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Ancient impactor components preserved and reworked in martian regolith breccia Northwest Africa 7034

Steven Goderis [a,b,c,*], Alan D. Brandon [a], Bernhard Mayer [d], Munir Humayun [d]

[a] Dept. of Earth and Atmospheric Sciences, University of Houston, Science and Research Building 1, Houston, TX 77204, USA
[b] Earth System Science, Vrije Universiteit Brussel, BE-1050 Brussels, Belgium
[c] Dept. of Analytical Chemistry, Ghent University, Krijgslaan 281 – S12, BE-9000 Ghent, Belgium
[d] National High Magnetic Field Laboratory and Dept. of Earth, Ocean & Atmospheric Science, Florida State University, Tallahassee, FL 32310, USA

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Abstract

Northwest Africa (NWA) 7034 and paired stones represent unique samples of martian polymict regolith breccia. Multiple breccia subsamples characterized in this work confirm highly siderophile element (HSE: Re, Os, Ir, Ru, Pt, Pd) contents that are consistently elevated (e.g., Os ~9.3–18.4 ppb) above indigenous martian igneous rocks (mostly <5 ppb Os), equivalent to ~3 wt% of admixed CI-type carbonaceous chondritic material, and occur in broadly chondrite-relative proportions. However, a protracted history of impactor component (metal and sulfide) breakdown and redistribution of the associated HSE has masked the original nature of the admixed meteorite signatures. The present-day $^{187}Os/^{188}Os$ ratios of 0.119–0.136 record a wider variation than observed for all major chondrite types. Combined with the measured $^{187}Re/^{188}Os$ ratios of 0.154–0.994, the range in Os isotope ratios indicates redistribution of Re and Os from originally chondritic components early in the history of the regolith commencing at ~4.4 Ga. Superimposed recent Re mobility reflects exposure and weathering at or near the martian and terrestrial surfaces. Elevated Os concentrations (38.0 and 92.6 ppb Os), superchondritic Os/HSE ratios, and $^{187}Os/^{188}Os$ of 0.1171 and 0.1197 measured for two subsamples of the breccia suggest the redistribution of impactor material at ~1.5–1.9 Ga, possibly overlapping with a (partial) resetting event at ~1.4 Ga recorded by U–Pb isotope systematics in the breccia. Martian alteration of the originally chondritic HSE host phases, to form Os-Ir-rich nuggets and Ni-rich pyrite, implies the influence of potentially impact-driven hydrothermal systems. Multiple generations of impactor component admixture, redistribution, and alteration mark the formation and evolution of the martian regolith clasts and matrix of NWA 7034 and paired meteorites, from the pre-Noachian until impact ejection to Earth.

Keywords: Osmium isotope systematics; Highly siderophile elements; Meteoritic contribution; Martian regolith breccia; NWA 7034 and paired meteorites

1. INTRODUCTION

Despite the wide distribution of regolith at the martian surface, all but one set of recovered martian meteorites represent igneous rocks (e.g., McSween and Treiman, 1998; Bridges and Warren, 2006). Geochemical and petrographic characterization of paired meteorites Northwest Africa (NWA) 7034 (Agee et al., 2013; Santos et al., 2015), 7475

* Corresponding author at: Earth System Science, Analytical, Environmental, and Geo-Chemistry (AMGC), Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels, Belgium. Tel.: +32 2 629 1480; fax: +32 2 629 3391.
E-mail address: Steven.Goderis@vub.ac.be (S. Goderis).

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(Wittmann et al., 2015), 7533 (Humayun et al., 2013), 7906, 7907, 8114, 8171, and 8674 (Meteorite Working Group, 2016; http://www.lpi.usra.edu/meteor/metbull.php; last accessed April 11, 2016) reveal that these meteorites represent the first polymict regolith breccia samples from Mars. A martian origin is supported by the Mn/Fe ratios determined in pyroxenes (Agee et al., 2013; Wittmann et al., 2015) and by the trapped noble gas signatures (Cartwright et al., 2014). The bulk chemistry of the NWA 7034 and paired meteorites (e.g., Agee et al., 2013; Humayun et al., 2013; Santos et al., 2015; Wittmann et al., 2015) is strikingly similar to the surface composition measured by NASA orbiter and lander missions (e.g., Boynton et al., 2007; McSween et al., 2009). The oxygen isotope data for bulk breccia samples of NWA 7034 and 7475, a magnetic separate of NWA 7475, and maghemite/magnetite and plagioclase separates of NWA 7034 do not plot within the martian meteorite field, while an orthopyroxene separate for NWA 7034 and the non-magnetic fraction of NWA 7475 do (Agee et al., 2013; Zeigler et al., 2013; Wittmann et al., 2015). These results reveal a martian origin with particularly close resemblance to the rocks and soils from the southern highlands of Mars (e.g., Humayun et al., 2013; Wittmann et al., 2015). The wide lithologic diversity among the characterized clasts (Hewins et al., 2013a,b, 2014; Humayun et al., 2013; Udry et al., 2014; Santos et al., 2015; Wittmann et al., 2015), as well as the presence of melt spherules, clast-laden impact melt rock fragments, and a rare accretionary lapillus (Hewins et al., 2013a,b; Humayun et al., 2013, 2014; Udry et al., 2014; Wittmann et al., 2015), categorize NWA 7034 and paired stones as a polymict impact breccia.

