Melting of the Chhota Shigri Glacier, Western Himalaya, Insensitive to Anthropogenic Emission Residues: Insights from Geochemical Evidence

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Abstract

Himalaya glaciers are invariably covered by supra-glacial debris. Of the glaciers, the Chhota Shigri Glacier (CSG) in the western Himalaya is basically debris-free yet has the highest melt rate compared to other central and eastern Himalayan glaciers. Here, utilizing osmium isotopic composition and major and trace element geochemistry of cryoconite — a dark-colored aggregate of mineral and organic materials —and glacial surface materials on the ablation zone of the CSG, we show that the surface of CSG is essentially free of anthropogenically emitted particles, contrary to many previous findings. Given this and the lack of debris, we conclude that the high melting rate in CSG is primarily related to the increase of the Earth's near-surface temperature in direct response to global warming. Thus, monitoring the ice mass loss is further critical given the water source to millions of people.

Melting of the Chhota Shigri Glacier, Western Himalaya, Insensitive to 1 Anthropogenic Emission Residues: Insights from Geochemical Evidence 2 S. Nizam¹, I. S. Sen¹, T. Shukla¹ and D. Selby^{2, 3} 3 4 ¹Department of Earth Sciences, Indian Institute of Technology Kanpur, Kanpur, UP 208016, 5 India. 6 ²Department of Earth Sciences, University of Durham, Durham DH1 3LE, UK. 7 ³State Key Laboratory of Geological Processes and Mineral Resources, School of Earth. 8 Corresponding author: S. Nizam (sarwa@iitk.ac.in) 9 **Key Points:** This study presents first osmium isotopic composition on glacier surface impurities from 10 • the Himalaya 11 12 Osmium isotopes and trace metal composition showed predominantly crustal sourced input • Anthropogenic emission residues are not one of the significant drivers of glacier melting 13 • 14 in the western Himalaya, as observed elsewhere.

15 Abstract

Himalaya glaciers are invariably covered by supra-glacial debris. Of the glaciers the Chhota Shigri 16 17 Glacier (CSG) in the western Himalaya is basically debris free yet has the highest melt rate 18 compared to other central and eastern Himalayan glaciers. Here, utilizing osmium isotopic 19 composition and major and trace element geochemistry of cryoconite — a dark colored aggregate 20 of mineral and organic materials —and glacial surface materials on the ablation zone of the CSG, 21 we show that the surface of CSG is essentially free of anthropogenically emitted particles, contrary 22 to many previous findings. Given this and the lack of debris, we conclude that the high melting 23 rate in CSG is primarily related to the increase of the Earth's near-surface temperature in direct 24 response to global warming. Thus, monitoring the ice mass loss is further critical given the water 25 source to millions of people.

26 Plain Language Summary

Industry derived particles are common to Himalayan glaciers being proposed as a major driver to glacier melting. Yet, the abundance of such material is highly variable across the Himalayan. The CSG is a glacier with minimal ice cover yet has a very high ice volume loss. We show that the elevated glacial mass wastage in western Himalaya is insensitive to anthropogenically sourced pollutants but primarily climate controlled.

32 **1 Introduction**

33 Air pollutants of the southern slopes of the Himalayas has reached high-altitude sparsely 34 populated regions such as Khumbu (5079 m a.s.l.) in Nepal (Bonasoni et al., 2010) and Hanle 35 (4520 m a.s.l.) in India (Babu et al., 2011). The pollutants emitted from different anthropogenic 36 sectors in the Indo-Gangetic Plains (Saikawa et al., 2019) are transported to the high-altitude 37 Himalaya by the southwest Indian Summer Monsoon (Cristofanelli et al., 2014; Singh et al., 2020). 38 The presence of anthropogenic emission residues on the Himalayan glaciers has been linked to 39 enhance glacier melting. As a consequence, the ambient air and its suspended particulate matter in 40 high-altitude Himalayan sites have been intensely monitored over last few decades for greenhouse 41 gases and aerosols (Ran et al., 2014; Rupakheti et al., 2017; Shrestha et al., 2010; Stockwell et al., 42 2016).

Among the particulate impurities, various types of carbon such as organic carbon: (OC),
black carbon: (BC), trace metal and biogenic pollutants are the major focus of current research

(Beaudon et al., 2017; Gabrielli et al., 2020; Hong et al., 2009; Kaspari et al., 2011; Nizam et al.,
2020; Yan et al., 2019). Studies have shown that the Himalayan ice record exhibits a factor of three
increase in BC between 1975-2000 (Kaspari et al., 2011). Similarly, increased anthropogenic metal
pollution in glaciers has also been reported in several parts of the central Himalaya and Tibetan
Plateau (Beaudon et al., 2017; Gabrielli et al., 2020; Hong et al., 2009; Q. Zhang et al., 2009).
Despite the rise in BC concentrations and anthropogenic metal pollution, the concentration of
inorganic impurities in the Western Himalayan glaciers remains poorly known.

52 Existing data in the Western Himalayan region mainly focuses on the source of pollutants (CO_x, NO_x, SO₂, BC, and PM₂, that are mostly derived from receptor and chemical transport 53 54 modeling, and emission inventories (Alvarado et al., 2018; Bonasoni et al., 2010; Rupakheti et al., 55 2018; Yarragunta et al., 2020). Although these models provide invaluable insights to the influence 56 of anthropogenic emissions on the western Himalayan cryosphere, the results exhibit disagreement 57 due to the large uncertainties in emission inventories and meteorological parameters. Therefore, 58 given that the Himalayas is neighbored by some of the world's largest emitters of anthropogenic 59 particles, understanding the concentrations, origin, and pathways of other anthropogenically 60 emitted particles, such as metals, is required to ultimately understand the driving mechanism(s) 61 enhancing ice mass wastage and its impact on the downstream population. Understanding the 62 emission source of metals that also emits CO_x, NO_x, SO₂, BC, and PM_{2.5}, will permit the independent evaluation of emission sources and support estimates studies based on transport and 63 64 receptor models (Jeong et al., 2016; Yang et al., 2020).

65 Thus, to establish the contribution of emission sources to the western Himalayan glaciers, we utilize major and trace element geochemistry together with osmium (Os)- primarily emitted 66 67 from automobile exhaust catalysts (Poirier & Gariépy, 2005)-isotope systematics of glacial surface impurities. The Os-isotope composition (¹⁸⁷Os/¹⁸⁸Os) of natural and anthropogenic 68 69 materials only records the time-integrated fractionation of the Re/Os ratio in the sources. Due to the extremely long half-life of ¹⁸⁷Re (ca. 42 billion years), the present-day ¹⁸⁷Os/¹⁸⁸Os composition 70 of natural and anthropogenic materials practically remains constant throughout the process of 71 72 particle generation, transportation, and deposition. As a result, the Re-Os isotopic system is an 73 emerging tool widely used in tracing anthropogenic sources in precipitation, snow, and ice in 74 remote regions (Chen et al., 2009; Rauch et al., 2005; Rodushkin et al., 2007; Sen et al., 2013), as

well as marine systems (Ownsworth et al., 2019; Sproson et al., 2020). As such, the objective of the study is to apply major and trace element geochemistry, coupled with ¹⁸⁷Os/¹⁸⁸Os compositions of cryoconite and moraine samples to constrain the metal composition across the ablation zone of the Chhota Shigri Glacier (CSG) in the western Himalaya. The latter is used to evaluate and discuss the sources of the metal impurities on the ablation zone of CSG in relation to the reported values for the Himalayan glaciers and ultimately the relationships to the driving mechanisms of glacier mass wasting.

82 2 Materials and Methods

83 2.1 Sample Collection

84 Twenty samples of supraglacial cryoconite were collected from cryoconite holes across the 85 entire ablation zone of the CSG between 4500 to 4930 m a.s.l. (details in Text S1-S2 and Figure S1). The light grey to dark black colored sediments was collected into Corning[®] 50 mL centrifuge 86 87 tube using pre-cleaned plastic scoops. In addition to the cryoconite samples, seven moraine debris 88 samples of ca. 0.3-0.5 kg (cobbles to clay size) were also collected in polyethylene sterile Whirl-89 Pack® bags. All samples were kept frozen prior to analysis. To permit evaluation of anthropogenic 90 emission particulates in the CSG our sample set also comprises samples of Gondwana and Tertiary 91 coal from two major coalfields of India (Jharia in the state of Jharkhand and Makum in the state 92 of Assam), and diesel engine exhaust particulates obtained from engine-exhaust experiments (Text 93 S3).

94 2.2 Rhenium-Osmium (Re-Os) Analysis

95 Cryoconite and moraine samples were dried, sieved (moraine only) and powdered for 96 geochemical analysis (details in Text S4). Ten cryoconite, two moraine samples (<63 µm fraction), 97 four coal samples, and two engine exhaust particulates samples were selected for Re-Os analysis. 98 The Re-Os concentration and isotopic compositions were determined at the Durham Geochemistry 99 Centre using aqua regia carius-tube digestion isotope-dilution negative ion mass spectrometry 100 analytical protocols (Cumming et al., 2013; Selby et al., 2009). Approximately, 1 g of cryoconite 101 and moraine, 0.2 g of coal, and 0.02 to 0.03 g of exhaust particulate were loaded into a carius tube with a known amount of mixed tracer solution (spike) of ¹⁹⁰Os and ¹⁸⁵Re and 9 ml of aqua regia 102 103 solution. The carius tube was sealed and heated to 240 °C for 48 hours. The Os of the digested 104 samples was isolated and purified using standard solvent extraction (CHCl₃) and micro-distillation

105 (CrO₃-H₂SO₄-HBr). The Re fraction was isolated and purified using NaOH-acetone solvent 106 extraction and anion chromatography. The isolated Re and Os fractions were loaded onto Ni and 107 Pt filament, respectively. The Re and Os isotopic compositions were determined using negative 108 thermal ionization mass spectrometry using a Thermo Fisher TRITON mass spectrometer via static 109 Faraday collection mode for Re and ion-counting using a secondary electron multiplier in the peak-110 hopping mode for Os. Total procedural blanks were 2.1 ± 0.02 and 0.1 ± 0.01 ppt for Re and Os, respectively, with an average ${}^{187}\text{Os}/{}^{188}\text{Os}$ value of 0.25 ± 0.03 (n = 2) for cryoconite and moraine 111 112 analysis, and 2.3 ± 0.2 and 0.1 ± 0.02 ppt for Re and Os, respectively, with an average 187Os/188Os 113 value of 0.20 ± 0.06 (n = 4) for coal and exhaust particulate analysis. In-house standard solution measurements yielded 185 Re/ 187 Re value of 0.59786± 0.00014 (1 SD, n = 7) for the Re solution 114 115 and a 187 Os/ 188 Os value of 0.16085±0.00017 (1 SD, n = 6) for the Durham Romil Osmium Solution 116 (DROsS), which are in agreement with those reported in the previous studies (Percival et al., 2019). The average value plus uncertainty of the Re standard solution together with the natural ¹⁸⁵Re/¹⁸⁷Re 117 118 value of 0.5974 (Gramlich et al., 1973) is used for the Re sample mass fractionation correction. 119 Data reduction includes the instrumental mass fractionation, isobaric oxygen interference, and 120 contribution of blanks and the tracer solution. The final two-sigma uncertainties of the Re-Os data 121 include the fully propagated uncertainties of sample-spike weighing, tracer calibration, blank 122 abundances, and isotope compositions, and the intermediate precision of the repeated 123 measurements on the Re and Os reference solutions.

