VOLATILE AND SIDEROPHILE METALS ON THE MOON: REAPPRAISAL IN THE LIGHT OF APOLLO 16 AND LUNA 20 DATA.

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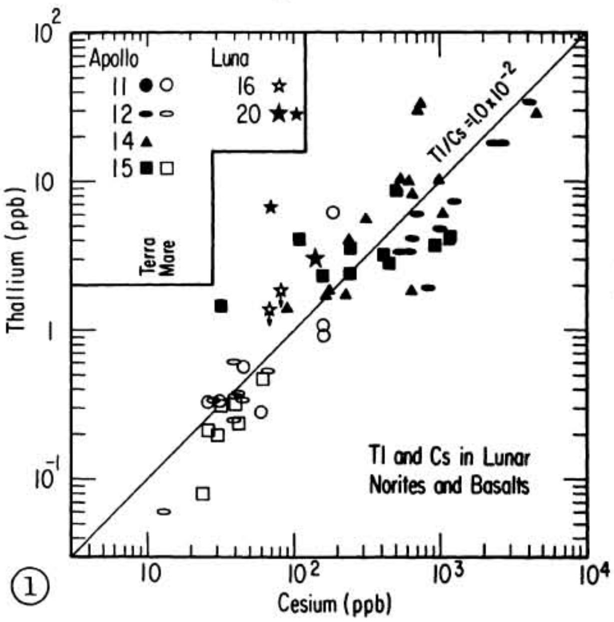
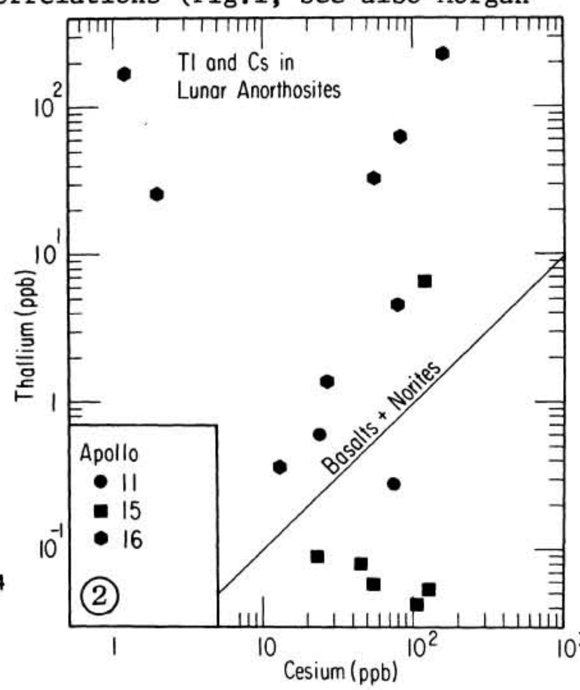
Three of the authors (UK,RG, and JWM) have analyzed 27 Apollo 16 and 2 Luna 20 samples for the following 17 elements, using neutron activation analysis: Ag, Au, Bi, Br, Cd, Cs, Ge, In, Ir, Rb, Re, Sb, Se, Te, Tl, U, and Zn. One author (KK) has measured distribution coefficients of Au and Re between nickel-iron and silicate melts.

Volatile Metals on the Moon. Lunar samples from the first 5 landing sites show rather good Tl-Cs and Cs-U correlations (Fig.1, see also Morgan





