiency has been calculated using a Monte Carlo code which has been shown to successfully model similar types of detectors [*Prettyman et al*., 1998]. The total efficiency of the GRS detector for the 2.5 – 2.7 MeV window is estimated to be 0.322 counts per incident γ-ray at 0° incident angle. This estimate compares well to efficiencies of other BGO detectors having a similar size [*Moss et al*., 1984].

The expected flux of γ-rays coming from the lunar surface is determined by assuming the Moon is an ideal sphere and the Th composition is constant over the sensitive depth of measurement. The calculated γ-ray flux at the spacecraft per μg/g of Th is then:

$$F_\gamma = n_{Th}\Gamma \Big/ 2\mu\left(1+h/R_m\right)^2. \qquad (2)$$

For nominal values of thorium atom density: n_{Th} = 4.02 x 10^{15} atoms/cm^3/(μg/g), gamma-ray production rate: Γ = 5.6 x 10^{-19} γ/s/atom, mean mass attenuation coefficient in the lunar regolith: μ = 0.0613 cm^{-1}, lunar radius: R_m = 1738 km, and spacecraft altitude: h = 100 km (all measured fluxes are normalized to a height of 100 km), the Th γ-ray production rate is calculated to be Fγ = 0.0164 γ s^{-1} cm^{-2} (μg/g)$^{-1}$. This rate is ~15% lower than that calculated by *Reedy* [1978] who modeled the Moon as an infinite plane. The measured variation of γ-ray counting rate with height is found to agree with this spherical approximation.

Results

The GRS detector is not collimated but measures γ-rays over 4π steradians. The surface resolution is therefore a direct function of the detector altitude above the lunar surface. For an altitude of 30 km, the GRS resolves surface elements of ~45 km [*Reedy et al*., 1973]. The data presented here include 367,616 32-second spectra measured from Dec. 19, 1998 to May, 22 1999. During this time the LP spacecraft had a mean altitude of 33±12 km. Corrections for gain, dead time, galactic cosmic ray variations in the background, and latitude variations in the instrument response have been made as described in *Lawrence et al.* [1998]. We have also made corrections for variations in the Moon's solid angle as viewed by the GRS (assuming the Moon is a sphere and using a geometric solid angle correction) by normalizing all spectra to a 100 km altitude.

Plate 1 shows a color-coded map of the derived absolute thorium abundances for the lunar mid-latitude (Mercator projection) and polar regions (stereographic projections). The derived abundances range from 0 – 2 μg/g in the highlands, to 1 – 5 μg/g in SPA, and to up to 9 – 10 μg/g in various nearside locations. In regions with the highest Th abundances, the LP measurements are somewhat lower than the range of abundances seen in returned samples. For example, the range of Apollo 14 soil Th abundances given by *Korotev* [1998] is 12.7 – 13.2 μg/g. This is almost 30% higher than the LP measurement of 9.3 μg/g seen in the 2° x 2° pixel nearest the Apollo 14 landing site. We also note that for Th abundances greater than 6 μg/g, the high altitude GRS data set (not shown here) has measured abundances that are ~5% lower than the low altitude measurements [*Lawrence et al*., in preparation]. From these low altitude/sample return and low altitude/high altitude comparisons, we conclude that the large area response of the GRS averages small area Th enrichments with surrounding areas that have lower Th abundances. Therefore, for small area Th enrichments, the measured abundance decreases as the GRS surface resolution becomes larger.

It should be noted that our derived Th abundances are not referenced to sample ground truth information, but only to the processes that are involved in creating and detecting γ-rays. This is important because orbital γ-ray measurements sample large regions (>5000 km^2 at low altitude). Unless the surface composition is homogenous over such areas, ground truth measurements from Apollo and Luna sites are not likely to be representative for the areas sampled by the GRS.