124 **3 Results**

125 **3.1 Trace Element Systematics**

126 Trace element concentrations of the cryoconite, bulk, and fine moraine normalized to the 127 local rock composition is shown in Figure S2. The fine moraine fractions and cryoconite exhibit similar patterns but possess higher trace element concentrations in comparison to the bulk moraine 128 129 fractions that resemble local rock compositions. The higher trace element concentrations in the 130 fine moraine compared to bulk fraction are consistent with additional contamination/mixing or 131 grain size/mineral sorting related enrichment as heavy metals (except Pb) including Sc, Ga, Sr, 132 Nb, and Ta negatively correlate with SiO₂ (Pearson correlation coefficients R \geq -0.70 to -0.94, p 133 =0.001-0.05; Figure S3a and S4) (Cai et al., 2015; Thorpe et al., 2019). Additionally, an overall 134 negative correlation is exhibited between other elements (except Li, Be, Rb, Cs, Ta and Ba) against

SiO₂. A similar relationship is exhibited between trace metals and SiO₂ in cryoconite samples
(Figure S3b). In comparison to the fine moraine fraction, the cryoconite samples exhibit higher
concentrations of V, Cr, Co, Ni, and Cd in more than 50% of the samples. Chondrite normalized
REE concentrations show LREE enrichment and a negative Eu anomaly for cryoconites and all
moraine fractions (Figure S5).

140 The relationship of the cryoconite trace element ratios to the local rock composition 141 suggests that the cryoconite composition has a local crustal provenance. For example, Cd/Zn 142 (0.001-0.007) and Pb/Cu (0.84-1.98) ratios are similar to that of the local rock signature (Cd/Zn = 143 0.001-0.014 and Pb/Cu = 0.45-5.87). Further, REE ratios including, La/Ce, La/Sm, La/Yb and 144 La/Lu ratios of cryoconite that vary between 0.44-0.51, 30-57, 15-26, and 106-194, respectively, 145 are similar to local rock values (0.37-0.48, 33-91, 15-41 and 113-317, respectively). Noteworthy, 146 the La/Ce, La/Sm, La/Yb and La/Lu ratios of cryoconite and moraine are much lower than 147 anthropogenic emission sources (La/Ce = 1.3-1.8, La/Sm = 19-28, La/Yb = 135-950, La/Lu = 148 5400-1000) (Kitto et al., 1992; Olmez & Gordon, 1985). As are the Co/Cs ratios in the cryoconite 149 samples (0.25 and 2.85, average = 1.12 ± 0.78 , versus >2.5 for anthropogenic emissions (Geagea 150 et al., 2007). Further, with the exception of Cr, Ni, and Cd, the enrichment factors (EF) values of 151 \leq 1 support a predominant crustal provenance for the cryoconite (Figure S6). The EF values for Cr 152 (2.2), Ni (2.7) and Cd (2.6) in cryoconite show a detectable non-crustal input.

153 **3.2 Re-Os Systematics**

154 Rhenium and Os concentrations of the cryoconite, moraine, coal, and vehicular exhaust 155 samples are reported in Table 1. In Figure 1a, the Re (ppb) and Os (ppt) concentrations together 156 with TOC (%) are shown for cryoconite and the fine moraine fraction. Overall, cryoconite sampled 157 between 4700-4930 m a.s.l. possess higher average TOC (~1.7 %), Re (0.24-0.47 ppb), and Os 158 (37-104 ppt) in comparison to cryoconite sampled between 4500-4700 m a.s.l. (average TOC = 159 0.8 %; Re = 0.16-0.21 ppb; Os = 11-32 ppt). The elevated TOC, Re and Os concentrations in 160 cryoconite above 4700 m a.s.l. also correspond to higher concentration of heavy metals (Figure 161 1b). For example, trace metals such as Cr, V, Co, Cu, and Zn follow the trends shown by Re and 162 Os suggesting that these elements are probably controlled by common mineral/sources (Chen et 163 al., 2016). The absolute abundances of Re and Os show a moderate positive correlation (R = 0.58, 164 p = 0.1) (Figure S3b and S7), with a similar correlation exhibited with TOC (R= 0.71 and 0.53,

respectively). The cryoconite ¹⁸⁷Os/¹⁸⁸Os composition fall between 0.38 and 1.31, with cryoconite 165 between 4700-4930 m a.s.l. possessing 187 Os/ 188 Os values between 0.38 and 0.83. Below 4700 m 166 a.s.l. the cryoconite samples possess more radiogenic ¹⁸⁷Os/¹⁸⁸Os values. The ¹⁸⁷Os/¹⁸⁸Os ratios 167 show a significant negative correlation with Os concentrations (R= -0.94, p = 0.001; Figure S3b 168 169 and S7). Further, the 187 Os/ 188 Os ratios correlate positively with major oxides such as SiO₂, Na₂O, 170 and K₂O (R = 0.71-0.89, p = 0.001-0.05). In contrast, heavy REE (HREE: Er to Lu), MgO, Fe₂O₃, MnO, and TiO₂ exhibit a significant negative correlation with 187 Os/ 188 Os ratios (R= -0.81 to -0.93, 171 172 *p* =0.001-0.01; Figure S7 and S8).

173 The Re and Os concentrations of two moraine samples from ~4750 and 4550 m a.s.l are 174 0.14 and 0.21 ppb and 13 and 30 ppt, being similar to the average upper continental crust (UCC) 175 composition (Re = ~ 0.20 ppb; Os = ~ 31 ppt) (Esser & Turekian, 1993; Peucker-Ehrenbrink & 176 Jahn, 2001). The Re and Os concentrations in Gondwana coal range between 0.26 and 0.76 ppb 177 and 7 and 18 ppt, respectively. For the Tertiary coal samples, the Re and Os concentrations range 178 between 0.47 and 0.53 ppb and 63 and 726 ppt, respectively. Unlike cryoconite, the Gondwana 179 and Tertiary coal show limited variability and are characterized by radiogenic ($^{187}Os/^{188}Os = 1.61$ -1.64) and unradiogenic osmium isotope compositions ($^{187}Os/^{188}Os = 0.14$ and 0.21), respectively. 180 181 The analysis of two engine exhausts yielded Re and Os concentrations of 0.07 and 1.04 ppb and 2 182 and 6 ppt, respectively. The engine exhaust samples are characterized by an unradiogenic osmium 183 isotope composition ($^{187}Os/^{188}Os = 0.21-0.22$), similar to catalytic converters (Poirier & Gariépy, 184 2005).

185 4 Discussion

186 **4.1 Cryoconite Provenance**

187 Glaciers are sites of active physical erosion, with their continuous movement effectively 188 powdering rock units in the glacial catchment that can be further eroded by wind action and 189 deflation (Brown et al., 1996; Sharp et al., 1995; Tranter et al., 2002). This local freshly weathered 190 rock that is subjected to deflation will overwhelm any long-range dust transport signal by covering 191 the neighboring glacier. This is illustrated by both the major (Figure S9) and trace element 192 systematics (Figure S2) of the CSG cryoconite, which are derived from weakly weathered rocks 193 of the glacial catchment. Most of the cryoconite (14 samples,) exhibit Co, Cr, Ni and Sc enrichment 194 that indicate a detectable non-crustal component. In contrast, cryoconite from Arctic, European,

195 Canadian and other South Asian glaciers exhibit several orders of magnitude higher heavy metal 196 enrichment compared to its local rock and moraine and were consistent with high activity 197 concentrations of anthropogenic radionuclides. (Baccolo et al., 2017; Beaudon et al., 2017; Łokas 198 et al., 2016; Owens et al., 2019; Singh et al., 2013). This suggests that the CSG seems relatively 199 pristine compared to other glaciers where significant anthropogenic pollution signal has been 200 recorded due to long range transport of the anthropogenic emission residues. Moreover, samples 201 showing detectable metal enrichment in the CSG ablation occur mainly in the upper reaches 202 (except first sample) of the glacier ablation zone i.e. above 4700 m a.s.l. These samples further 203 show minor deviation from the local moraine composition towards a more mafic rock composition 204 (Figure S10 and S11). Although heavy metals enrichment can also be attributed to anthropogenic 205 contributions, but correlation with TOC suggest that the enrichment seems most plausibly 206 attributed to sources of TOC (microorganisms) owing to its inherent characteristics to accumulate 207 fine particulates (Łokas et al., 2016). Furthermore, given that air-mass back trajectory modeling 208 clearly shows that 50% of the air mass that reaches the glaciers originates from the west, within 209 ~250 km of the study site, and possesses limited inputs from the Indo-Gangetic Basin (Nizam et 210 al., 2020), only minor input from anthropogenic sources can be considered. Lastly, the chondrite 211 normalized REE signature of moraine, local country rocks from the Himalaya, river sediments 212 from glacial catchments, cryoconite, snow and ice core dust (Figure S12) show similar REE 213 patterns, all exhibiting REE enrichment, similar to granitic or shale (PAAS)-like sources, which 214 are commonly observed in the Higher and the Lesser Himalayan rocks and sediment. The 215 anthropogenic dust mostly exhibits fractionated (enriched) LREE patterns with smooth HREE 216 enrichment, and often contains a strong positive Gd anomaly (Geagea et al., 2007; Hatje et al., 2016). The cryoconite show a large range in ¹⁸⁷Os/¹⁸⁸Os compositions that overlap with both 217 natural and anthropogenic sources that do not exhibit singular ¹⁸⁷Os/¹⁸⁸Os signatures (Figure 2). 218

The cryoconite unradiogenic ¹⁸⁷Os/¹⁸⁸Os signature can be explained by both contributions from natural Os sources such as cosmic dust, volcanic aerosols, mafic and ultramafic rocks, as well as anthropogenic Os from catalytic converters that are often recycled (¹⁸⁷Os/¹⁸⁸Os = ~0.38) (Poirier & Gariépy, 2005), fossil fuels, smelting of chromite, base-metal sulfide, and PGE ores and municipal solid waste incinerators (MSWIs). Contributions from volcanic aerosols and cosmic dust seem unlikely due to the absence of active volcanism in and around the Himalaya (Fitch, 1970), and the extremely low (40,000± 20,000 t yr⁻¹; t=10⁶ g) global cosmic dust flux (Love &

Brownlee, 1993) that can significantly affect the ¹⁸⁷Os/¹⁸⁸Os of sediments in the highly active 226 227 glacial ablation zones. Contribution from mafic rocks is plausible as ultramafic dykes, sills, and 228 pegmatitic veins (early Proterozoic-late Paleozoic age) are common in HHCS and locally in the 229 glacial catchment (Thakur & Patel, 2012; Thöni et al., 2012). Given that the unradiogenic ¹⁸⁷Os/¹⁸⁸Os signature in the cryoconite correlates with high Fe₂O₃-MgO and low SiO₂ 230 231 concentrations (Figure S8), a mafic/ultramafic source rock input is likely as supported by the 232 cryoconite trace element geochemistry. Therefore, from trace element systematics, Re and Os concentrations, and ¹⁸⁷Os/¹⁸⁸Os compositions it can be concluded that the glacial debris contains 233 234 felsic and mafic/ultramafic rock components, with essentially no input from anthropogenic 235 sources.