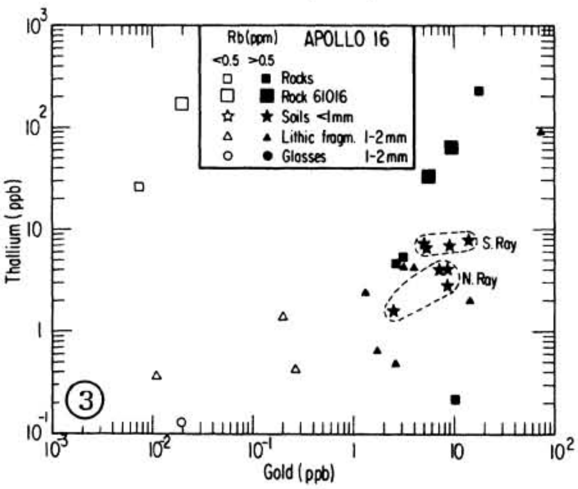
et al.[1]). Because these 3 elements all tend to concentrate in the crust during planetary differentiation, but differ greatly in volatility, the Tl/U and Cs/U ratios can be used to estimate a planet's overall depletion in volatiles. From Tl/U ratios for the first 5 landing sites, it appeared that the Moon was depleted in Tl by a factor of 2×10^{-4} relative to Cl chondrite abundances, compared to a factor of 2×10^{-2} for the Earth [1]. However, it has since then become apparent that lunar anorthosites often deviate strikingly from this trend (Fig. 2), being either too low in Tl (15415,12; 15455, 179; 15455, 70A; 15472,) or too high [60025,84; 61016,156 (light); 61016,132 (dark), and the limonite-stained rock 66095,55]. All show sporadic and lesser enrichments of other volatiles, such as Bi, Br, and Cd.

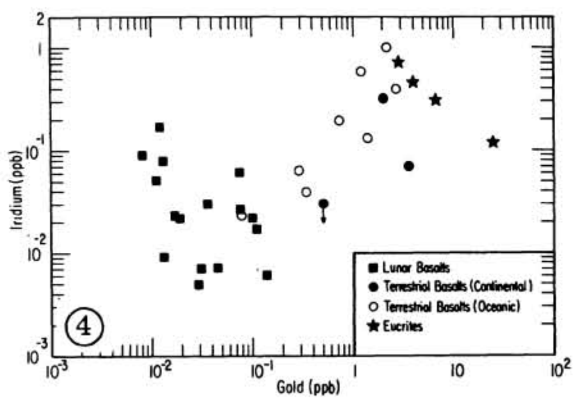
These data force a reappraisal of the Moon's overall depletion in volatiles. It appears that Tl-rich anorthosites make a significant contribution to the Moon's overall inventory of Tl, because Tl/Cs ratios of highland soils are generally higher than those of mare soils and rocks. The contrast would be even greater if these values were corrected for meteoritic Tl.

Highland soils	$Tl/Cs \times 10^{-2}$	Mare soils	$Tl/Cs \times 10^{-2}$
Apollo 14	3.6	Apollo 11	1.6
Apollo 15	2.3	Apollo 12	0.9
Apollo 16	5.7	Apollo 15	1.2
Luna 20	5.8	Luna 16	2.2

The whole-Moon abundance of Tl may therefore be 6×10^{-4} of the cosmic value.

Stratigraphy of Apollo 16 site. Some stratigraphic information may be inferred from the Au, Rb, and Tl data in Fig. 3. The "alkali-rich" (Rb>0.5





ppm) rocks and lithic fragments all are rich in siderophile elements such as Au, Ir, Re. As at other highland sites(2,3), these elements represent an ancient meteoritic component derived from basin-forming planetesimals and smaller objects that bombarded the Moon during the first ~0.5 AE of its history. They can therefore serve as "markers" for determining the depth of the ancient highlands regolith. All alkali-rich rocks in Fig. 3 have Au contents greater than 2 ppb, whereas the alkali-poor rocks have Au contents less than 0.02 ppb. Apparently the ancient regolith at the Apollo 16 site extended only to the base of the alkali-rich, surficial layer. The alkali-poor rocks (cataclastic anorthosites or Type II of LSPET) seem to come mainly from a deeper stratum, penetrated by N.Ray and S.Ray craters, but not by the ancient regolith. Interestingly, the two lithologies of rock 61016 seem to represent these two units (Fig. 3).

This interpretation is supported by data on bulk soils. Soil 67601,19 from the rim of N.Ray crater is markedly lower in Au, Tl, Rb, Cs, and U than any other bulk soil. Having been collected directly on the rim of N.Ray crater, it is likely to consist mainly of deep ejecta---probably the light-colored, friable unit(5). We believe that this unit consists of cataclastic anorthosites poor in Au, Rb, Cs, and U, while the overlying 100-m layer of light-matrix breccias represents the ancient highlands regolith.