The measured standard deviations of the mean abundance values in each 2° x 2° equal area pixel range from <0.1 μg/g near the poles to 0.4 μg/g near the equator. The dominant source of these uncertainties are statistical variations. There also exist systematic uncertainties which have not been accounted for – e.g. non-uniform variations in background counts, uncertainties in the modeling of the GRS efficiency, and residual latitude variations in the instrument response– but we do not expect them to be more than (+15%,-5%) of the total counting rate, which corresponds to (+1.9, -0.5) μg/g at the highest Th abundances [*Lawrence et al*., in preparation].

On the lunar nearside (Plate 2), there are at least four high-Th regions (8.5 – 10.4 μg/g) directly associated with craters near the rim of Imbrium basin: Aristarchus (25°N, 48°W), Mairan (41°N, 43°W), Aristillus (33°N, 3°E), and Kepler (7°N, 38°W). Also notable are some large craters near Imbrium basin that do not have large Th abundances such as Plato (52°N, 9°W) and Copernicus (10°N, 20°W).

The Th abundance patterns around Copernicus are particularly interesting. The crater itself shows a relatively low abundance of 4.2 – 5.2 μg/g, which is similar to the thorium abundances seen within the southwestern portion of Imbrium basin. The Th abundances surrounding Copernicus are asymmetric, with high Th regions to the north, south, and west and lower Th abundances to the east.

There also exist high Th regions (7.5 – 10.5 μg/g) in the highlands surrounding Imbrium basin that do not appear to be associated with craters. For example, the entire region extending from the Carpathian Mountains (15°N, 30°W) to west of Fra Mauro (5°S, 10°W) has very high Th abundances that appear to follow terrain thought to be ejecta from the Imbrium impact [*Wilhelms*, 1987]. High Th regions also exist in the highlands north of Imbrium basin which are thought to be Imbrium ejecta [*Wilhelms*, 1987]. These associations, however, need to be confirmed with a more detailed analysis between the Th data and the Wilhelms geologic maps and other photogeologic data. There are also high Th abundances around the Apennine Bench (25 – 28°N, 0 – 10°W) southeast of Imbrium basin, a region that possibly formed by post-Imbrium KREEP basalt volcanism [*Spudis*, 1978]. Within the mare basalt floor of Imbrium basin, we note that the Th abundance is significantly lower (2 – 5 μg/g) than the surrounding highlands and distinctly non-uniform.

As seen previously in *Lawrence et al*. [1998], the SPA basin region has relatively elevated Th abundances compared to the surrounding highlands. With these new data, we see that SPA basin has Th abundances in the range of 1 – 5 μg/g while the surrounding highlands have Th abundances generally less than 1 μg/g. Most of SPA basin has Th abundances in the range of 1.5 – 3 μg/g. While more study needs to be carried out with small scale regions [*Blewett et al*., 1999], these Th abundances are generally consistent with the *Lucey et al*. [1998] hypothesis that the floor of SPA basin is one-half lunar mantle and one-half lower crustal material. We can also identify two distinct regions of moderately high-Th abundances (3 – 5 μg/g) within SPA. These regions are located at (41°S, 165°E) and (30°S, 175°E) and are generally not located in areas containing mare basalt [*Wilhelms*, 1987]. This is in contrast to the suggestion given by *Hawke and Spudis* [1980] that the anomalous Th regions near Van de Graaf might be due to locally generated and exposed mare basalt. The location with highest Th abundances in the SPA (41°S, 165°E) is relatively close to the Imbrium antipode (33°S, 162°E). While more study is needed, this raises the possibility that at least some of this high Th material may have been delivered to SPA by the Imbrium impact [*Haskin*, 1998a]. *Hawke and Spudis* [1980] have also suggested that some of the Th within SPA could be due to covered over, pre-Imbrium mare basalt deposits. As we explore elsewhere, we believe such a scenario is unlikely [*Lawrence et al*., in preparation].