4.2 Further Evaluation of Natural and Anthropogenic Sourced Osmium

237 The relative contributions from various source end-members are quantified using a threecomponent mixing model using ¹⁸⁷Os/¹⁸⁸Os and Os concentration as tracers. The first end-member 238 239 represents local rocks, which is very similar in composition to the Higher Himalayan Crystalline 240 Sequence (Pierson-Wickmann et al., 2000) and eroding UCC (Peucker-Ehrenbrink & Jahn, 2001). For which, we assign an Os abundance of 30.4 ppt and 187 Os/ 188 Os value of ~1.48 (Table 1). For 241 242 the second end-member, mafic-ultramafic rocks are selected having an Os concentration of 850 ppt and an ¹⁸⁷Os/¹⁸⁸Os value of ~0.12 (Table 4; Data from (Meisel et al., 2001), Sample Number: 243 244 KH80-100, peridotite xenoliths). To explain the data distribution (Figure 3a), the third endmember should contain low Os concentration and an intermediate ¹⁸⁷Os/¹⁸⁸Os composition. This 245 246 end-member could represent an Os-poor mineral such as aeolian quartz or granitoid and/or 247 gneisses (Peucker-Ehrenbrink & Blum, 1998) and therefore we assign an Os concentration of 1 ppt and a 187 Os / 188 Os value of ~0.90. It is noteworthy that the 187 Os/ 188 Os composition could be 248 249 more radiogenic and Os concentrations can be significantly lower (Peucker-Ehrenbrink & Blum, 250 1998). Keeping in mind that the three end-members of our mixing model should enclose all data 251 points (Figure 3a), we performed our mixing model with the defined end-members as outlined above. Our mixing calculations suggest that the cryoconite ¹⁸⁷Os/¹⁸⁸Os signature is derived from 252 253 local rocks ($67.4 \pm 18.6\%$), with fractional contributions from an Os-poor mineral phase ($29.6 \pm$ 254 19.9%), and limited input from the mafic-ultramafic rocks ($3.0\pm 2.8\%$, Table S4, Figure 3b). In

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general, the upper elevation of the glacier showed a greater Os contribution from maficrock/mineral phase, which is consistent with the trace element systematics (Figure 1b).

257 We acknowledge that the choice of end-member compositions will change the end-member 258 contributions, but we emphasize that the conclusion of the study will not change. Further, we did 259 not include any anthropogenic sources because enrichment factors, trace and major elements, 260 supports a predominant crustal provenance for the cryoconite. Moreover, this is supported by the 261 fact that the glacier ablation zone is free of fossil fuel derived carbon (Nizam et al., 2020) and 262 therefore we did not include coal and engine exhaust as suitable end-members. We additionally 263 emphasize that the metal enrichment in the cryoconites can also be modified (enriched) by 264 microbial processes. Given the elevated TOC concentration observed in upper ablation zone of the 265 CSG a higher level of microbial activity is implied (Anesio et al., 2009). The δ^{13} C enrichment (-266 18.19‰) in cryoconite samples and its relationship with N enrichment and or depletion supports 267 contributions from photo-autotrophic and heterotrophic micro-organisms that may have also 268 modified predominantly heavy metal (Cr, V, Ni, and Co) signature (Nizam et al., 2020).

4.3 Implications of Absence of Anthropogenic Emission Residues in the Western Himalayan Glacier

271 The Himalayan glaciers receive a large supply of metals in the form of mineral dust from 272 wind-blown rock dust from the erosion of the UCC and mafic rocks, with inputs from 273 anthropogenic sources (Casey, 2012; Cristofanelli et al., 2014; Wake et al., 1993). The knowledge 274 of the amount, composition, and source of dust and anthropogenic emission is essential to calculate 275 the heat-absorbing capacity of the residue, and in turn, ice melting rates. For example, 1 ppb of 276 BC residue on the glacier has the same effect on albedo as that of 75 ppb dust (Jacobi et al., 2015). 277 In this study, we show that CSG has negligible metal impurity residues from anthropogenic 278 sources. Further, carbon characterization (Ramped Pyrolysis Oxidation, RPO, δ^{13} C, and 14 C 279 chronology) of total organic carbon (OC) in both cryoconite and the <63 µm fraction of moraine 280 from the same glacier reveals that the cryoconite have negligible contributions from fossil fuel emission sources (Nizam et al., 2020). The RPO, δ^{13} C, and 14 C data reveal that 98.3± 1.6% of the 281 282 OC is sourced from local biomass sources, atmospheric organic matter, and glacial microbes, with 283 only $1.7 \pm 1.6\%$ of the OC being sourced from petrogenetic sources. Further, previously we have 284 shown that the 50% of the air mass (annual basis) originates far (>1000 km) from west of the

receptor (CSG) site (Nizam et al., 2020). Therefore, based on the Os isotopic systematics and previous findings we conclude that the CSG is essentially free of anthropogenic residues and receives limited long-range dust inputs.

288 It is well established that glaciers in the CSG basin are losing mass at an average rate of 289 0.50 meter water-equivalent per year (m w.e. yr^{-1}) over the last two decades (Azam et al., 2019), which is higher than the central $(0.35 \text{ m w.e. yr}^{-1})$ and eastern Himalavan $(0.43 \text{ m w.e. yr}^{-1})$ glaciers 290 291 having higher debris covered glaciers (18-24%) and substantial contribution of anthropogenic 292 sourced pollutants from the Indian subcontinent (Babu et al., 2011; Brun et al., 2017; Li et al., 293 2016). The high glacial mass wastage rate observed in western Himalaya is likely due to elevated 294 mean annual tropospheric warming trend (0.016 \pm 0.005 ° K/year) during ablation season, which 295 is higher than Central and Eastern Himalayan region (Prasad et al., 2009). Consequently, warming 296 induced melting of snow (which is 80% of total precipitation) constitute the largest faction (15-297 66%) of the annual hydrological budget in the western Himalaya (Azam et al., 2019; Bookhagen 298 & Burbank, 2010). In contrast, central and western Himalayan glaciers are Indian Summer 299 Monsoon fed (contribute ~80% of the annual hydrological budget) and receives significant fraction of anthropogenic (50% of total anthropogenic carbon) pollutants from the heavily polluted Indo-300 301 Gangetic Plains (Li et al., 2016) that can pose an additional melting stress of 340 kg m⁻² yr⁻¹ (Ginot 302 et al., 2014).

303 The near absence of anthropogenic particles on the nearly debris free CSG therefore reveals 304 that heat-absorbing anthropogenic particles deposited on the surface of the CSG are not one of the 305 primary drivers behind CSG melting, as observed in other parts of the world such as the Greenland, 306 Alaska, and Tibet (Dumont et al., 2014; Nagorski et al., 2019; Xu et al., 2009). Despite an increase 307 in anthropogenic emissions in the Indian subcontinent over the last 50 years (Crippa et al., 2018), 308 we conclude that anthropogenic emission residues on the surface of CSG will not significantly 309 enhance the glacier mass wastage rates in CSG in the near future. The rapid retreat of CSG can be 310 best explained by elevated temperature trends and morphological characteristic of the catchment 311 (Gantayat et al., 2017). It is noteworthy that numerical modeling of CSG reveals that the glacier 312 will cease to exist by AD 2109 with a temperature rise of 5.5 K. (Gantayat et al., 2017).

313 **5 Conclusions**

314 The concentration, origin, and pathways of metals over the CSG was investigated for the 315 first time using major and trace elements, and Re-Os isotope systematics of supraglacial debris 316 namely from cryoconite and moraine samples. Our study highlights two important points regarding 317 the presence of metal impurities on the CSG glacier surface. Firstly, although the Himalaya is 318 surrounded by some of the world's largest emitter of anthropogenic particles, we find limited 319 anthropogenic metal impurities over the CSG likely due to the source region of the air mass 320 reaching the CSG. Mixing model calculations show that Os in the CSG is exclusively sourced 321 from crustal rocks. Secondly, integration of geochemical and air-mass back trajectory modeling 322 data reveal that the sediment/dust is mostly of local origin. We conclude that the enhanced CSG 323 melting rate is insensitive to organic and inorganic anthropogenic emission deposits on the surface 324 of the CSG glacier, and predominately controlled by climate warming.

325 **Data availability**

- Full data and supporting information are available as supplementary material. We assure that the
- 327 supplementary will be made available in suitable data repository archive upon acceptance of the328 manuscript.

329 Author contributions

I.S.S. conceived the study. S.N. performed laboratory measurements. S.N., I.S.S., T.S. and D.S.
analysed the data. S.N. and I.S.S. wrote the paper with input from all authors. I.S.S. handled
funding acquisition.

333 Competing interests

334 The authors declare that they have no competing interests.

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346 Supplementary Materials:

- 347 Text S1-S5
- 348 Figure S1-S12 and their captions.
- 349 Table S1-S4 and their captions.

