Shock-enhanced aqueous alteration of the nakhlite Miller Range 03346 [#6120]

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Introduction: The nakhlite meteorites sample a stack of 1.3-1.4 Ga martian lava flows [**1**]. These rocks are composed principally of augite and olivine phenocrysts, between which is a glass- or feldspar-rich mesostasis. Olivine phenocrysts in most nakhlites have been aqueously altered to form iddingsite veins [**2**,**3**]. Iddingsite has been dated to ~0.63 Ga [**4**], showing that this alteration was unrelated to the magmatic activity that produced the nakhlite lavas. The source of water and driver of fluid/rock interaction remain unknown.

An electron backscatter diffraction (EBSD) study of Miller Range (MIL) 03346 has shown that augite grains in discrete regions of this nakhlite have been deformed by shock, and the adjacent mesostasis has been pervasively aqueously altered. Here we explore the nature and significance of this apparent link between water-rock interaction and an impact.

EBSD results: A thin section of MIL 03346 was polished in colloidal silica, then EBSD maps were acquired using a Zeiss Sigma field-emission scanning electron microscope (SEM) operated at 20 kV and in variable pressure mode. The maps were collected from a 1 cm^2 area using a step size of 4 µm/pixel. Grain relative orientation distribution (GROD) angle maps reveal 2 mm wide bands within which the augite phenocrysts have experienced 2-10° of crystal plastic deformation (**Fig. 1A**), and Euler maps reveal mechanical twinning and some brecciation (**Fig. 1B**). These 'deformation bands' are similar to areas of shock-produced cataclasis in the nakhlite Northwest Africa 998 [**5**], and to 'granular zones' in Nakhla [**6**].

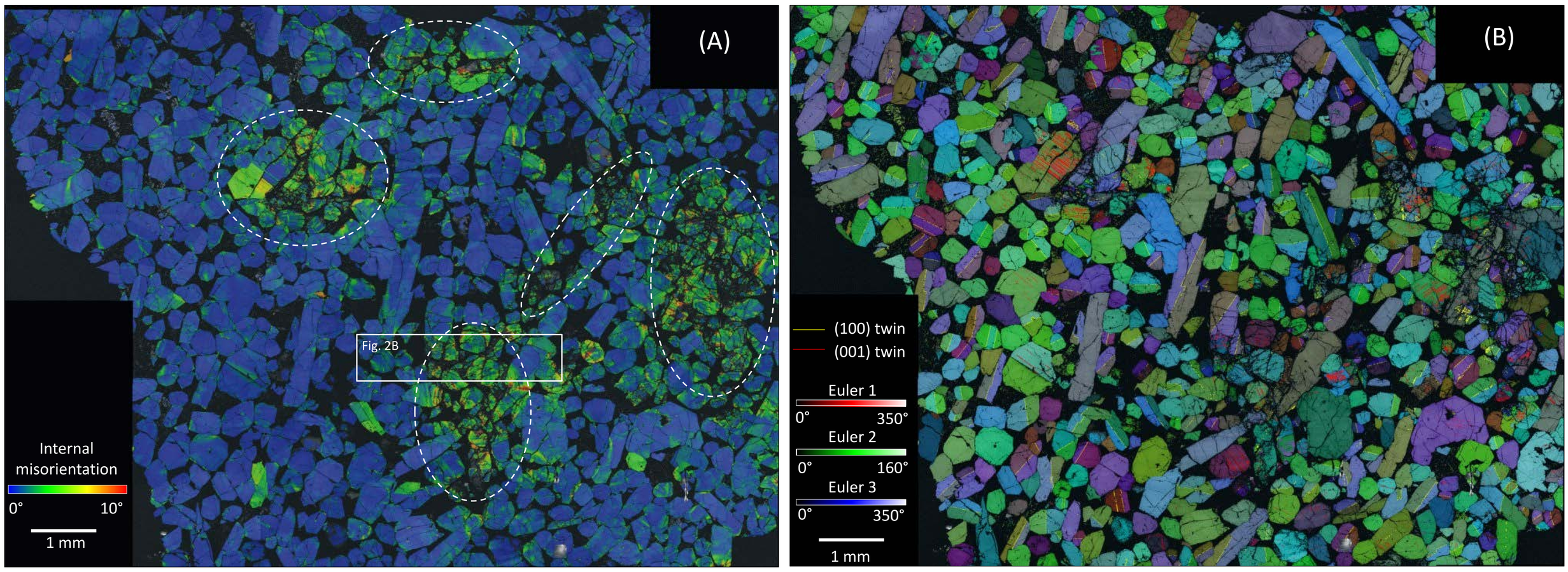

Figure 1: EBSD maps of MIL 03346. A) GROD angle map to visualize internal deformation of augite. The average internal orientation of each grain is compared to each pixel within the grain. Pixels are coloured relative to this average orientation where blue represents no internal deformation and greens through to red indicate increasing degrees of internal misorientation up to a maximum of 10°. Deformation is concentrated here into five bands, each a few cm in size (outlined by dashed white lines). B) Euler image where colours indicate the orientation of each augite crystal. Mechanical twinning is clearly seen (red lines) in the vicinity of brecciated or fractured regions and correlated with the bands of deformation seen in the GROD angle map and are absent away from these areas.

