EROS SULFUR DEFICIENCY: A CLOSER LOOK AT METEORITE COMPARISONS. A. Kracher, D. W. G. Sears, P. H. Benoit, and A. J. Meier. Arkansas-Oklahoma Center for Space and Planetary Sciences, and Department of Chemistry and Biochemistry, University of Arkansas, Fayetteville, AR 72701 (akracher@uark.edu).

Introduction: The NEAR Shoemaker spacecraft that orbited and eventually landed on asteroid 433 Eros carried two experiments to determine the chemistry of the surface layer: an x-ray spectrometer (XRS) and a gamma ray spectrometer (GRS). Arguably the most surprising result obtained by these instruments was the discovery that, in spite of an otherwise chondritic chemistry, the sulfur content of Eros regolith is very low. Here we address several possible explanations, consider their plausibility, and propose steps toward resolving the conundrum.

NEAR results: The sulfur x-ray signal was barely detectable by XRS. Nittler *et al.* [1] suggest an upper limit of S/Si=0.05 (weight ratio); the model calculations of McCoy *et al.* [2] use an average of 0.014. Normalized to CI chondrites, the upper limit corresponds to (S/Si)*=0.1, the McCoy estimate (S/Si)*=0.027 [where $(S/Si)^* = (S/Si)_{sample}/(S/Si)_{CI}$].

For comparison with meteorites two other results are important: the K content determined by GRS (0.070±0.028%) and the Fe/Si weight ratio determined by XRS (1.65±0.27). For comparison with meteorites the absolute value of the K determination has to be converted to a K/Si ratio. We have adopted the nominal value of 17.65wt% Si of McCoy for this purpose; any error in the Si estimate is probably trivial compared to the uncertainty in K.

Possible causes: There are three classes of explanations for the low S content found by NEAR: (1) the depletion is primary, (2) sulfur has been lost into space, or (3) sulfur has migrated from the surface layer analyzed by XRS to a deeper level in the regolith. The issue of primary depletion can be addressed to some extent by comparison with meteorites. The other two possible explanations for sulfur depletion can be best studied by laboratory simulations of asteroidal processes.

Primary depletion: Comparisons are complicated by the fact that there are at least two major fractionation processes affecting chondrites: volatility and mineral separation. The mineral fractionation has primarily been conceived as metal/silicate fractionation. Sulfur, however, is not hosted in either fraction, but in a separate mineral, FeS. The behavior of FeS during metal/silicate fractionation is poorly understood.

Figures 1 and 2 show (S/Si)* of major chondrite groups plotted against (K/Si)* and (Fe/Si)*, respectively. The former is a measure of fractionation related to volatility, the latter mostly a measure of metal/silicate fractionation. Since many chondrite groups are apparently affected by both processes, neither diagram shows a very tight correlation.

The width of the boxes representing Eros are defined by the stated errors for the determination of K [3] and Fe/Si [1]; the height of boxes spans the range

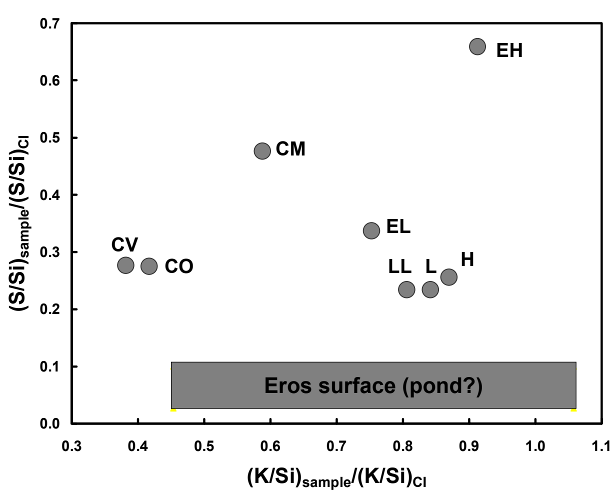

Figure 1. (S/Si)* *versus* (K/Si)* in major chondrite groups and Eros. Meteorite data from [9,10]. See text for Eros data. Variations in K/Si are primarily related to volatility.

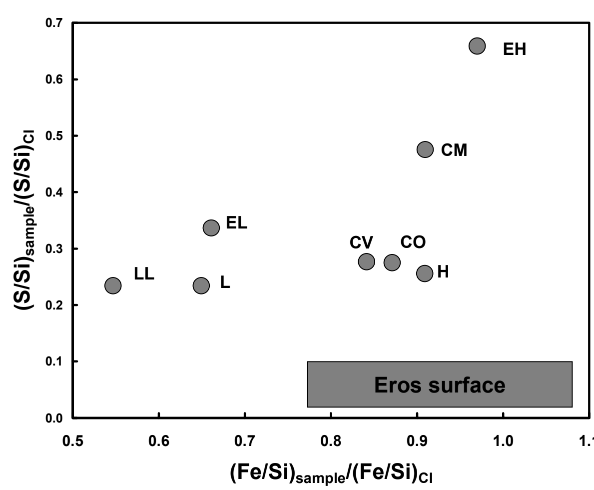

Figure 2. (S/Si)* *versus* (Fe/Si)* in major chondrite groups and Eros. Meteorite data from [9,10]. See text for Eros data. Variations in Fe/Si are primarily due to metal/silicate fractionation.

of $0.027 \le (S/Si)^* \le 0.1$. Even with these uncertainties the Eros values do not fall on extrapolations of chondrite trends. It should be noted, however, that GRS data were obtained in contact with the regolith at the landing site. Thus the K value represents one small locality of atypical chemistry on the Eros surface, perhaps one of the "pond" deposits. In the absence of other measurements it is possible that bulk Eros is much more depleted in volatiles than suggested by the local K analysis.