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Figure 1. (a) Rhenium-Osmium concentration, ¹⁸⁷Os/¹⁸⁸Os ratios and Total Organic Carbon (TOC)
in cryoconite (open symbols) and fine moraine fraction (<63µm, filled symbols) (b) Trace metal
concentration in cryoconite and TOC (scale is identical to a) along the ablation zone of the CSG.
TOC data are from (Nizam et al., 2020)



Figure 2. Comparison of osmium isotopic ratio of cryoconite and moraine with different potential sources. The dashed vertical line marks the limit of the measured unradiogenic Os that can be directly contributed by vehicular emission in the atmosphere. Moraine Os isotopic ratios lie within the crustal range of both eroding i.e. global river (Levasseur et al., 1999) and non-eroding crust: Higher Himalayan Crystalline Sequence (Pierson-Wickmann et al., 2000), black shale (van Acken et al., 2019; Ackerman et al., 2019; Selby & Creaser, 2003; S. K. Singh et al., 1999). Cryoconite, in contrast, exhibits a range in ¹⁸⁷Os/¹⁸⁸Os ratios that encompass a crustal signature to an

- unradiogenic signature similar to that of recycled catalytic converters (Poirier & Gariépy, 2005),
- volcanic aerosol (Krähenbühl et al., 1992; Yudovskaya et al., 2008) and municipal waste (Funari
- 740 et al., 2016). Data reference: cosmic dust (Schmitz et al., 1997; Walker et al., 2002),
- 741 mafic/ultramafic rock (Hanski et al., 2001; Meisel et al., 2001), Taklimakan desert and Kunlun
- 742 moraine (Hattori et al., 2003), catalytic convertor (Poirier and Gariépy, 2005), liquid fossil fuel
- 743 (Corrick et al., 2019; Cumming et al., 2014; Lillis & Selby, 2013; Selby et al., 2007), chromite ore
- 744 (Mondal et al., 2007), PGE ore (Coggon et al., 2012), and municipal waste (Funari et al., 2016).



Figure 3. (a) Three-component mixing modeling plot for Os concentration and ¹⁸⁷Os/¹⁸⁸Os for cryoconite and the proposed three end-members: LM (Local Moraine), LR (Less Radiogenic Os poor mineral phase: aeolian quartz/granite/orthogneiss), and UR (Ultramafic Rocks). (b) Source percent contribution of the Os within the collected cryoconite relative to elevation along the ablation zone of the CSG. See text for discussion.

752 **Table 1.** Re-Os isotopes composition and Re-Os abundance analyzed in selected cryoconite (C), moraine

753 (DF:<63 µm), diesel engine exhaust (DEE) and Indian coal (GC: Gondwana coal, TC: Tertiary coal)

samples.

Sample	Total Re (2s)	Total Os (2s)	¹⁹² Os (2s)	¹⁸⁷ Re/ ¹⁸⁸ Os	¹⁸⁷ Os/ ¹⁸⁸ Os	rho	%Re	% ¹⁸⁷ Os	% ¹⁸⁸ Os
	(ng g ⁻¹)	(pg g ⁻¹)	(pg g ⁻¹)	2s	2s		Blank	Blank	Blank
C1	0.206± 0.002	32.3 ± 0.2	12.1 ± 0.1	33.8 ± 0.4	$0.911{\pm}0.008$	0.402	1.16	0.09	0.33
C3	0.163± 0.002	10.9 ± 0.1	3.9 ± 0.1	83±1.4	$1.278{\pm}0.170$	0.599	1.47	0.2	1.03
C5	0.211 ± 0.002	14.2 ± 0.1	5.1 ± 0.1	82.4± 1.1	$1.310{\pm}0.015$	0.596	1.13	0.15	0.79
C9	0.235 ± 0.002	$37{\pm}0.2$	14.1 ± 0.1	33.3 ± 0.4	$0.790{\pm}0.007$	0.414	1.02	0.09	0.29
C11	0.252 ± 0.002	77.3 ± 0.3	30.5 ± 0.2	16.4 ± 0.2	$0.479{\pm}0.004$	0.386	0.95	0.07	0.13
C13	0.463 ± 0.002	$63.6{\pm}0.3$	24.2 ± 0.1	$38.1{\pm}0.3$	$0.777 {\pm} 0.006$	0.522	0.52	0.05	0.17
C14	0.416± 0.002	$39.4{\pm}0.2$	14.9 ± 0.1	55.5 ± 0.5	$0.829{\pm}0.007$	0.543	0.58	0.08	0.27
C17	0.35 ± 0.002	$41.1{\pm}0.2$	15.6 ± 0.1	$44.7{\pm}0.4$	$0.803{\pm}0.006$	0.504	0.69	0.08	0.26
C18	0.403 ± 0.002	104 ± 0.4	$41.5{\pm}0.2$	19.3 ± 0.2	$0.378{\pm}0.003$	0.483	0.6	0.06	0.1
C19	0.465 ± 0.002	55 ± 0.2	$21.1{\pm}0.1$	43.9 ± 0.3	$0.702{\pm}0.006$	0.531	0.51	0.07	0.19
DF6	0.208± 0.002	30.4 ± 0.2	11.1 ± 0.1	37.4 ± 0.5	$1.118{\pm}0.010$	0.408	1.15	0.08	0.36
DF12	0.141± 0.002	12.5 ± 0.1	4.4 ± 0.1	63.9±1.2	$1.478{\pm}0.018$	0.518	1.7	0.15	0.91
GC1	0.261± 0.002	6.9 ± 0.1	2.4 ± 0.1	$217{\pm}8.2$	$1.644{\pm}0.069$	0.856	4.39	0.83	6.38
GC2	0.757± 0.003	17.9 ± 0.1	6.2 ± 0.1	243 ± 4.2	$1.606{\pm}0.032$	0.801	1.52	0.33	2.56
TC1	0.527 ± 0.003	726 ± 2.8	$299{\pm}2.6$	3.5 ± 0.04	$0.144{\pm}0.002$	0.609	2.18	0.08	0.05
TC2	0.468± 0.002	$63.4{\pm}0.3$	$25.9{\pm}0.3$	35.9 ± 0.4	$0.213{\pm}0.003$	0.562	2.46	0.59	0.63
DEE1	0.073± 0.011	2.1 ± 0.5	0.9 ± 0.5	166 ± 95	$0.218{\pm}0.185$	0.631	48.4	63.23	40.75
DEE2	1.032 ± 0.018	5.7 ± 0.8	2.3 ± 0.8	884± 294	$0.205{\pm}0.126$	0.541	10.48	64.54	39.86

755 Note: Total procedural blanks were 2.1 ppt for Re and 0.1 ppt for Os, with a¹⁸⁷Os/¹⁸⁸Os ratio of 0.25.

AGU PUBLICATIONS

1	
2	Geophysical Research Letters
3	Supporting Information for
4 5	Melting of the Chhota Shigri Glacier, Western Himalaya, Insensitive to Anthropogenic Emission Residues: Insights from Geochemical Evidence
6	S. Nizam ¹ , I. S. Sen ¹ , T. Shukla ¹ and D. Selby ^{2, 3}
7 8 9	¹ Department of Earth Sciences, Indian Institute of Technology Kanpur, Kanpur, UP 208016, India. ² Department of Earth Sciences, University of Durham, Durham DH1 3LE, UK. ³ State Key Laboratory of Geological Processes and Mineral Resources, School of Earth.
10	
11	Contents of this file
12 13 14	Text S1 to S5 Figure S1 to S12 and their captions Table S1 to S5 and their captions

15 Introduction

- 16 This supporting information provides brief notes on study area, engine exhaust sampling
- 17 experiment, supplementary analytical details, and additional figures and tables to
- 18 support results and discussion.

19 Text S1. Study Area

20 The majority of the western Himalayan glaciers have up to 19% of its surface area covered with 21 debris (Brun et al., 2019). In contrast, the CSG has only 3.4% (lowest in the basin) of its surface 22 area covered with debris (Vincent et al., 2013) and is therefore an excellent site to study long-23 distance emission inputs. The CSG (32.28° N, 77.58° E) is located in the Lahaul-Spiti valley, 24 western Himalaya, India at an elevation between 4050 and 6263 m a.s.l. (Figure S1). The total 25 axial length of the glacier is ca. 9 km and covers an area of ca.15.5 km². The equilibrium line of 26 the CSG occurs at an altitude of ca. 4900 m a.s.l. (Wagnon et al., 2007). Presently, CSG has a total 27 ice mass of ~1.57×10¹² kg (after ice density 900 kg/m³ and ice volume 1.74 km⁻³) (Cogley, 2012; 28 Ramsankaran et al., 2018) and has an ice mass wasting rate of 0.50 m w.e.a⁻¹ since the end of the 29 last century (Azam et al., 2019). The meltwater feeds the Chandra River, which ultimately joins 30 the Indus (Sindhu) river and provides water to an excess of 300 million people in the region of the 31 Indus Basin.

32 Text S2. Geology and Meteorology of the Study Area

The CSG is surrounded and underlain by the late Proterozoic to early Cambrian age High Himalayan Crystalline Sequence (HHCS), which comprises highly metamorphosed granitegneiss, schistose gneiss, augen gneiss, muscovite-biotite schist, quartzite, schist and low-grade metamorphic rocks (Kumar and Dobhal, 1997). Specifically, in the CSG catchment the glacial valley walls consist of mildly metamorphosed, intensely deformed fine-grained black slates, phyllites, and schists. The HHCS are often intruded by late Proterozoic to early Paleozoic mafic dykes, sills, and pegmatitic veins (Miller et al., 2001; Thakur & Patel, 2012; Thöni et al., 2012).

40 Meteorological data sets recorded within the glacier catchment divide the year into four seasons. 41 These are, a warm summer monsoon (June to September), a cold winter (December to March), 42 a pre-monsoon (April to May) and post-monsoon (October to November) period (Azam et al., 43 2014). Two principle atmospheric circulation patterns are prevalent over the CSG region; the 44 southwest monsoon, which originates in the Arabian Sea and the Bay of Bengal during the 45 summer from July through to September, and the Western Disturbances that originate in the 46 Mediterranean Sea during winter from January through to April (Bookhagen & Burbank, 2010). 47 The majority of the annual precipitation across the CSG region originates from Western 48 Disturbances (79%), with the remaining 21% being derived from monsoon precipitation (Azam 49 et al., 2019). Noteworthy is that the western disturbance brings heavy snowfall to the CSG region 50 (e.g., average 6.3 mm w.e.d⁻¹ was recorded between Dec 2012–Jan 2013), with only 0.5 mm w.e. 51 d⁻¹ average rainfall being derived from the southwest monsoon, resulting in the region being 52 within the monsoon-arid transition zone (Azam et al., 2014). In addition to the two principle 53 atmosphere circulation patterns, Hybrid Single Particle Lagrangian Integrated Trajectory Model 54 (HYSPLIT) modeling results reveal 50% of the air mass that reaches the glaciers originates from 55 the west, within ~250 km of the study site, while the remaining air masses being more long-range 56 in origin (Nizam et al., 2020)

57 Text S₃. Engine Exhaust Experiment

58 To obtain diesel engine exhaust particulates, engine experiments were performed in a 59 contemporary common rail direct injection (CRDI) diesel engine (Tata; Safari DICOR 3.0 L) 60 coupled with an eddy current dynamometer. The experiments were conducted in the Engine 61 Research Laboratory at the Indian Institute of Technology Kanpur, India by following published 62 protocols (Agarwal et al., 2018). In brief, exhaust particulates were collected on a 47 mm quartz 63 filter paper (PM2.5) that was fitted on the exhaust tail type of the CRDI diesel engine. The 64 operating conditions of the engine were optimized to those types of vehicles driven in India 65 (outlined in (Agarwal et al., 2018). To avoid the possibility of any contamination with previous 66 experiments, the walls of the photochemical chamber were thoroughly cleaned using ethanol 67 and high purity water (18.2 M Ω cm) from a Millipore water purification system, and before 68 sampling, zero air supply (containing less than 0.1 ppm of total hydrocarbon) was used to flush 69 the photochemical chamber thoroughly.