While most of the lunar highlands appear to have little or no thorium (0 – 2 μg/g), we have identified a small region in the northern highlands that has elevated Th abundances of 2 – 4 μg/g. This Th enrichment is located at (60°N, 100°E) between the two craters Compton (55°N, 105°E) and Belkovich (63°N, 90°E) and has a size of 150-300 km. Because this region is so close in size to the spatial resolution of the GRS at 100 km altitude, it was not identified in our previous analysis. We also see evidence that this region is enriched in potassium relative to the surrounding highlands. An inspection of this region using Clementine spectral parameters sensitive to Fe and Ti composition [*Lucey*, J. Geophys. Res. submitted, 1999] shows no significant differences relative to the surrounding highlands.

Discussion and Summary

While there are many complexities associated with how KREEP was formed and distributed, these new data provide insight about how KREEP was distributed on the lunar surface. The observation that the highest surface Th abundances are localized in and around Imbrium basin is consistent with the assumption by *Haskin* [1998a] that there exists a single Th-rich province on the Moon. If the general picture of the Haskin model is assumed to be correct, the Imbrium impact spread large amounts of Th-rich material over the Moon, while other large impacts (e.g., SPA) distributed very little Th-rich material. There also may have been periods of KREEP volcanism that produced Th-rich units such as the post-Imbrium Apennine Bench Formation, located particularly around the Apennine bench, Aristillus, around the massifs of the Alpes, and near Sinus Iridum [*P. D. Spudis*, pers. comm., 1999]. Following these periods of KREEP volcanism, mare basalt filled in much of the Imbrium basin with varying but lower amounts of Th-rich material. Finally, additional high-Th material was excavated in various locations around Imbrium basin when impacts that produced the craters Aristarchus, Mairan, Kepler and Aristillus punched through the relatively thin mare basalt layer (<5 km) exposing underlying high-Th material. This picture is complicated by the fact that some craters such as Plato and Copernicus do not appear to have excavated Th-rich material. However, according to basin ejecta modeling described by *Haskin* [1998b], it is possible that ejecta from large basins such as Imbrium can be considerably inhomogeneous in spatial extent. So the lack of a high-Th signature at Plato and Copernicus may mean these regions happened to be places where the Imbrium ejecta were absent or had lower Th abundances.

Within SPA basin, there is a general Th enhancement of 1.5 – 3 μg/g which is consistent with this material being 50:50 mantle:lower crustal material. There is also a region of higher Th abundances in the northwestern portion of SPA basin. Because of the close association of this moderately Th-rich region in SPA with the Imbrium antipode, it is possible that some of the Th-rich material in

SPA was deposited by the Imbrium impact as proposed by *Haskin* [1998a]. Finally, we have discovered a new, moderately high Th region in the northern highlands near the craters Compton and Belkovich that does not appear to be associated with any other abundance anomalies.

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References

Binder, A. B. and M. A. Lange, On the thermal history, thermal state, and related tectonism of a moon of fission origin, *J. Geophys. Res*., 85, 3194, 1980.

Binder, A. B., The initial thermal state of the Moon, in *Origin of the Moon*, W. K. Hartmann, R. J. Phillips, and G. J. Taylor eds., Lunar and Planetary Institute, pg. 425, 1986.

Blewett, D. T., G. J. Taylor, P. G. Lucey, B. R. Hawke, and J. Gillis, High-Resolution, Quantitative remote sensing of South Pole-Aitken Basin, *Proc. Lunar Planet. Sci. Conf., 30th*, Abstract #1438, 1999.

Elphic, R. C., D. J. Lawrence, W. C. Feldman, B. L. Barraclough, S. Maurice, A. B. Binder, and P. G. Lucey, Lunar Fe and Ti abundances: Comparison of Lunar Prospector and Clementine data, *Science*, 281, 1493, 1998.

Feldman, W. C., B. L. Barraclough, K. R. Fuller, D. J. Lawrence, S. Maurice, M. C. Miller, T. H. Prettyman, and A. B. Binder, The Lunar Prospector gamma-ray and neutron spectrometers, *Nuc. Inst. and Meth. A*, 422, 562, 1999.