Some differentiated meteorites are much more depleted in volatiles than any known chondrite group. Eucrites have very low alkali contents, and some iron meteorites have Ge/Ni ratios orders of magnitude lower than the CI value. It is not certain that this volatile depletion reflects the chondritic precursor rather than the differentiation process. However, it is at least possible that some chondritic materials were much more depleted in volatiles than those represented in our meteorite collections, and that Eros is an example of this. The available data, however, strongly suggest that a primary S deficiency is less plausible than secondary S loss from the Eros surface.

Secondary depletion by volatilization: If the low S/Si ratio on Eros is due to loss of S into space, why is the loss process so selective? Volatility is the most probable answer; perhaps K is not affected because it is less volatile, or the K value determined by GRS is a local anomaly. It is also possible that the difference in the behavior of S and K is a mineralogical effect, since S mostly occurs as a major element in discrete minerals (probably FeS), but K is a minor component in feldspar.

The energy source for volatilization is presumably the same that is responsible for "space weathering," solar wind irradiation and micrometeorite bombardment. Most of our understanding of this process comes from the study of lunar soils, but since their sulfide content is negligible, the hypothesis of weathering-related sulfur loss cannot be tested on the moon. Volatile lithophiles do not seem to be lost by lunar space weathering, since the finest fraction that shows the strongest weathering [4] is enriched rather than depleted in Na [5]. If space weathering leads to sulfur depletion, the effect appears to be element-specific.

Secondary depletion by migration: Space weathering need not necessarily lead to loss of S into space; it could also have caused migration to deeper levels of the regolith. Most of the ion sputtering associated with solar wind occurs in the forward direction in a loose regolith, i.e., downward from the exposed surface [6]. Since the depth of XRS analysis is <100µm [1], the depleted layer need not be very thick.

McCoy *et al.* [2] have considered partial melting as an alternative mechanism of S depletion, but regard it as unlikely because it would leave lateral heterogeneities. However, it is not known whether the relative chemical homogeneity of the Eros surface reflects the absence of local fractionation processes, or is due to more or less homogeneous regolith redistribution. Partial melting should still be taken into account, even though we consider other mechanisms more probable.

Laboratory simulations: Space weathering is a result of both solar wind and micrometeorite impact. The effects of solar wind, which include sputtering and ion implantation, can be simulated with a plasma source which produces an ion beam of similar energy as the solar wind [6]. Micrometeorite impacts can be simulated by laser irradiation, provided the laser impuls is of appropriate energy and duration [7].

Laboratory simulations of space weathering should be able to answer the question whether this process is responsible for the sulfur deficiency on Eros, either because of loss into space, or migration to deeper regolith levels. However, because both possibilities need to be considered, the required experiments are necessarily complex. If the thickness of the sulfur-depleted regolith layer is on the same order as the XRS analysis depth, simulant sampling may be quite difficult. Also the mechanical processes on asteroid surfaces such as gardening, impact-induced mineral sorting [8], etc., must eventually be taken into account.

Conclusions: ***1.*** The low S/Si ratio on Eros is probably due to secondary alteration of the surface, but primary volatile deficiency should not be ruled out.

2. Sulfur loss may be related to space weathering.

3. Further insight can be obtained by simulating space weathering in the laboratory, using sulfide-bearing simulants.

4. Sample return missions are the most desirable way toward improved asteroid-meteorite comparisons; where this is impossible, at least improved data on volatile (Na,K) as well as siderophile (Ni) elements should be a major goal for analytical instruments on future asteroid missions.

References: [1] Nittler *et al.* (2001) *MAPS* **36,** 1673. [2] McCoy *et al.* (2001) *MAPS* **36,** 1661. [3] Evans L. G. *et al.* (2001) *MAPS* **36,** 1639. [4] Noble S. K. *et al.* (2001) *MAPS* **36,** 31. [5] Taylor L. A. *et al.* (1999) *LPS XXX* abstract#1885. [6] Hapke B. (2001) *JGR E* **106,** 10039. [7] Sasaki *et al.* (2001) *Nature* **410,** 555. [8] Benoit *et al.* (2003) *LPS XXXIV,* this volume. [9] Wasson J. T. & Kallemeyn G. W. (1988) *Phil. Trans. R. Soc. Lond.* A **325,** 535. [10] Dreibus *et al.* (1995) *Meteoritics* **30,** 439.