70 Text S₄. Sample Preparation

71 To remove any moisture, all cryoconite and moraine samples were first dried at ~70 °C. 72 Cryoconite sediments size varies from fine granule (\leq_3 mm) to clay-sized fraction ($\leq_0.002$ mm). 73 Several handpicked rock particles (3-60 mm) from each moraine sample were collected to 74 represent the local lithology (hereafter referred to as local rock). Moraine samples were sieved 75 to obtain bulk (<3 mm) and fine (<63 μm) fractions for geochemical analysis. The fine fraction 76 serves as a proxy of any wind-blown material (Pye, 1995; Shao, 2009), whereas, the bulk fraction 77 represents the local rocks as stated above. Bulk cryoconite (20-50 g), moraine (10-15 g fine 78 fraction, 100 g bulk), local rock (100 g), and coal (100 g) samples were grounded to a 79 homogeneous powder (20 µm) in an agate mill for major and trace elemental (details in Text S5) 80 and Re-Os analysis.

81 Text S5. Major and Trace Element Analysis

82 Major elements for the cryoconite, fine, and bulk moraine size fractions were measured 83 with a Wavelength Dispersive X-Ray Fluorescence spectrometer (Rigaku ZSX Primus II) at the 84 Indian Institute of Technology, Kanpur, India. Oxide abundances were determined from sample 85 powders that were fused with lithium tetra borate mixed with lithium bromide (Li₂B₄O₇-LiBO₂-86 LMR) flux (1:10 ratio) in a Pt crucible at 1800 °C for 30 minutes to form fused glass beads. The 87 reference standard SDTSD-4 (stream sediment) from Canadian Certified Reference Material 88 Projects was used as a calibration standard. Loss on ignition (LOI) was determined by heating 1 89 g sample in an oven from 100 to 1000 °C. A combination of NIST SRM 2709a (San Joaquin soil) 90 and NIST SRM-8704 (Buffalo River sediment) from the USGS was used to assess the data quality. 91 The measured values of the reference materials were within the uncertainty of the certified 92 values (Table S2).

93 Trace metal and Rare Earth Element (REE) concentration analyses were performed at 94 the Indian Institute of Technology Kanpur, India on an Agilent Triple Quadrupole Inductively 95 Coupled Plasma Mass Spectrometer (QQQ-ICP-MS). Approximately 100 mg of sample powder was digested in pre-cleaned Teflon beakers at 150± 5 °C using a 2 mL mixture of HF: HNO₃ (4:1) 96 97 for 48 hours. After digestion, the samples were dried and re-dissolved in aqua regia for 24 hours. 98 To remove any organic materials, the cryoconite samples were further digested in 2 mL of ultra-99 clean HNO₃ for 24 hours at 130°C. The digested samples were slowly evaporated to dryness at 100 100 °C, and if required, acid digestion steps were repeated for incomplete digestion. Trace 101 element concentrations were determined from ~350 ppm total dissolved solid solutions. Three 102 procedural blanks, and three Reference Material GS-N (granite), GeoPT28 (shale) and SRM-2704 103 (river sediment) were also digested following the same procedures. All samples and standards 104 were spiked with ~5 ppb Rh internal standard solution to monitor and correct any drift in 105 intensities due to matrix/drift effects. The instrument was run both in He and O₂ gas reaction 106 mode to optimize the separation of measured isotopes from polyatomic interferences. Sample 107 duplicates show reproducibility within 5% for most of the elements (Table S3). The final 108 concentrations are all blank corrected using the average procedural blank concentrations. 109 Average blank corrections were less than 1% for the majority of the elements. The measured 110 trace element concentrations are in agreement with the reference materials (Table S₃ and S₄).



Figure S1. Map showing geographical location and cryoconite and moraine sampling points
along the ablation zone of the CSG. Inset figure shows regional atmospheric circulation patterns
in the glacier valley and desert distribution traced after (Parsons & Abrahams, 2009).



Figure S2. Local rock normalized elemental patterns for supraglacial cryoconite and moraine.
Trace metal and rare earth elements are arranged in increasing atomic number. The upper and
lower end of the bars represent the minimum and maximum values, the open symbol within the
bar is the median value. Dashed straight line passing through unity is average local rock
composition and any deviation from this line reflects additional source input or mineral sorting
and elemental mobility attributed to physical weathering and transportation processes.



Figure S₃. Correlogram showing Pearson correlation between trace metal, SiO₂, Re-Os, and ¹⁸⁷Os/¹⁸⁸Os for (a) moraine (b) cryoconite. Positive correlations are displayed in blue and negative correlations in red color. The color intensity and the size of the circle are proportional to the correlation coefficients.

2	6 10 14		20 60		4 8 14		50 150	1	5 25 3	5	50 70 90) :	10 20 30	0	15 25 35		1 2 3 4 5		0.5 1.5 2.5		5 15	10).1 0.4 0.7
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U U	0.92 ***	0.10	0.087	-0.088	0.16	-0.024	-0.11	0.07	0.40	0.93	-0.20	0.083	0.58	-0.093	0.88 ***	-0.26	0.46	-0.26	C.D41	0.038	0.021	-0.26	-0.19
	Be	-0.10	-0.073	-0.23	-0.053	-0.19	-0.19	-0.027	0.18	0.94	-0.34	-0.084	0.41	-0.24	0.74	-0.22	0.41	-0.27	-0.10	-0.15	-0.22	-0.0097	-0.32
	Ser	So	0.98	0.95	0.89	0.93	0.85	0.92	0.64	-0.12	0.72	0.50	0.76 *	0.92	0.16	0.70	0.41	0.76	0.59	0.49	0.62	-0.88	0.90
	<u></u>	2200	v	0.98	0.93	0.98	0.87	0.92	0.62	-0.14	0.77 **	0.48	0.76	0.95	0.16	0.80	0.43	0.79	0.62	0.48	0.64	-0.86	0.94
	\sim			Cr	0.90	0.98	0.88	0.90	0.57	-0.30	0.82 **	0.49	0.66	0.97	0.038	0.84	0.38	0.84	0.64	0.50	0.67	-0.81	0.98 ^{***} E
	\sim	:7		1	Co	0.95	0.75	0.78	D.78	-0.10	0.85	0.62	0.79	0.92	0.32	0.70	0.48	0.64	0.66	0.64	C.79	-0.94	0.85
1	<u> </u>		aca a a			Ni	0.86	0.88	0.64	-0.27	0.86	0.54	0.70	0.98	0.13	0.82	0.41	0.80	0.68	0.55	0.72	-0.87	0.96
R E							Cu	0.97	0.45	-0.36	0.75	0.44	0.59	0.91	0.0049	0.86	0.45	0.97	0.73	0.42	C.43	-0.70	0.88
						02.00	-	Zn	0.50	-0.17	0.68	0.40	0.69	0.90 ***	0.13	0.82	0.48	0.91	0.66	0.37	0.42	-0.75	0.87
	~			7		8	2	5.	Ga	0.15	0.75	0.90	0.89 ***	0.67	0.60	C.33	0.78 **	0.36	0.71	0.90	0.85	-0.91	0.50
	-		1 min	k.	-	man.			1	Fib	-0.45	-0.17	0.35	-0.35	0.74	-0.42	0.24	-0.47	-0.27	-0.21	-0.21	0.012	-0.40 E
. The	\sim				_			1		- v	Sr	0.50 **	0.62	0.91	0.078	0.76	0.54	0.75	0.79	C.83 **	0.85	-0.83	0.82
° 7.3				1	1	1-	r	7-			1-	Y	0.67	0.63	0.34	0.34	0.72	0.42	0.78	0.99	··· 28.0	-0.77	0.47
	/	all a	-			5		1	1	1		Nº 14	Nb	0.70	0.64	0.46	0.83 **	0.48	0.65	0.65	0.63	-0.89	0.57
	\wedge						and the second	1		See .	1. gr			Gd	0.076	0.85	0.50	0.87	0.76	0.64	0.73	-0.87	0.96
		A		7			-	7	~						Cs	-0.21	0.61	-0.13	0.37	0.33	0.34	-0.43	-0.011
	~	-			-		-			-						Ba	0.35	0.90 ***	0.53	0.33	0.38	-0.66	0.82 ^{**} E
-		·	· see ·	*	~		*	×			e				1000	in.	Та	0.43	0.77	0.69	0.52	-0.64	0.34
							-		· · ·		× /	*						РЬ	0.70	0.40	C.38	-0.60	0.85
				1		-	-	1										-	в	0.77	0.72	-0.72	0.69
			· · · · ·			7	7	7		.1.	1	-	1.1					·		Th	0.80 ***	-0.78	0.48
R I X I				1					···· ·			10.00	· ··· ···					-	20-0		0.05	-0.82	0.67
	-	12		5 C		C										-		2		<		SiO,	-0.75
	X	>						->		•••			/	>		\rightarrow		-		X			00
a ann an a		A TITT	a.079.*			1 1 1 1			-					TTTT			, 	TTTT		1	and the	111111	
40 100 160		4 8 12		20 60		10 30		50 150 25	0	300 400		0 30 50	0	.05 0.20	2	00 300 4	00 20	40 60		10 30 50		64 70 76	

Figure S4. Distribution plot for each variable associated with trace metal and major oxides of moraine samples. On the bottom of the diagonal: the bivariate scatter plots with a fitted line are displayed. At the top of the diagonal: the value of the correlation plus the significance level as stars. Each significance level is associated to a symbol "***", "*", "*", "*", ", " and associated p-values are 0.001, 0.01, 0.05, 0.1, 1) respectively.



136 ablation zone of CSG. Cryoconite samples showed negative EU anomaly of magnitude between local rocks and fine moraine fractions

¹³⁷ indicating local or geogenic origin.



Figure S6. Enrichment Factor (EF) for trace metal and rare earth element in cryoconite (n=20, 1 SD), moraine (n=7, 1 SD) debris collected from CSG. EF (as (X/Sc)_{sample}/(X/Sc)_{LR} for element X is calculated using Sc in local rock: LR (>3mm) (Barbieri, 2016). The EF value ≤ 1 corresponds to exclusively natural origin and EF value 1-3, 3-5, and 5-10 suggests low, moderate, and strong enrichment respectively.