Evidence for aqueous alteration: Undeformed regions of the thin section contain olivine phenocrysts with iddingsite veins (46 wt.% SiO_2, 33 wt.% FeO, 3 wt.% MgO) (**Fig. 2A**). The mesostasis in these regions is composed of glass with fayalite, titanomagnetite, cristobalite, sulphides and apatite [**7**] (**Fig. 2B**).

The mesostasis within deformation bands consists of hematite together with patches/concentric layers of two fine-grained materials: (i) a Fe-Mg silicate whose chemical composition is comparable to olivine-hosted iddingsite (46 wt.% SiO_2, 30 wt.% FeO, 3 wt.% MgO, 3 wt.% Al_2O_3), and (ii) a Fe-oxide/hydroxide (54 wt.% FeO, 20 wt.% SiO_2, 3 wt.% SO_3) (**Fig. 2B**).

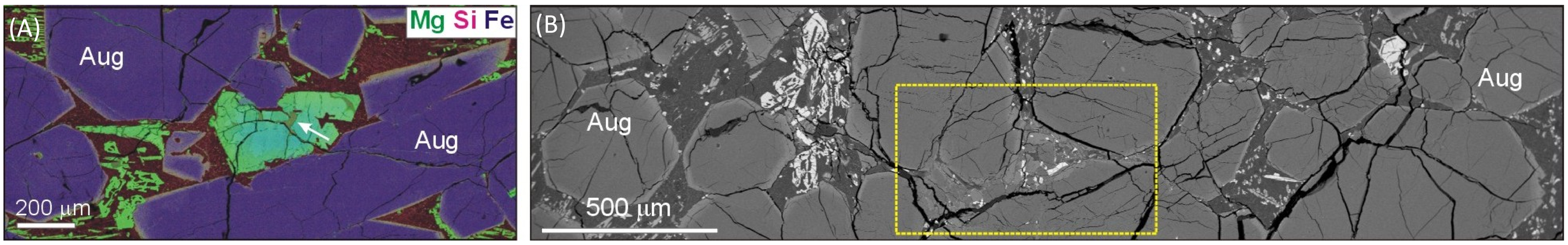

Figure 2: (A) False coloured multi-element X-ray map showing an olivine grain (turquoise) containing iddingsite veins (brown, arrowed). The mesostasis (dark red) contains skeletal crystals of titanomagnetite (lime green). (B) Backscattered electron SEM image of the area indicated in Fig. 1A, which contains augite phenocrysts (Aug) and mesostasis (M). The mesostasis in the area indicated by the yellow box has been pervasively aqueously altered.

Interpretation: Mechanical twinning of augite and the microstructure of the deformation bands is consistent with shock metamorphism (5-15 GPa) linked to an impact [**8**]. Hematite, Fe-Mg silicate and Fe-oxide/hydroxide within the deformation bands is interpreted to have formed by aqueous alteration of mesostasis glass, fayalite and titanomagnetite. The restriction of aqueously altered mesostasis to deformation bands therefore indicates that prior impact-induced plastic deformation, fracturing , and brecciation facilitated the ingress and interaction of liquid water.

Discussion: Mesostasis aqueous alteration postdated shock deformation of MIL 03346 – but was the water sourced from the hydrosphere/cryosphere of Mars, or was it terrestrial in origin (i.e., Antarctic meltwater)? The formation of mesostasis Fe-Mg silicate on Mars is implied by its compositional similarity to olivine-hosted iddingsite, whose martian origin is demonstrated by hydrogen isotopic data [**9**]. This scenario requires two impacts on the nakhlite lava stack: Impact 1 between 1.4-1.3 Ga (nakhlite volcanism) and ~0.63 Ga (iddingsite formation); Impact 2 at ~11 Ma (ejection of MIL 03346 from Mars). Terrestrial alteration would be consistent with evidence for Antarctic weathering of MIL 03346 and its paired meteorites [**10**]. Further work to discriminate between these two possibilities is ongoing.

References: **[1]** Cohen B.E. et al. (2017) *Nat. Comms.* 8:640 **[2]** Ashworth J.R. and Hutchison R. (1975) *Nature* 256:714–715. **[3]** Bunch T.E. and Reid A.M. (1975) *Meteoritics* 10:303–315. **[4]** Borg L. and Drake M. J. (2005) *Jour. of Geophys. Res.* 110:E12S03. **[5]** Treiman A.H. and Irving A.J. (2008) *MAPS* 43:829–854. **[6]** Treiman A.H. (2005) *Chemie der Erde* 65:203–270. **[7]** Day J.M.D. et al. (2006) *MAPS* 41:581–606. **[8]** Stoffler D. et al., (1991), *Geochim. et Cosmochim. Act.*, 55, 3845–3867.[**9**] Hallis L.J. (2012) *Geochim. et Cosmochim. Act.* 97:105–119. **[10]** Velbel M.A. (2016) *Geochim. et Cosmochim. Act.* 180:126–145. **Acknowledgements:** We thank NASA ANSMET for the loan of MIL 03346, and the UK STFC for funding.