Haskin, L. A., The Imbrium impact event and the thorium distribution at the lunar highlands surface, *J. Geophys. Res*., 103, 1679, 1998a.

Haskin, L. A., R. L. Korotev, K. M. Rockow, and B. L. Joliff, The case for an Imbrium origin of the Apollo thorium-rich impact-melt breccias, *Met. and Plan. Sci*., 33, 959, 1998b.

Hawke, B. R. and P. D. Spudis, Geochemical anomalies on the eastern limb and farside of the Moon, *Proc. Conf. Lunar Highlands Crust*, 467, 1980.

Joliff, B. L. and G. Ryder eds., *Workshop on the New Views of the Moon: Integrated Remotely Sensed, Geophysical, and Sample Datasets*, LPI Contribution No. 958, Lunar and Planetary Institute, Houston, TX, 1998.

Korotev, R. L., Concentrations of radioactive elements in lunar materials, *J. Geophys. Res*., 103, 1691, 1998.

Korotev, R. L., A new estimate of the composition of the feldspathic upper crust of the Moon, *Proc. Lunar Planet. Sci. Conf., 30th*, Abstract #1303, 1999.

Lawrence, D. J., W. C. Feldman, B. L. Barraclough, A. B. Binder, R. C. Elphic, S. Maurice, and D. R. Thomsen, Global elemental maps of the Moon: The Lunar Prospector gamma-ray spectrometer, *Science*, 284, 1484, 1998.

Lederer, C. M, and V. Shirley, eds., *Table of Isotopes, 7th Edition*, John Wiley & Sons, 1978.

Lucey, P. G., G. J. Taylor, B. R. Hawke, and P. D. Spudis, FeO and TiO2 concentrations in the South Pole-Aitken basin: Implications for mantle composition and basin formation, *J. Geophys. Res*., 103, 3701, 1998.

Prettyman, T. H., C. S. Cooper, P. N. Luke, P. A. Russo, M. Amman, D. J. Mercer, Physics-based generation of gamma-ray response functions for CdZnTe detectors, *J. Radioanaly. and Nuc. Chem*., 233, 257, 1998.

Moss, C. E., E. W., Tissinger, and M. E. Hamm, Efficiency of 7.62 cm bismuth-germanate scintillators, *Nucl. Inst. and Meth.*, 221, 378, 1984.

Reedy, R. C., J. R. Arnold and J. I. Trombka, Expected γ-ray emission spectra from the lunar surface as a function of chemical composition, *J. Geophys. Res*., 78, 5847, 1973.

Reedy, R. C., Planetary gamma-ray spectroscopy, *Proc. Lunar Planet. Sci. Conf. 9th*, 2961, 1978.

Spudis, P. D., Composition and origin of the Apennine bench formation, *Proc. Lunar Planet. Sci. Conf. 9th*, 3379, 1978.

Warren, P. H. and J. T. Wasson, The origin of KREEP, *Rev. of Geophys. and Space Phys*., 17, 73, 1979.

Warren, P. H., The magma ocean concept and lunar evolution, *Annu. Rev. Earth Planet. Sci*., 13, 201, 1985.

Wilhelms, D. E., The Geologic History of the Moon, U. S. Geological Survey Professional Paper 1348, 1987.

Zuber, M. T., D. E. Smith, F. G. Lemoine, and G. A. Neumann, The shape and internal structure of the Moon from the Clementine mission, *Science*, 266, 1839, 1994.

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Plate 1. Color coded map of absolute thorium abundances using the low altitude GRS data overlaid with a lunar surface features map.

Plate 2. Overlay of measured absolute thorium abundances (color coded) with a surface relief map for the Imbrium basin region.