Figure S8. Correlogram showing Pearson correlation coefficient between REE and major oxide analyzed in cryoconite samples. Positive

- 148 correlations are displayed in blue and negative correlations in red color. Color intensity and the size of the circle are proportional to the correlation
- 149 coefficient



150 CN (CaO^{*} + Na₂O) K (K₂O) 151 Figure S9. A-CN-K plot for supraglacial cryoconite, moraine, local granitoid rock, higher 152 Himalayan Crystalline Sequence (HHCS), UCC, and PAAS. The vertical solid line plotted with a 153 10-unit interval represents weathering trends. Highly weathered sediments will move towards 154 clay fraction end. The oxides abundance is in molar mass fraction and CaO* represents only the 155 silicate fractions and determined by using the methodology described in an earlier study 156 (Mclennan, 1993). Data source: Local rock (Maibam et al., 2016), HHCS (Richards et al., 2005), 157 PAAS (Taylor & McLennan, 1985), and UCC (Rudnick & Gao, 2014).





Figure S10. Bivariate concentration ratios plot of Th/Co versus La/Co showing cryoconite and
moraine signature compared to different rock units and UCC. The open symbols are average
values of lithology plotted as field abbreviations LH and HH refer to Lower Himalaya and Higher
Himalaya respectively. Data source: granitic and mafic rocks (Miller et al., 2001), gneiss (Islam et
al., 2011), Siwalik: clastic rocks (Ranjan & Banerjee, 2009) and UCC (Rudnick & Gao, 2014).



Figure S11. Ternary Th-Sc-La diagram illustrating lithological control on the composition of
 cryoconite and moraine debris. Fields of different rock types traced after published literature
 mentioned in Figure S10 except for mafic rocks (Srivastava & Sahai, 2001), and river sediments
 (Alizai et al., 2011).



169 170

171 Figure S12. Comparison of chondrite normalized (McDonough and Sun, 1995) REE pattern of 172 cryoconite and moraine with (a) local rock and sediment (b) snow dust, glacial moraine, sand and 173 soil from other Himalayan regions and the Thar and Sahara deserts. Data source: (a) local 174 granitoid (Maibam et al., 2016), Lesser Himalayan sediment (Das & Haake, 2003), Higher 175 Himalaya (river sediment (Panwar et al., 2017), PAAS (Taylor & McLennan, 1985), intrusive mafic 176 rock (Srivastava & Samal, 2019) and UCC (Rudnick & Gao, 2014); (b) Chinese glacial moraine 177 cryoconite (Chang et al., 2000; Li et al., 2011), Glacial dust from Tibet and Nepal (Li et al., 2012) 178 and Everest ice core dust (Zhang et al., 2009), Thar (Ferrat et al., 2011; Roy & Smykatz-Kloss, 179 2007) and Sahara sand (Castillo et al., 2008).

181	Table S1. Re-Os isoto	pes composition	and Re-Os abundar	nce analyzed in select	ed cryoconite (C),
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182 moraine (DF:<63 μm), diesel engine exhaust (DEE) and Indian coal (GC: Gondwana coal, TC:

Sample	Total Re (2s)	Total Os (2s)	¹⁹² Os (2s)	¹⁸⁷ Re/ ¹⁸⁸ Os	¹⁸⁷ Os/ ¹⁸⁸ Os	rho	%Re	%¹ ⁸⁷ Os	% ¹⁸⁸ Os
	(ng g⁻¹)	(pg g⁻¹)	(pg g⁻¹)	25	25		Blank	Blank	Blank
C1	0.206± 0.002	$32.3{\pm}0.2$	12.1 ± 0.1	33.8 ± 0.4	$0.911{\pm}0.008$	0.402	1.16	0.09	0.33
C3	0.163± 0.002	10.9 ± 0.1	3.9 ± 0.1	83±1.4	$1.278{\pm}0.170$	0.599	1.47	0.2	1.03
C5	0.211± 0.002	14.2 ± 0.1	5.1 ± 0.1	82.4± 1.1	$1.310{\pm}0.015$	0.596	1.13	0.15	0.79
C9	0.235± 0.002	37 ± 0.2	14.1 ± 0.1	33.3± 0.4	$0.790{\pm}0.007$	0.414	1.02	0.09	0.29
C11	0.252± 0.002	77.3 ± 0.3	30.5 ± 0.2	16.4 ± 0.2	$0.479{\pm}0.004$	0.386	0.95	0.07	0.13
C13	0.463± 0.002	63.6±0.3	24.2 ± 0.1	38.1 ± 0.3	$0.777{\pm}0.006$	0.522	0.52	0.05	0.17
C14	0.416± 0.002	39.4 ± 0.2	14.9 ± 0.1	55.5 ± 0.5	$0.829{\pm}0.007$	0.543	0.58	0.08	0.27
C17	$\begin{array}{c} 0.35 \pm \\ 0.002 \end{array}$	$41.1{\pm}0.2$	15.6 ± 0.1	$44.7{\pm}0.4$	$0.803{\pm}0.006$	0.504	0.69	0.08	0.26
C18	0.403± 0.002	104± 0.4	41.5 ± 0.2	19.3± 0.2	$0.378{\pm}0.003$	0.483	0.6	0.06	0.1
C19	0.465± 0.002	55 ± 0.2	$21.1{\pm}0.1$	43.9± 0.3	$0.702{\pm}0.006$	0.531	0.51	0.07	0.19
DF6	0.208± 0.002	30.4 ± 0.2	11.1 ± 0.1	37.4± 0.5	$1.118{\pm}0.010$	0.408	1.15	0.08	0.36
DF12	0.141± 0.002	12.5 ± 0.1	4.4 ± 0.1	63.9±1.2	$1.478{\pm}0.018$	0.518	1.7	0.15	0.91
GC1	0.261± 0.002	6.9 ± 0.1	2.4 ± 0.1	217 ± 8.2	1.644 ± 0.069	0.856	4.39	0.83	6.38
GC2	0.757± 0.003	17.9 ± 0.1	6.2 ± 0.1	243 ± 4.2	$1.606{\pm}0.032$	0.801	1.52	0.33	2.56
TC1	0.527± 0.003	726 ± 2.8	$299{\pm}2.6$	3.5 ± 0.04	$0.144{\pm}0.002$	0.609	2.18	0.08	0.05
TC2	0.468± 0.002	63.4 ± 0.3	25.9 ± 0.3	35.9±0.4	$0.213{\pm}0.003$	0.562	2.46	0.59	0.63
DEE1	0.073± 0.011	2.1 ± 0.5	0.9 ± 0.5	166±95	$0.218{\pm}0.185$	0.631	48.4	63.23	40.75
DEE2	1.032± 0.018	5.7 ± 0.8	2.3 ± 0.8	884 ± 294	$0.205{\pm}0.126$	0.541	10.48	64.54	39.86

183 Tertiary coal) samples.

84 Note: Total procedural blanks were 2.1 ppt for Re and 0.1 ppt for Os, with $a^{187}Os^{/188}Os$ ratio of 0.25.

Sample	Elevation	SiO₂	TiO₂	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na₂O	K₂O	P_2O_5	LOI	Total
id	m a.s.l.	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%
C1	4515±2	63.4	0.84	14.06	5.71	0.13	2.03	1.3	1.79	3.62	0.22	6.79	99.9
C2	4582±2	65.5	0.74	13.76	5.11	0.08	1.72	1.38	2.46	3.92	0.23	4.58	99.43
C3	4595±3	68.6	0.52	13.48	4.05	0.07	1.08	1.34	2.21	4.54	0.28	3.27	99.42
C4	4649±3	67.9	0.64	13.44	4.61	0.07	1.56	1.52	2.21	3.89	0.32	3.27	99.43
C5	4665±2	71.4	0.43	12.3	3.32	0.05	0.86	1.36	2.31	4.14	0.3	2	98.45
C6	4683±2	64.8	0.71	14.11	5.02	0.1	1.81	1.41	2.6	3.93	0.19	4.5	99.13
C7	4695±3	67.1	0.64	13.43	4.76	0.08	1.54	1.44	2.06	3.97	0.29	3.9	99.19
C8	4701±3	61.8	0.79	14.09	5.8	0.14	2.19	1.3	2.94	3.81	0.21	6.03	99.05
C9	4715±3	62.1	0.84	14.18	5.98	0.12	2.36	1.32	1.68	3.47	0.2	7.09	99.37
C10	4738±3	72.8	0.4	12.16	3.08	0.05	0.79	1.45	2.24	4.22	0.39	1.69	99.31
C11	4747±3	61	0.9	14.49	6.54	0.15	2.62	1.31	1.58	3.29	0.2	6.98	99.04
C12	4750±3	58.8	0.98	14.94	6.35	0.06	3.02	1.33	2.87	3.39	0.22	7.29	99.2
C13	4778±3	62	0.81	14.35	5.96	0.11	2.37	1.33	1.99	3.54	0.23	7.2	99.9
C14	4816±3	61	0.77	15.05	5.76	0.08	2.13	1.44	2.15	3.94	0.23	6.38	98.92
C15	4831±3	60.7	0.91	14.74	6.46	0.11	2.71	1.42	1.69	3.35	0.21	7.4	99.65
C16	4871±3	62.7	0.79	14.58	5.41	0.09	2.04	1.55	2.04	3.74	0.23	6.54	99.75
C17	4877±3	62.1	0.89	14.54	5.99	0.1	2.49	1.5	1.77	3.42	0.23	6.87	99.86
C18	4908±3	59.7	0.89	13.82	6.59	0.16	3.35	2	1.55	2.96	0.22	8.69	99.92
C19	4914±3	58.5	0.93	13.25	6.55	0.16	3.18	1.63	1.42	2.54	0.29	10.56	98.98
C20	4928±3	63.5	1.01	14.97	6.51	0.13	2.44	1.49	1.76	3.57	0.23	3.79	99.38
DF6	4556±4	63.2	0.88	15.1	6.04	0.08	2.04	1.57	2.27	3.76	0.3	4.48	99.75
DF8	4657±6	65.1	0.55	16.31	4.53	0.09	1.16	1.65	3.15	4.53	0.38	2.36	99.83
DF10	4715±3	63.6	0.73	15.09	5.54	0.11	1.7	1.51	2.45	4.22	0.27	3.54	98.79
DF12	4751±3	68.2	0.41	15.42	3.41	0.06	0.76	1.79	3.83	4.37	0.47	1.69	100.37
DF14	4823±2	63.4	0.52	17.29	4.57	0.09	1.06	1.53	3.45	4.85	0.35	2.85	99.96
DF16	4890±3	67.6	0.46	15.85	3.26	0.05	0.77	1.61	3.28	4.79	0.38	1.77	99.79
DF18	4928±2	66.1	0.73	14.31	5.11	0.09	1.51	1.58	2.54	3.99	0.32	3.28	99.53
DB6	4556±4	73.7	0.27	13.9	2.21	0.04	0.49	0.74	2.17	4.62	0.19	0.54	98.88
DB8	4657±6	70.7	0.47	13.7	3.89	0.07	0.81	0.82	1.93	5.02	0.26	1.38	99.04
DB10	4715±3	70.9	0.44	14.5	3.54	0.06	0.9	0.9	2.66	4.76	0.21	1.22	100.05
DB12	4751±3	72.3	0.35	13.49	2.86	0.04	0.59	0.78	2.37	4.84	0.24	1.07	98.96
DB14	4823±2	72.1	0.34	13.59	2.9	0.05	0.6	0.8	1.95	4.77	0.27	1.21	98.54
DB16	4890±3	77.4	0.17	11.59	1.36	0.02	0.26	0.71	1.81	4.61	0.24	0.61	98.74
DB18	4928±2	72.2	0.36	14.14	3.07	0.05	0.63	0.76	1.79	4.84	0.25	1.37	99.42
NIST refe	erence mater	ial											
SRM 270)9a ^м	63.9	0.57	13.34	4.95	0.07	2.47	2.84	1.67	2.52	0.17	7.8	99.15
		±0.73	±0.01	±0.82	±0.21	±0.00	±0.06	±0.24	±0.04	±0.03	±0.01	±0.01	
SRM 270)9a ^c	59.6-	0.56-	14.06-	0.005-	0.06-	2.34-	2.65-	1.70-	2.41-	0.15-		93.61

