THE CONCENTRATION OF OXYGEN (AND SILICON) IN LUNAR MATERIALS. Randy L. Korotev, Bradley L. Jolliff, and Larry A. Haskin, Department of Earth and Planetary Sciences, Campus Box 1169, Washington University, Saint Louis, MO 63130 (rlk@levee.wustl.edu)

Although the most abundant element in the crust of the Moon, oxygen is of little geochemical interest because the relative variation in the concentration is small among common lunar rocks and soils. The low variability occurs because the oxygen concentrations of common lunar rock-forming minerals all fall in a narrow range (Fig. 1). However, because it is abundant, oxygen is an important target element in nuclear reactions occurring on the lunar surface, and oxygen lines are prominent in the gamma-ray spectra of the lunar surface [1]. Although oxygen is a poor absorber of thermal neutrons, it has a moderate cross section for capture of fast neutrons [2]. In order to provide information useful for determining the effects of the small variation in oxygen abundance in different types of lunar materials on interpretation of nuclear data obtained remotely [e.g., 3], we present here data on oxygen concentrations in lunar rocks and soils.

Oxygen: There are few direct measurements of the concentration of oxygen in lunar materials, and no data are available for many types of materials. The few available data were obtained by 14 MeV neutron activation analysis [e.g., 4–7]. However, because nearly all atoms of metallic (Al, Fe) and nonmetallic elements (Si, P) in lunar material exist as oxy-anions or oxides, the concentration of oxygen can be accurately calculated from the concentrations of other elements.

We have compiled average compositions of lunar rock types and regoliths from many literature sources

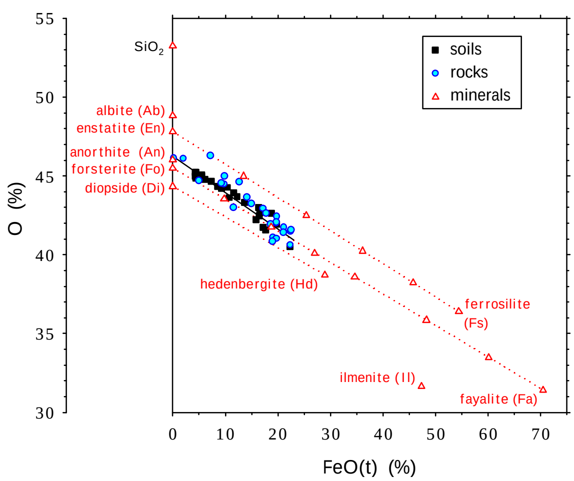

Figure 1. Stoichiometric concentrations of O and Fe (as FeO) in some lunar minerals and comparison to actual concentrations in soils and rocks. For the orthopyroxene and olivine trends, points corresponding to En80, En60,… and Fo80, Fo60,… are plotted. In pyroxenes and olivine, O concentrations decreases systematically with increasing Fe/Mg ratio. The solid diagonal line is the regolith regression line of Fig. 2a.

Table 1. Concentration (mass %) of oxygen in lunar rocks and soils (in order of increasing O concentration).

