Mineralogy and Petrology (2003) 77: 279–285

Mineralogy and Petrology

Reply to comment: "The Nakhla Martian meteorite is a cumulate igneous rock" by A. Treiman

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Received April 14, 2002; revised version accepted August 30, 2002
Editorial handling: E. F. Stumpfl

Introduction

Varela et al. (2001) reported the first heating experiments performed on glass-bearing inclusions in Nakhla augite. These in situ heating experiments allowed us to estimate the initial composition of a liquid co-existing with Nakhla augite at 1150 °C and 1 atm pressure. During heating experiments the glass melted and crystals inside inclusions were dissolved in the melt whereby its chemical composition changed. The behavior of the glass-bearing inclusions during heating experiments mimic that of a homogeneous melt that has subsequently evolved as a closed system during cooling. The results on re-melted glasses, however, indicate that these inclusions represent a heterogeneous system. Glass-bearing inclusions in augite from Nakhla 1) have a quartz-normative composition when homogenized in melting experiments, 2) cannot be in equilibrium with olivine, which is a requirement for the Nakhla parental liquid as Nakhla contains about 10 vol% olivine, 3) the experimentally derived liquid is out of equilibrium with the augite with respect to the Fe/Mg ratio, 4) have highly variable mineral and glass contents and 5) have highly variable Na/K ratios as well as highly variable absolute alkali contents. All these features are incompatible with trapping of a homogeneous parental melt and suggest a more complex and possibly non-magmatic genesis of Nakhla. The highly variable Na/K ratios in individual glasses are present without any K- or Na-bearing phases being stable near the liquidus of any possible parental liquid for Nakhla. Such a feature is totally atypical for parental melt inclusions and must have its roots in the very beginning, during augite and inclusion formation. Thus, the variable glass compositions could then represent heterogeneous sampling of Na-rich and K-rich phases from the environment in which Nakhla augites grew. Our results are clearly in conflict with the widely entertained igneous cumulate model and therefore we had to question its validity.

In his comment on our report, *Treiman* (2003) stresses his conviction that Nakhla is a "Cumulate Igneous Rock". However, he seems to be aware of some problems as he states that "*the composition of the glass inclusions in augite must be seen as anomalous*" (*Introduction*).

There are many more "anomalous" features in Nakhla if viewed from the igneous cumulate point of view. The apparently young ages (e.g., *Ganapathy* and *Anders*, 1969; *Podosek*, 1973; *Bogard* and *Nyquist*, 1979; *Nakamura* et al., 1982) are possibly due to a disturbance of the chronometers (*Jagoutz*, 1991) rather than a melting event as the melt needs to be depleted and the cumulates enriched in incompatible elements (*Jagoutz*, 1997; *Jagoutz* and *Dreibus*, 1997; *Jagoutz* and *Jotter*, 1999). This is also supported by U–Pb ages which are inconclusive (*Nakamura* et al., 1982; *Jagoutz* et al., 2002). New data on Nakhla apatites gave concordia intercepts for 4318 ± 320 and 1146 ± 340 Ma (*Terada* et al., 2002) supporting an old age and a young disturbance of the chronometer. Nakhla and other SNC meteorites have positive ε ^{142}Nd and positive ^{182}W anomalies (*Harper* et al., 1995; *Lee* and *Halliday*, 1997; *Jagoutz* et al., 2000), indicating very early fractionation.