The complexity of these samples is supported by distinct U–Pb age groups of 4.43–4.35 Ga and ~1.4 Ga for zircon and baddeleyite, and ~1.35 Ga for phosphate in NWA 7034 and 7533 (Humayun et al., 2013; Yin et al., 2014; Bellucci et al., 2015). A disturbed Rb-Sr age of ~2.1 Ga for clasts, and a Sm-Nd age of ~4.4 Ga for mineral separates were obtained for NWA 7034 (Agee et al., 2013; Nyquist et al., 2016). From these ages, it is inferred that NWA 7034 and NWA 7533 contain components of the earliest crust formed on Mars during the pre-Noachian. In contrast, noble gas data for NWA 7034 set a K-Ar closure age to less than ~1.56 Ga, while a U–Th/He age of ~170 Ma is indistinguishable from the crystallization ages of most shergottites (Cartwright et al., 2014; Lindsay et al., 2014). Cosmogenic noble gas results indicate cosmic-ray exposure (CRE) ages of ~5 and ~9 Ma (Cartwright et al., 2014). Busemann et al. (2015) argued for an ~8 Ma ejection age using both their noble gas data and that of Cartwright et al. (2014). These ages are different from most other martian meteorite CRE ages, and may suggest a distinct ejection event (Cartwright et al., 2014; Wittmann et al., 2015).

Throughout NWA 7533 and NWA 7475 bulk rock fragments, microbasalt clasts, clast-laden impact melt rock fragments and intraclast crystalline matrix, siderophile element abundances, including the highly siderophile elements [HSE: Re, Os, Ir, Ru, Pt, Rh, Au] and Ni, occur in relatively chondritic ratios and reach levels equivalent to the admixture of ~5% CI chondrite (Humayun et al., 2013; Wittmann et al., 2015). These are much higher than the levels found for shergottite-nakhlite-chassignite (SNC) martian meteorites at the same MgO content (e.g., Kong et al., 1999; Warren et al., 1999; Brandon et al., 2000, 2012; Yang et al., 2015) and were almost certainly added by meteorite impact on the martian highlands. Several generations of impact melt emplacement record the occurrence of multiple impact events (Humayun et al., 2013; Udry et al., 2014; Wittmann et al., 2015). Highly siderophile elements have proven to be a powerful geochemical tool to characterize the nature of the dominant impactor signatures on Earth and the Moon, have helped to improve our knowledge of ancient terrestrial and lunar indigenous crustal contributions, and could potentially do the same for Mars and its impactors (e.g., Day et al., 2016). This is because most planetary surfaces are significantly depleted in siderophile elements compared to many meteorites, especially chondrites and iron meteorites, which are also characterized by unique chemical and isotopic fingerprints (e.g., Puchtel et al., 2008; Fischer-Gödde and Becker, 2012; Goderis et al., 2012; Sharp et al., 2014; Liu et al., 2015).

In this study, multiple subsamples from three different fragments of the martian breccia NWA 7034 were measured for Os isotope ratios and for the abundances of highly siderophile elements Re, Os, Ir, Ru, Pt, and Pd. Previous analyses of HSEs in NWA 7533/7475 have not reported Os isotopic compositions or Pd abundances (e.g., Humayun et al., 2013; Wittmann et al., 2015), both essential in characterizing impactor compositions and tracing HSE fractionation. Thus, in this study, the kind of spatial resolution obtained by LA-ICP-MS (Humayun et al., 2013) was sacrificed in exchange for better precision, and Os isotope and Pd abundance determinations.

2. SAMPLES AND ANALYTICAL METHODS

Three fragments of NWA 7034, labeled fragment 1, 2, and 3 with weights of 0.63, 0.60, and 0.48 g, respectively (Table 1), were provided by the Institute of Meteoritics in Albuquerque (Agee et al., 2013). The small sizes of the clasts and the well-indurated texture of the breccia made it difficult to separate individual clasts. Accordingly, to recognize inter-sample variability, while obtaining a meaningful average composition for the bulk breccia, siderophile element abundances were determined on subsamples prepared by crushing the main fragments. All sawn surfaces of the original three fragments were polished with carborundum before subsampling. Using reflected-light microscopy, 16 subsamples between 5 and 77 mg (labeled 1-1 to 1-9, 2-1 to 2-7, and 3-1 to 3-5 for fragment 1 to 3 subsamples, respectively; Table 1) were prepared from the three fragments of NWA 7034 with the prospect of sampling variable proportions of these breccia components (Supplementary Fig. S1). The selected subsamples were manually ground with a dedicated ceramic alumina mortar and pestle. Between samples, the mortar and pestle were cleaned by grinding quartz sand in ethanol to a fine powder, subsequently boiled in dilute nitric acid, and repeatedly rinsed with Milli-Q™ ultra-pure water. Sample digestion followed