Source of Tl-rich rocks. High Tl contents are found in both alkali-rich

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and alkali-poor rocks (Fig. 3). Possibly the Tl-enrichment was caused by a post-igneous volatilization process (fumarole activity?), after emplacement of the rocks. There is a slight suggestion in the data that the Tl-enrichment was limited in areal extent: four soils from the S.Ray crater area (61221,6; 61241,6; 64501,9; and 68841,15) have consistently higher Tl and Tl/Cs ratios than 4 soils from the N.Ray crater area (63321,1; 63341,1; 63501,13; and 67601,19). The Tl-rich rocks also seem to be S.Ray crater ejecta. Possibly the source of the Tl-rich material is localized in the southern part of the site.

Origin of N.Ray and S.Ray craters. In 61221 soil, we see no perceptible enrichment of Tl and Bi paralleling the enrichment of H_2O, HCN, CH_4, etc. that prompted Gibson and Moore[6] to suggest a cometary projectile for N.Ray crater. This does not contradict their suggestion in any way, because at typical cometary impact velocities, enrichments of only 0.1% Cl equivalent would be expected: undetectable against the background of indigenous Tl, Bi at the Apollo 16 site. By the same token, we wonder if the H_2O, HCN, etc. detected by Gibson and Moore does not come from the same indigenous (volcanic?) source as the excess Tl, Bi, Cd, etc.

Four lithic fragments from soil 64502,4 showed metal splashes centered on zap pits, and were very rich in Au (Fig.3). They may have been struck by metal particles from the ejecta cloud of S.Ray crater, as suggested by Carter and McKay[7]. Attempts to characterize the metal are in progress.

Distribution coefficients of Au and Re between metal and silicate. Equilibrium was approached from both directions, with the Au^{197} or Re^{186} tracer initially in the metal or silicate phases. Three pairs of measurements on Mauna Loa basalt TLW 67-75 and metal with 30 to 90% Ni gave a mean distribution coefficient of 3×10^4 for Au at 1500 C. Single measurements on Gorda Ridge basalt KD1154 and a simulated lunar basalt gave less accurate results of the same order. A tentative value for Re in lunar basalts also fell near 3×10^4. Since separation of metal and silicate phases was not perfect in any of these experiments, the true distribution coefficients may well be higher.

Siderophile Metals on the Moon. Latest data for Apollo 15 (Fig.4) still uphold the previous trend[1]: lunar basalts are consistently lower in Ir and especially Au than are terresrrial basalts[8,9] or eucrites[9]. With a distribution coefficient of 3×10^4 (and an asuumed 8% Ni in the core) one would expect terrestrial basalts to contain 4×10^{-2} ppb Au, nearly 2 orders of magnitude less than observed. This value should also apply to lunar basalts, if the Moon's metal phase content is greater than about 1/3000 $M_{☽}$. The lunar values indeed cluster around 4×10^{-2} ppb, but this agreement may be fortuitous, because our D probably is a lower limit. In any case, the persistent difference in siderophile element pattern between Earth and Moon confirms our earlier conclusion that the Moon and Earth segregated their metal phase in two separate events, contrary to the fission hypothesis.

(1) MORGAN J.W. *et al*.(1972) *GCA Suppl.3*, 1361. (2) MORGAN J.W. *et al*. (1973), this issue. (3) MORGAN J.W. *et al*.(1972) *GCA Suppl.3*, 1377. (5) AFGIT (1973), *Science 179*, 69. (6) GIBSON E.K.,JR. and MOORE G.W.(1973) *Science 179*, 69. (7) CARTER J.L. and MCKAY D.S. (1972) *GCA Suppl.3*, 953. (8) WASSON J.T. and BAEDECKER P.A. (1970) *GCA Suppl.1*, 1741. (9) LAUL J.C. *et al*. (1972) *GCA 36*, 329.