PRE-TERRESTRIAL ORIGIN OF "RUST" IN THE NAKHLA METEORITE.

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INTRODUCTION. As part of our campaign to identify and rigorously test evidence for aqueous geochemistry in shergottite, nakhlite, and chassignite (SNC) meteorites, we previously reported evidence for pre-terrestrial origin of calcium carbonate associated with silicate "rust" in Nakhla [1]. Here we present quantitative elemental compositions and summarize textural evidence for pre-terrestrial origin of the rust. We denote the material in question as "rust" because its phase composition remains unknown. The rust is probably the same as the iddingsite-like material reported by Bunch and Reid [2] and might be related to pockets of material called "brownies" by Papanastassiou and Wasserburg [3].

SAMPLES AND METHODS. Although our previous work on Nakhla [1,4,5] has also involved untreated interior and exterior chips obtained from the British Museum (Natural History), all data reported here were obtained from polished thin sections prepared from Nakhla specimen, USNM-426 (Smithsonian Institution). Scanning electron microscopy (SEM) and energy-dispersive X-ray spectrometry (EDS) followed our previously described procedures and included mineral-standardized, quantitative EDS analyses. Relative to conventional wavelength-dispersive microprobe analyses, our method permitted beam-spot sizes of 1-10 μm, as necessitated by the rust occurrences.

RESULTS AND DISCUSSION. *MICROSTRATIGRAPHY.* Compelling evidence for pre-terrestrial origin of the rust is found as rust veins truncated by fusion crust (Fig. 1) and preserved as faults in sutured igneous crystals (Fig. 2). Rust veins that approach the meteorite's fusion crust become discontinuous and exhibit vugs that suggest partial decrepitation; no rust veins that penetrate fusion crust have been found. Because the rust probably contains volatile compounds (see below), it is reasonable to expect that heating near the ablation surface (formed during atmospheric entry to Earth) would encourage devolatilization of the rust. Hence, absence of rust veins in fusion crust and vugs in rust veins near fusion crust (but not at distance from fusion crust) clearly imply that the rust existed in the meteorite before atmospheric entry. At least one unmistakable example of a vein post-dated by later endogenous events occurs as a faulted rust vein enclosed in an olivine crystal (Fig. 2). It is obvious that the rust vein has been broken by a fault but the two disjointed sections of the vein are separated by clear olivine rather than an open fracture. We infer that, after faulting, the fracture was at least partially healed by elevated pressure. It is difficult to conceive any reasonable natural processes that would break and suture an igneous mineral after the meteorite arrived on Earth. Accordingly, disturbance of the rust vein must have occurred before the meteorite arrived on Earth and, most likely, on the Nakhla parent planet. *COMPOSITION.* Our results for the average elemental composition of the rust (Table 1) generally agree with those of Bunch and Reid [2] except for Al and Na. Compared with the earlier data [2], we find much lower Al. Because our analyses of Al in Nakhla plagioclase and pyroxene agree with the respective data of Bunch and Reid [2], no systematic analytical error is suspected in our Al data. Our Na results for plagioclase agree with those of Bunch and Reid [2] but are systematically high relative to reference samples that contain very minor to trace Na. We conclude that the rust actually contains < 1% Na_2O. Low analytical totals, both in

Table 1. Elemental compositions (weight percent) of rust in Nakhla determined by electron probe microanalysis (all iron calculated as Fe_2O_3; EDS background problem makes our Na results systematically high; nr = not reported).

	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	Fe_2O_3	NiO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	SO_3	Cl	Total
Avg. of 78 spots	40.21	0.02	0.74	0.03	37.93	< 0.01	0.63	6.82	1.14	(1.16)	0.60	0.06	0.14	0.66	90.13
Standard deviation (this work)	3.66	0.03	0.31	0.03	4.68	0.01	0.26	0.71	1.51	(0.37)	0.17	0.09	0.12	0.33	
Unknown "iddingsite" (Bunch and Reid [2])	43.6	nr	5.8	nr	30.56	nr	0.37	9.4	0.73	0.21	0.10	nr	nr	nr	90.77

RUST IN THE NAKHLA METEORITE: Wentworth S. J. and Gooding J. L.

our data and in those of Bunch and Reid [2], suggest that the rust contains water. Although admixed carbonate occurs in some places [1], carbon contents in carbonate-free areas are near background levels and do not contribute significantly to the deficit. Intrinsic sulfur is very low except in those places where admixed calcium sulfate is found. Chlorine, however, is a characteristic component that is not correlated with known occurrences of sodium chloride. The fluids that deposited the rust probably carried chloride that was not indigenous to the igneous-rock parent of Nakhla. Absence of significant interelemental correlations implies that the rust is a single phase with compositional heterogeneities at the scale of 1-10 μm. Poor crystallinity was previously inferred from a preliminary transmission electron microscopy (TEM) study [6]. In terms of a single-phase model, structural-formula calculations by the method of Gooding [7] show that our average rust composition gives nearly equal goodness-of-fit values for dioctahedral smectite and stilpnomelane. By definition, genuine iddingsite (a smectite-goethite mixture), would contain smectite as a major component. New high-resolution TEM analyses are needed to verify whether the rust is crystalline or mostly a colloidal gel.