Plate 1, Lawrence et al., *Geophys. Res. Letters*, 1999

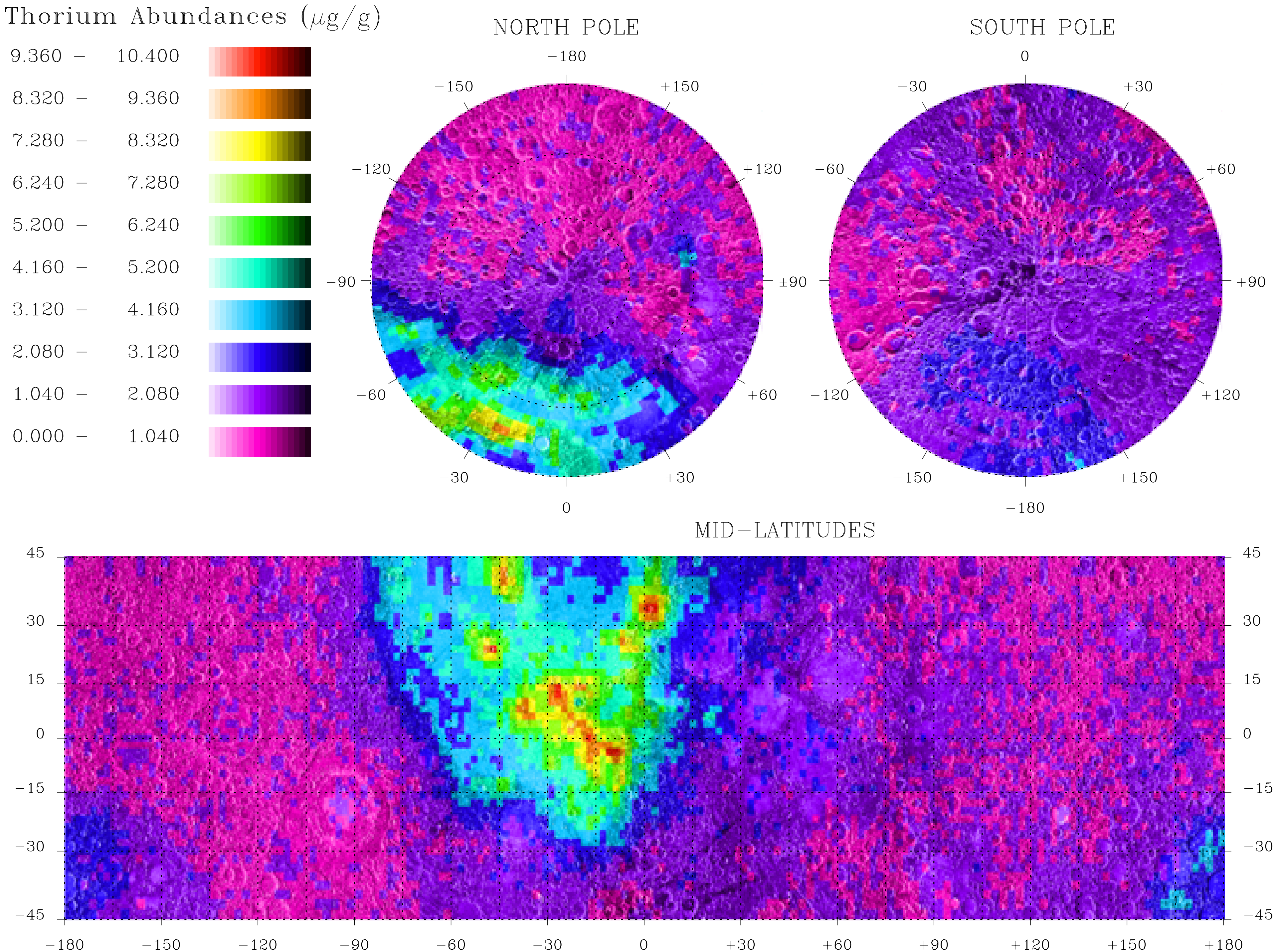

Plate 2, Lawrence et al., *Geophys. Res. Letters*, 1999

Thorium Abundances (μg/g)