sample type	category	O (%)	Σ of oxides
orange glass soil 74220	"soil"	40.5	99.8
A17 orange glass	picritic glass	40.6	100.0
A17 ilmenite (high-Ti)	MB	40.8	99.3
A11 ilmenite, type A	MB	41.0	99.6
A11 ilmenite, type B	MB	41.1	99.5
A12 ilmenite	MB	41.4	99.8
A15 olivine	MB	41.5	100.3
Asuka 881757	MB	41.6	100.3
A17, stn. 5	soil, 95% MB	41.6	100.0
A12 olivine	MB	41.7	100.4
A17, stn. LM & 1	soil, 90% MB	41.7	100.0
Luna 16	MB	41.9	100.2
Luna 24	soil, ~95% MB	41.9	99.9
A15 green glass	picritic glass	42.0	100.1
A12 pigeonite	MB	42.1	100.0
A11	soil, ~70% MB	42.2	100.1
A15 quartz	MB	42.4	100.3
Luna 16	soil, ~90% MB	42.5	100.0
A12 feldspathic	MB	42.6	100.3
EET87521	FrBr, mare	42.6	100.3
A12, typical	soil, 50-50 MB-KREEP	42.7	100.0
A17 very-low-Ti	MB	42.9	100.0
dunite 72415	Mg-suite	43.0	99.8
A15, valley	soil, ~80% MB	43.0	100.4
A17 KREEP basalt	KREEP	43.2	99.7
QUE94281/Yam793274	RegBr, ~50% mare	43.3	99.8
A17, stn. 6	soil, mostly nonmare	43.6	99.8
quartz monzodiorite	evolved	43.6	99.6
A15, Apennine Front	soil, nonmare	43.8	99.9
Calcalong Creek	RegBr, KREEPy	44.2	100.0
A14, typical	soil, KREEPy	44.3	100.1
A17, stn. 2&3	soil, nonmare	44.3	99.9
norite	Mg-suite	44.5	99.0
mafic melt breccias, mean	KREEP	44.5	100.1
sodic ferrogabbro 67915	evolved	44.6	100.0
Luna 20	soil, nonmare	44.7	100.2
troctolite 76535	Mg-suite	44.7	99.6
Yamato 791197	RegBr, feldspathic	44.8	99.7
QUE93069	RegBr, feldspathic	44.8	99.1
ALHA81005	RegBr, feldspathic	45.0	99.9
A15 KREEP basalt	KREEP	45.0	100.1
Yamato 86032	FrBr, feldspathic	45.0	99.5
A16, Cayley Plains	soil, feldspathic	45.1	100.1
Dar al Gani 262	RegBr, feldspathic	45.2	100.1
MAC88104/5	RegBr, feldspathic	45.2	99.8
alkali anorthosite	evolved	46.1	100.3
ferroan anorthosite	99% plagioclase	46.1	100.0
felsite (granite)	evolved	46.3	99.9

MB = mare basalt; FrBr = fragmental breccia; RegBr = regolith breccia.

and calculated oxygen concentrations from the sum of the oxides. In all cases we have included the minor elements Mn, Na, K, Cr, P, Zr, and Ba. When data for minor elements were missing, an estimate was made. For the regoliths and breccias, we have made a correction for the reduced Fe occurring in FeNi metal based on Ni. The calculated oxygen concentration and the sum of oxides, Fe^0, and sulfur obtained in this manner are reported in Table 1. The standard deviation in the