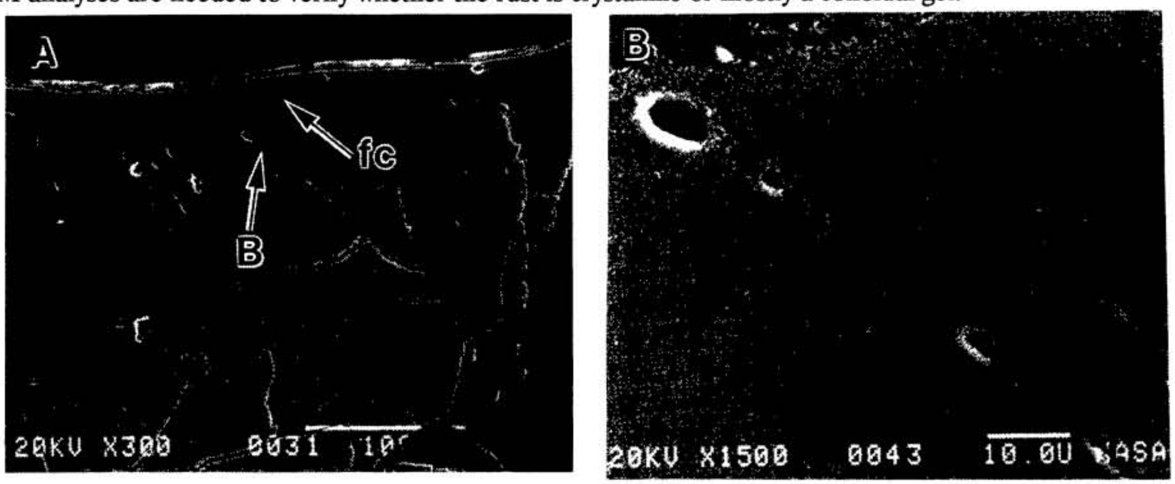

Figure 1. SEM photomicrographs (secondary-electron images) of a Nakhla rust vein truncated and partially decrepitated as it approaches fusion crust (fc). Scale bars are in micrometers.

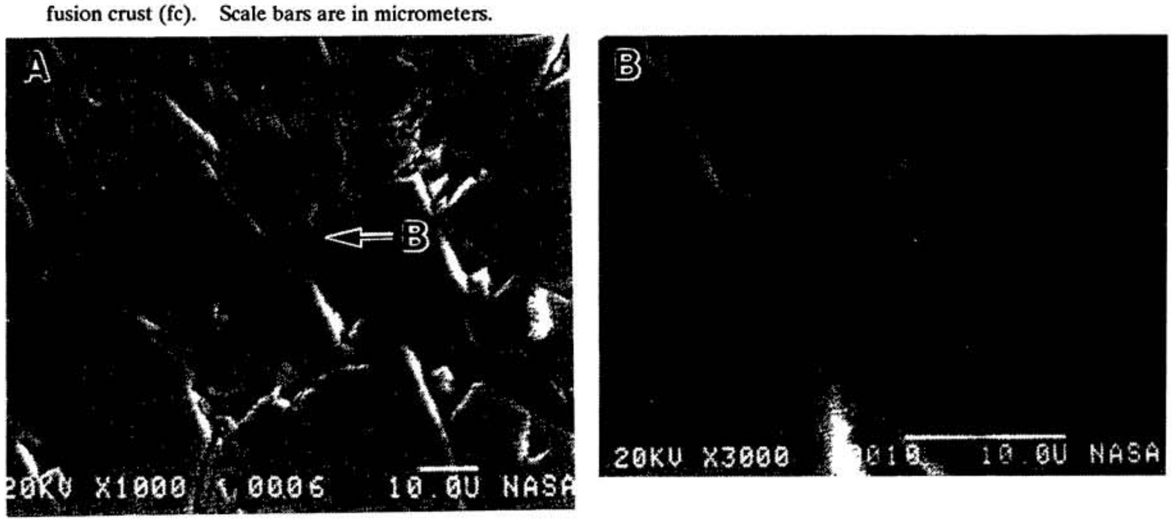

Figure 2. SEM photomicrographs (secondary-electron images) of a Nakhla rust vein broken by a partially healed fault in an olivine grain. Frame (B) is a detailed view of the area marked by an arrow in (A). Scale bars are in micrometers.

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