With respect to H isotopes, all phases in Nakhla are out of equilibrium with δD values of -93 to $+210$‰ in olivines, $+560$ to $+814$‰ in augite and $+1408$‰ in a glass of a glass-bearing inclusion (e.g., *Leshin* et al., 1996; *Boctor* et al., 2002). Carbon isotope abundances are highly variable among SNC meteorites with carbonates having heavy C (δ^{13}C: $+30$ to $+52$‰) – very similar to Cl and CM chondrite carbonates (*Jull* et al., 1995). The organic matter in Nakhla is isotopically non-equilibrated (with δ^{13}C -33 and -15‰, respectively) – similar to that present in carbonaceous (CM) chondrites (*Jull* et al., 1999, 2000). Nakhla contains also an isotopically light nitrogen component (δ^{15}N ~ -30‰) which is similar to a component known from ordinary chondrites (*Wright* et al., 1992; *Mathew* et al., 1998; *Sugiura* et al., 1998). *Wright* et al. (1999) report "at least three, and possibly four, separate components present" in ALH 84001 with δ^{15}N ranging from -30‰ to $+29$‰, again a typical igneous signal? Olivine and pyroxene contain heavy N components and are out of equilibrium with each other (e.g., *Schwenzer* et al., 2002). Oxygen isotopes in silicates and carbonates of SNC meteorites vary widely with Nakhla siderite having δ^{18}O of $+34$‰ and other carbonates up to $+45$‰ – very similar to dolomite and ankerite from Cl chondrites (*Saxton* et al., 2000) and bulk SNC oxygen has an isotopic composition very similar to Cl magnetites (*Franchi* et al., 1999). In addition, anhydrite and carbonate in Nakhla are far out of equilibrium with the rock's silicates with respect to the O isotope abundances (*Saxton* et al., 1998, 2000; *Farquhar* and *Thiemens*, 2000). *Ott* and *Begemann* (1985) expressed their doubts on an origin of SNC meteorites from Mars, based on their rare gas isotope data. This list is far from being complete. There are many indication that Nakhla and the SNC meteorites are relatives of carbonaceous chondrites (e.g., *Brandenburg*, 1996; *Kurat*, 1996). Also, the texture of Nakhla is

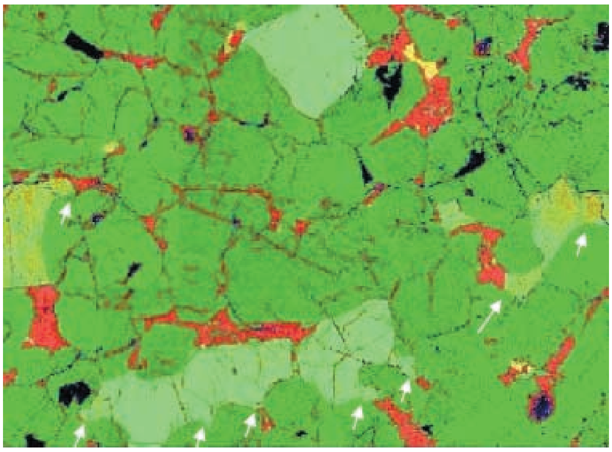

Fig. 1. Texture of Nakhla is not that of a cumulate igneous rock but rather suggestive of an origin by metasomatic transformation of an unknown precursor mineral association. Note that olivine (light green to yellow in this false color back scattered electron image) fills interstitial space (white arrows indicate relevant points) between augites and that it has inhomogeneous chemical composition (yellow = Fe-rich) with irregular Fe distribution. In an igneous cumulate rock olivine shall have subhedral to euhedral crystal shape and surface-related chemical zoning. Red areas (usually referred to as ''intercumulus liquid'') are rich in Si and Al and contain feldspars, glasses, phosphates, carbonates, sulfides (bright yellow), sulfates, halite and many other phases and thus must be considered highly ''anomalous'' for an igneous mineral assemblage. Length of picture is ~2 mm

very unusual (Fig. 1) with olivines (the ''primary'' precipitate) filling voids and having irregular zoning, all very, ''anomalous'', indeed, yet obviously not enough to convince strong believers in the igneous origin of SNC meteorites on Mars (*Wood* and *Ashwal*, 1981). *Brandenburg* (1996) – being also a strong believer in SNC meteorites coming from Mars – consequently concluded that **carbonaceous chondrites must come from Mars**. *Treiman*, however, prefers to recognize a few ''anomalies'' but still accepts an already erroneous model. Such models need to be revised (e.g., *Popper*, 1963), they should be made to fit reality and not the other way around. Nothing has to be ''anomalous''.

Glassy and glass-bearing inclusions

Treiman (2003) incorrectly refers to glass-bearing inclusions in Nakhla augites as ''**glassy inclusions**'', a term that obviously denotes an inclusion consisting only of glass (+/− bubble). In our sample of Nakhla, augite does not contain such inclusions, it contains multi-phase inclusions with one of the phases being glass. We believe that our description (*Varela* et al., 2001) is clear and unequivocal. This is a very important point as the presence of one or more phases – in addition to the glass – gives additional information on the cooling rate of the host crystal and on the physico-chemical conditions prevailing during the evolution of the inclusion. We took advantage of this situation and concluded (*Varela* et al., 2001, page 163): ''*A rapid growth of augites' cores has been inferred due to the small size of its glass-bearing inclusions by* Treiman (*1993*). *However, inclusions present in the* *core and at the surface of grains are similar not only in their sizes but also in their phase contents (glass + crystals + bubble). If rapid growth of the crystal had occurred in the augite core, and considering the small sizes of the inclusions, glassy inclusions could be expected to be found. However, the small volumes of the inclusions trapped in the augite cores and surfaces had enough time to develop euhedral and subhedral crystals that occupy a large volume of the inclusion cavity. This suggests that growth conditions have not undergone significant changes during augite formation*".