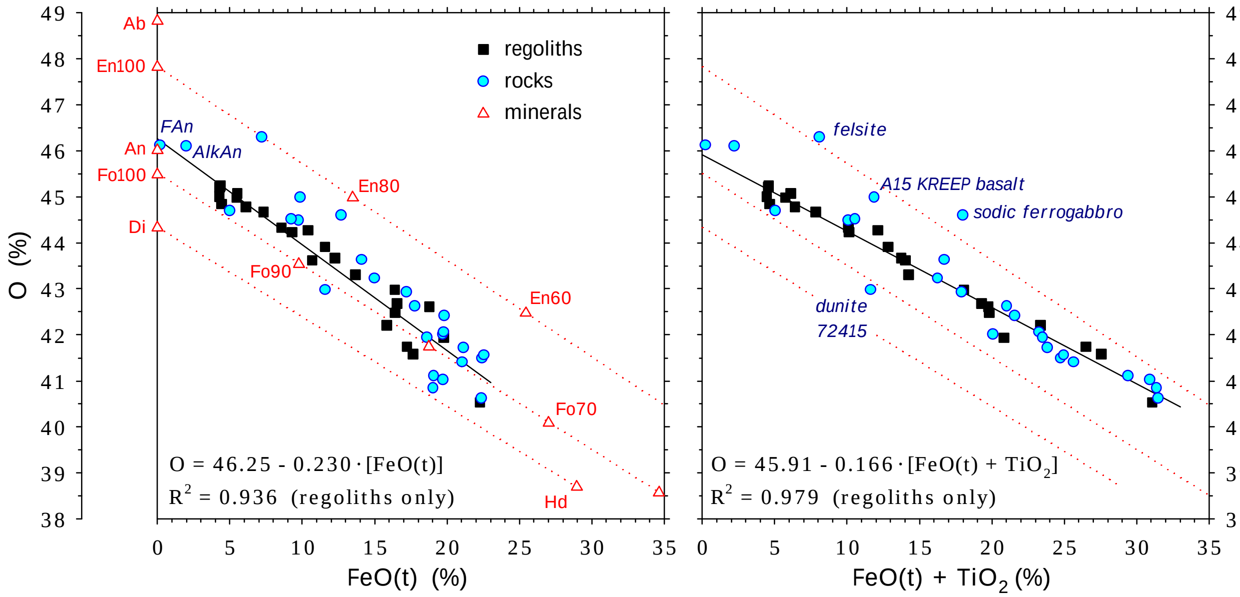

Figure 2. Variation of O concentrations in lunar rocks and regoliths (Table 1) with FeO(t) (total Fe as FeO) and FeO(t)+TiO_2 concentrations. The solid diagonal lines (equations given in the figure) are simple linear regressions for the regoliths (squares = soils and lunar meteorite breccias of Table 1). For reference, the mineral trends of Fig. 1 are also shown. Lunar rocks that plot significantly off the regolith trends are either rich in silica (felsite, sodic ferrogabbro) or olivine (dunite). The mineral trends reflect variable Fe/Mg ratios (Fig. 1); the rock and regolith trend reflects variation in the ratio of feldspar to Fe and Ti bearing minerals. All points with >15% FeO are mare basalts, pyroclastic glasses, or regolith dominated by mare basalt or pyroclastic glass.

sum of oxides is 0.3% (mean sum = 99.91%); this value provides an estimate of the uncertainties associated with the calculated oxygen concentration values.

The relative range of O variation in lunar rocks and soils is small, only 13% (Table 1). As expected from simple consideration of stoichiometry of the major minerals, the oxygen concentration decreases as concentrations of heavy elements increase (Fig. 2). For regoliths, the anticorrelation of O with FeO(t) + TiO_2 is very strong (R^2 = 0.979) and is only somewhat less strong with FeO(t) alone (R^2 = 0.936). There are few outliers, and only dunite, apparently exposed in central uplifts of craters [8], is suspected of being quantitatively important at the surface. With that one exception, the oxygen concentration beneath any remotely sensed location can be accurately assessed from Fe and Ti concentrations.

The production of fast neutrons is poorer for Fe- and Ti-poor regoliths because of the lower mean atomic number and consequently lower neutron/proton ratio [8]. Fig. 2 shows, however, that the production of fast neutrons via oxygen in Fe,Ti-poor regoliths is greater than in Fe,Ti-rich regoliths simply because there is more oxygen

Silicon: Data for Si are widely available, but we review them here for completeness. Silica concentrations for regoliths with <4% TiO_2 are nearly constant and average 45.5% (s = 1.3%). Among such materials, there as a weak tendency of SiO_2 to increase with increasing FeO (Fig.3). SiO_2 concentrations of high-Ti (>7% TiO_2) basalts and regoliths are lower, ~40%.

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References: **[1]** Reedy (1978) *PLPSC9*, 2961–2984. **[2]** Laul (1979) *Atomic Energy Review* **17**, 603–695. **[3]** Elphic et al. (1998) *Science* **281**,1493–1496. **[4]** Wänke et al (1971) *PLSC2*, 1187–1208. **[5]** Wänke et al. (1972) *PLSC3*, 1251–1268. **[6]** Ehmann and Morgan (1971) *PLSC2*, 1237–1245. **[7]** Janghorbani et al. (1973) *PLSC4*, 1115–1126. **[8]** Pieters & Wilhelms (1985) *PLPSC15*, C415–C420. **[9]** Feldman W. C. et al. (1998) *Science* **281**, 1489–1493.

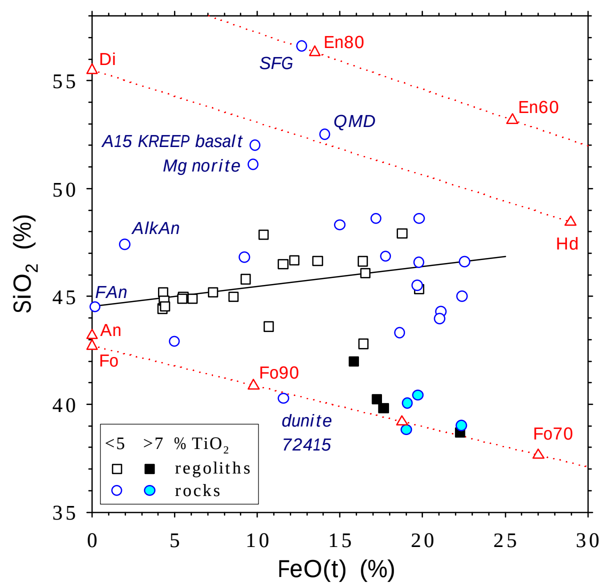

Figure 3. Variation of SiO_2 with FeO(t) in lunar materials. The solid diagonal line is a simple linear regression to regoliths with <4% TiO_2 (O = 44.5 + 0.93·[FeO(t)]; R^2=0.138).