Table S2. Major element abundance in cryoconite (Cx) and selected moraine samples (Fine187fraction: DF:<63 μ , Bulk fraction: DB:<3 mm).</td>

	64	0.65	14.66	5.85	0.08	4.18	3.53	1.74	2.54	0.31		
SRM 8704 [™]	61.9	0.78	11.24	6.06	0.08	2.18	3.82±	0.97	2.44	0.23	10.04	99.59
	±0.01	±0.01	±0.41	±0.12	±0.001	±0.09	0.08	±0.13	±0.01	±0.01	±0.01	
SDM 9704B	61.9-	0.71-	10.96-	5.62-	0.07-	1.90-	3.69-	0.71-	2.42-	0.20-		99.53
SRM 8704**	62.2	0.78	13.74	6.02	0.08	2.14	3.83	0.78	2.57	0.22		

Note: Superscripts M refers to measured and C corresponds consensus values (<u>http://georem.mpch-mainz.gwdg.de/sample_query.asp</u>).

189 Table S3. Trace metal concentration (in ppm) in cryoconite and moraine samples. Cryoconite

190 (Cx), local rocks (DB3-x, > 3 mm), moraine bulk fraction (DB-x, <3 mm), fine moraine (DF-x, <63

191 μm). Samples marked with apostrophe (`) are duplicate analysis.

Sample	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	GeoPT28 ^M	GeoPT28 ^c
Element												(n=3, 1 SD)	
Li	86	87	135	91	111	87	103	89	72	96	64	161± 17	164± 3
Be	3.9	5.7	12	8.5	6.5	9.7	6.5	4.3	3.2	9.8	3.1	3.29± 0.33	3.19 ± 0.08
Sc	15	13	11	11	8.7	12	10	15	15	6.9	17	24± 0.4	20± 0.2
V	93	80	60	67	47	76	64	93	100	37	116	250± 8	220± 1
Cr	90	71	46	56	32	66	53	88	98	27	115	117±5	109± 1
Co	18	13	10	9.9	7.3	13	10	18	18	6.1	21	24± 0.8	23± 0.3
Ni	46	34	23	28	15	35	26	44	51	12	60	86± 3.1	83± 0.8
Cu	26	22	24	19	13	21	18	27	28	12	33	30±1.2	31 ± 0.6
Zn	113	103	110	93	89	96	96	115	120	79	128	197± 7.1	187± 1.7
Ga	27	26	30	25	24	26	25	26	27	23	27	32 ± 0.8	27± 0.3
Rb	248	285	359	304	337	282	296	268	228	300	211	154± 6	147± 1.1
Sr	81	72	65	68	57	70	63	77	83	41	89	196± 4.7	178 ± 1.4
Υ	30	32	27	31	26	25	33	31	32	29	36	36± 3.4	37± 0.3
Nb	25	24	30	23	22	25	23	24	22	19	23	19± 3.2	15 ± 0.2
Cd	0.25	0.14	0.21	0.11	0.08	0.19	0.14	0.24	0.32	0.08	0.35	0.4± 0.01	0.4± 0.19
Cs	17	20	29	22	24	18	23	22	16	24	13	7.9± 0.15	8.2± 0.1
Ba	379	375	288	337	243	374	294	380	400	224	407	772± 18	788± 8
Та	2.7	2.4	3.4	2.3	2.4	3.4	2.5	2.2	1.9	1.9	2	2.4 ± 0.95	1.1± 0.03
Pb	35	30	28	25	26	29	28	37	38	23	40	31±0.3	35± 0.3
Bi	1.38	1.1	1.3	0.82	0.57	0.76	0.75	0.97	0.85	0.77	0.81	0.59 ± 0.007	0.7± 0.02
Th	20	21	21	19	15	20	18	20	20	14	20	15± 0.04	16± 0.2
U	5.2	5.1	4.9	3.9	4.5	4.2	3.8	4.7	4.7	3.7	4.8	5.0± 0.12	5.76± 0.11

192 193 Note: Superscripts M and C correspond to measured and consensus values of GeoPT₂₈ (http://georem.mpch-

mainz.gwdg.de/sample_query.asp).

Sample	C11'	C 12	C13	C14	C15	C16	C17	C18	C19	C 19'	C20	SRM-2704 ^M	SRM-
Element												(n=3, 1 SD)	2704 ^c
Li	64	73	70	106	85	108	87	64	43	49	85	40± 4.8	48
Be	2.8	3.1	3.1	5.3	3.3	4.4	3.6	3.1	2.5	2.6	3.1	1.76± 0.2	0.97-1.5
Sc	16	18	16	14	17	15	16	17	18	17	16	14± 0.4	12
V	108	126	113	90	112	96	110	124	129	119	103	103± 4.9	95± 4
Cr	107	116	102	89	111	98	113	123	136	127	102	135± 5.6	135±5
Со	20	18	17	14	19	17	17	29	23	22	19	14± 0.4	14± 0.6
Ni	56	62	53	44	59	47	57	73	74	71	49	43± 1.3	44± 3
Cu	31	37	30	29	33	33	34	50	39	37	30	92± 2.6	99± 5
Zn	121	126	133	134	126	154	139	157	189	177	126	391± 9	438± 12
Ga	25	28	28	30	27	29	27	25	23	21	30	18± 0.4	15
Rb	197	218	263	280	212	280	223	168	129	120	261	102± 0.4	100
Sr	87	95	87	68	93	93	93	115	113	109	86	133± 6.4	130
Y	32	33	32	33	32	33	35	33	37	35	37	29± 3.8	27-33
Nb	22	25	25	26	22	26	25	22	21	19	27	15± 1.3	15
Cd	0.32	0.3	0.29	0.32	0.3	0.47	0.39	1.11	1.31	1.28	0.29	3.1± 0.04	3.5±0.22
Cs	13	14	17	24	14	21	16	10	8.1	7.9	18	5.5± 0.1	6
Ва	425	465	397	348	407	381	426	407	377	376	411	398± 19	414± 12
Та	1.9	2.2	2.6	2.9	1.8	2.4	2.4	1.5	2.5	2.4	2.6	1.2± 0.3	0.97
Pb	40	38	45	39	43	53	43	42	60	61	37	138± 3	161±17
Bi	0.95	0.91	0.95	0.89	0.81	0.96	0.89	0.56	0.52	0.64	0.67	0.5± 0.01	NA
Th	20	20	22	21	20	20	22	14	15	16	22	7.8± 0.08	9.2
U	4.8	4.8	5.3	4.3	4.9	4.8	4.7	4	3.4	3.3	5.8	3.03±0.04	3.13± 0.13
Note: Super	rscripts	M an	d C c	orrespo	ond to	avera	ge me	asured	and	consensus	values	of NIST-270	94
(<u>nttp://geore</u>	<u>m.mpch</u>	-mainz.	<u>gwag.d</u>	e/samp	<u>le_quer</u>	<u>v.asp</u>).							

Table S₃ continued

Sample	DB3- 6	DB3- 6'	DB3- 8	DB3- 10	DB3- 12	DB3- 14	DB3- 16	DB3- 18	DB- 6	DB- 8	DB- 10	GS-N ^M	GS-N ^c
Element												(n=3, 1SD)	00 11
Li	67	79	78	93	74	91	40	73	91	167	106	56± 7	56± 8
Be	5	5.2	4.1	4.3	2.9	28	2.1	3.8	7.1	14	6.6	5.7±0.5	5.4± 0.15
Sc	3.5	3.6	1.8	6.3	4.5	4.5	3.5	4.8	5.4	8.2	8	9.1±0.3	7.3± 0.7
V	21	20	24	29	18	18	17	22	28	44	44	71±3	65± 17
Cr	11	11	14	17	10	10	10	13	17	25	31	60± 2	55± 11
Co	2.9	2.9	3.5	4.7	2.8	3.2	2.4	3.7	4	8.3	8	76± 6	65± 11
Ni	4.3	4.2	5.6	7	4.2	4.9	3.6	5.4	6.3	12	15	37± 1.3	34± 11
Cu	7.4	7.4	7.1	6.4	5.1	10	7	7.9	15	17	16	20± 0.7	20± 1.8
Zn	47	48	56	59	50	44	42	63	72	102	83	49± 1.5	48± 9
Ga	16	17	20	21	19	18	16	21	21	27	23	28± 1.3	22± 6.6
Rb	317	330	308	340	346	310	272	345	335	418	315	208± 12	185± 14
Sr	50	51	51	65	52	47	58	58	48	44	59	648± 30	570± 52
Υ	12	12	13	14	10	11	10	12	10	22	17	15± 1.8	16± 12
Nb	13	13	13	13	13	12	8.9	13	20	26	40	27± 3.1	21± 4.5
Cd	0.03	0.03	0.79	0.04	0.06	0.04	0.03	0.04	0.06	0.07	0.51	0.06±0.002	0.04±0.012
Cs	19	19	17	28	24	20	11	20	20	30	31	5.5±0.26	5.4 ± 0.5
Ba	278	280	302	368	234	287	337	248	277	256	321	1436± 83	1400± 124
Та	1.5	1.6	1.9	1.3	1.6	1.5	0.8	1.7	3.4	3.1	20	3.4 ± 0.85	2.6± 0.36
Pb	31	31	28	30	30	29	32	32	31	23	27	45± 2.2	53± 9.2
Bi	0.72	0.75	0.44	0.93	0.4	0.57	0.3	2.56	0.82	0.45	1.31	0.20-0.07	0.18-0.57
Th	9.7	9.7	11	17	10	9	10	13	7.1	13	13	40± 2.3	41± 6.9
U	1.6	1.6	2.9	2.6	2.2	3.2	2.2	6.1	1.5	4.2	3	7.1±0.42	7.5± 1.71

199 Table S₃ continued

200Note: Superscripts M and C correspond to average measured and consensus values of GS-N (http://georem.mpch-mainz.gwdg.de/sample_query.asp).