Wrong terminology has been attributed to *Varela* et al. (2001) in quoting two sentences that are not in our paper:

*– "*If Nakhla is a cumulate igneous rock, how can one explain the varied compositions of the glassy inclusions in Nakhla's augite* (Varela *et al., 2001*)?"

*– *If this is so,* Varela *et al.* (*2001*) *are correct in their inference that ...*"*the glassy inclusions do not represent parental magma or some such...*". (*page 5*, Treiman, 2003)

Chemical composition of glass-bearing inclusions

The main point made by *Treiman* (2003) is that the variability observed, mainly with respect to alkali elements in the glass-bearing inclusions studied by us, should be explained by disequilibrium processes during crystal growth and can be attributed to contamination with the melt boundary layer adjacent to the growing augite crystal.

The boundary layer

According to *Roedder* (1979), the width of the zone in which significant compositional differences might occur during crystallization will increase, among other parameters, with the speed of crystallization and the viscosity of the melt. Regarding the viscosity of the melt, *Roedder* (1984) states: "the large number of crystals of any given phase stems from the high viscosity of the melt, which results in large number of nuclei and little growth on each". The growth conditions and the viscosity of the melt can be very well established from the petrography of the glass-bearing inclusions.

The small volumes of the inclusions trapped in the augite cores and surfaces had enough time to develop euhedral and subhedral crystals that occupy a large portion of the inclusion cavity. Thus, characteristics of Nakhla glass-bearing inclusions strongly point towards a slow growth of the augite crystals, as well as a low viscosity of the trapped melt. Both parameters point towards a very thin boundary layer.

"The application of these concepts to actual studies of inclusions in magmatic minerals show that the real effects of boundary-layer problems on melt-inclusion chemistry, as revealed by quenched-in compositional gradients are generally minor" (*Roedder*, 1984). The boundary layer seems to have a negligible effect only.

Treiman (2003) also indicates that the variability in the chemical composition of the glass-bearing inclusions as reported by *Varela* et al. (2001) can be expected if inclusions have different sizes and shapes. However, we have pointed out that there was no variation, neither in the size nor in the type of the inclusions observed in the core and surface of the studied augites crystals. We thus suspect that the chemical variability observed was not related to the size of the objects but could be related to inhomogeneities of the trapped melt (or another glass precursor). In all our heating experiments, the quenched glass is always enriched in Na_2O with respect to K_2O. A variation in the Na_2O content in the re-melted glass from 0.5 wt% to $\approx$6 wt% (see Fig. 4 of *Varela* et al., 2001) is more likely a direct consequence of the dissolution of a Na phase present in the glass-bearing inclusion in Nakhla augite than the effect of a thin boundary layer that is enriched in Na due to its incompatibility in the augite crystal.

In addition, recent heating experiments on glass-bearing inclusions in augite of Nakhla that achieved homogenization at $\approx$1175 °C (*Stockstill* et al., 2002) produced melts that are rich in Na, very similar to what we found.

Conclusion

Our results on glass-bearing inclusions in augites and olivines of Nakhla and Chassigny, both believed by *Treiman* and others to be igneous cumulate rocks, do not support the cumulate hypothesis. In Chassigny, the crystalline phases within inclusions did not dissolve during heating experiments, but the residual glass of the inclusion turned out to be in equilibrium with the host olivine (*Varela* et al., 2000). Conversely, crystalline phases in Nakhla glass-bearing inclusions did dissolve but the quenched homogenized glass is not in equilibrium with the host augite.

This situation opens an excellent opportunity to explore new mineral- and rock-forming processes beyond the limitations of popular theories and we are ready to learn from these rocks.

Acknowledgement

We thank *E. Wäsch*, Berlin, for the SEM picture of Nakhla.

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