Sample	DB-12	DB-14	DB-16	DB-18	DF-6	DF-6'	DF-8	DF-10	DF-12	DF-14	DF-16	DF-18
Element												
Li	130	129	35	85	82	100	128	143	122	138	80	84
Be	11	20	1.9	2.4	4.2	4	7.8	4.8	8.1	7.5	4	3.5
Sc	6.5	6.6	3.4	7.6	15	14	8.9	9.2	6.6	8	8.5	11
V	31	31	16	30	91	88	52	89	33	43	39	68
Cr	17	18	10	18	89	90	37	62	23	26	29	67
Co	5	6.4	2.8	5.2	17	16	15	15	8.6	15	8.2	15
Ni	7.1	8.8	4.2	8	43	42	24	35	13	21	13	33
Cu	11	17	8.2	11	170	166	42	46	34	50	24	42
Zn	79	80	42	70	251	246	107	122	85	117	82	110
Ga	24	25	15	21	32	31	34	33	35	36	33	32
Rb	399	380	259	313	280	262	351	322	334	415	314	311
Sr	46	44	54	42	91	88	75	82	72	59	71	81
Y	17	21	13	13	47	45	39	36	64	33	57	43
Nb	21	21	8.7	16	30	29	27	26	26	35	24	25
Cd	0.04	0.05	0.04	0.05	0.28	0.28	0.14	0.61	0.11	0.12	0.11	0.19
Cs	32	30	11	21	22	22	32	43	35	42	19	24
Ba	234	216	280	194	399	399	287	357	242	229	269	308
Та	2.7	2.6	0.9	1.2	4.1	3.6	3.3	3.6	5.1	5.3	3.3	2.8
Pb	26	25	30	21	76	80	31	37	33	31	32	35
Bi	0.62	0.62	0.38	0.64	2.6	2.81	1.36	2.6	2.67	1.85	0.88	1.46
Th	11	11	8.8	11	39	40	37	36	56	40	49	40
U	4.4	4.7	2.4	5.6	13	13	13	11	16	18	12	20

202 Table S₃ continued

Sample		<u>C</u> 2	Dr	Nici	6	E	64	ТЬ	Dv	ᆔ	E-	Tm	Vh	1
Element	La	Ce	Pr	Na	Sm	Eu	Ga	D	Dy	но	Er	IM	TD	Lu
C1	46	96	10.6	38.3	7.82	1.141	6.8	1.016	5.61	1.051	2.84	0.385	2.31	0.324
C2	45	93	10.1	37.3	8.03	1.004	6.97	1.051	5.72	1.062	2.88	0.384	2.3	0.316
C3	39	85	9.34	34.2	7.73	0.806	6.75	1.007	5.17	0.871	2.19	0.267	1.5	0.202
C4	35	76	8.54	31	7	0.837	6.32	0.98	5.12	0.924	2.39	0.308	1.76	0.237
C5	28	59	6.67	24.6	5.9	0.638	5.4	0.877	4.63	0.795	2	0.248	1.38	0.184
C6	38	83	8.95	32.6	6.8	0.932	5.82	0.863	4.7	0.86	2.32	0.316	1.89	0.265
C7	35	78	8.3	30.5	6.89	0.8	6.17	0.97	5.2	0.935	2.43	0.315	1.83	0.249
C8	43	92	10.1	36.6	7.69	1.084	6.57	1.006	5.61	1.049	2.93	0.404	2.46	0.336
C9	45	96	10.4	38.4	7.97	1.142	6.77	1.016	5.74	1.073	2.98	0.417	2.54	0.357
C10	24	54	5.82	21.8	5.73	0.565	5.67	0.952	4.95	0.837	2.06	0.253	1.38	0.179
C11	47	97	10.8	39.2	7.96	1.238	6.93	1.065	6.11	1.189	3.32	0.465	2.84	0.408
C 11'	46	96	10.6	38.7	7.98	1.249	6.92	1.058	6.04	1.175	3.32	0.462	2.86	0.402
C 12	50	101	10.9	39.9	8.18	1.32	7.04	1.045	5.88	1.16	3.24	0.448	2.75	0.389
C 13	48	98	11.2	40.6	8.53	1.188	7.26	1.077	5.9	1.105	2.99	0.408	2.47	0.344
C 14	41	87	9.89	36.2	7.78	0.982	6.68	0.99	5.31	0.969	2.62	0.353	2.09	0.289
C 15	47	97	10.8	39.1	7.96	1.21	6.9	1.014	5.64	1.063	2.97	0.417	2.51	0.348
C 16	44	91	10.2	37.4	7.82	1.156	6.74	0.997	5.62	1.048	2.84	0.387	2.31	0.323
C 17	49	101	11.4	42	8.73	1.257	7.45	1.116	6.22	1.184	3.24	0.451	2.73	0.384
C 18	38	79	8.55	31.9	6.74	1.268	6.11	0.918	5.28	1.017	2.86	0.392	2.39	0.34
C 19	41	83	9.58	35.1	7.25	1.368	6.46	0.971	5.59	1.107	3.14	0.437	2.72	0.386
C 19'	41	80	9.34	34.4	7.08	1.33	6.29	0.955	5.53	1.086	3.08	0.431	2.66	0.384
C 20	55	113	12.4	45.2	9.24	1.299	7.9	1.171	6.31	1.148	3.11	0.417	2.53	0.35
DB3-6	15	35	3.76	13.9	3.3	0.477	2.92	0.464	2.43	0.414	1.04	0.129	0.7	0.091
DB3-6'	15	34	3.84	14.2	3.27	0.483	2.98	0.471	2.48	0.423	1.06	0.129	0.7	0.092
DB3-8	21	48	5.36	19.2	4.48	0.505	3.9	0.591	2.97	0.474	1.12	0.131	0.68	0.087
DB3-10	24	53	6.03	22.2	4.85	0.598	3.95	0.576	2.96	0.497	1.24	0.156	0.87	0.115
DB3-12	15	35	3.95	14.2	3.42	0.492	2.97	0.453	2.19	0.343	0.8	0.094	0.5	0.065
DB3-14	13	30	3.36	12.4	2.97	0.459	2.68	0.433	2.29	0.398	0.98	0.118	0.65	0.084
DB3-16	15	34	3.81	13.8	3.28	0.516	2.9	0.448	2.22	0.349	0.8	0.093	0.5	0.062
DB3-18	19	43	4.82	17.5	4.15	0.509	3.7	0.568	2.75	0.412	0.93	0.112	0.64	0.086
DB-6	11	29	2.82	10.7	2.71	0.468	2.53	0.412	2.19	0.364	0.89	0.106	0.57	0.073
DB-8	19	46	5.1	19.2	4.79	0.511	4.58	0.772	4.17	0.724	1.85	0.226	1.23	0.162
DB-10	24	58	5.6	20.8	4.74	0.66	4.1	0.63	3.39	0.6	1.56	0.203	1.16	0.157
DB-12	18	42	4.67	17.3	4.34	0.497	4.12	0.682	3.54	0.589	1.46	0.176	0.93	0.122
DB-14	18	40	4.63	17.4	4.43	0.477	4.49	0.777	4.25	0.743	1.82	0.222	1.19	0.156
DB-16	13	31	3.55	13.3	3.41	0.506	3.35	0.567	2.95	0.469	1.11	0.132	0.7	0.088
DB-18	17	44	4.54	16.5	4.07	0.454	3.82	0.607	3	0.463	1.06	0.13	0.74	0.098
DE-6	76	165	18.4	66.2	111	1 404	12 1	1 760	0 /3	1 664	4 35	0 563	3 33	0 453

Table S4. Rare earth element concentration (in ppm) in cryoconite and moraine samples. Sample
 notions are same as Table 2 and Table 3 and apostrophe symbol refers to duplicate samples.

DF-6'	80	165	18.4	67	14.4	1.429	12.3	1.816	9.48	1.684	4.44	0.566	3.31	0.457
DF-8	73	164	17.5	63.7	14.4	1.08	12	1.737	8.31	1.299	3.08	0.364	1.92	0.246
DF-10	70	154	17.3	63.6	13.4	1.28	10.9	1.549	8.04	1.374	3.6	0.466	2.69	0.36
DF-12	100	217	25.2	88	20.2	1.216	17.5	2.619	13.1	2.16	5.29	0.631	3.39	0.453
DF-14	68	152	17.1	61.8	13.9	0.942	11.6	1.692	7.9	1.205	2.76	0.31	1.67	0.213
DF-16	84	184	21.8	74.9	17.2	1.094	14.8	2.255	11.6	1.931	4.72	0.577	3.2	0.411
DF-18	85	197	21.4	73.3	16.4	1.451	13.9	2.011	9.72	1.541	3.72	0.469	2.71	0.371
GeoPT28 ^M	51±	106±	12.1±	45±	9.1±	1.84±	7.8±	1.15±	6.5±	1.3±	3.7±	0.53±	3.38±	0.49±
	1.4	3.2	0.2	1.2	0.21	0.03	0.08	0.019	0.16	0.02	0.05	0.01	0.07	0.009
GeoPT28 ^c	53±	108.2±	12.6±	49.2±	9.62±	1.98±	8.54±	1.23±	7.1±	1.36±	3.79±	0.56±	3.64±	0.54±
	0.6	0.92	0.1	0.5	0.11	0.018	0.1	0.016	0.089	0.017	0.05	0.01	0.039	0.008
SRM- 2704 [™]	30±	59±	7±	27±	5.5±	1.2±	5.3±	0.82±	5±	1.02±	2.96±	0.43±	2.72±	0.39±
	1.2	1.9	0.08	0.35	0.04	0.01	0.04	0.01	0.03	0.01	0.04	0.005	0.03	0.0002
SRM- 2704 ^c	29	72	7.2	32	6.7	1.3	5.5	0.89	6	1.2	3.3	0.48	2.8	0.6
GS-N ^M	75±	138±	14±	46±	7.1±	1.5±	4.8±	0.59±	3±	0.55±	1.5±	0.21±	1.35±	0.20±
	4.2	7.3	0.7	2.5	0.37	0.0.08	0.23	0.03	0.16	0.03	0.08	0.01	0.07	0.01
GS-N ^c	75±	135±	14.5	49±	7.5±	1.7±	5.2±	0.6±	3.1±	0.68±	1.5±	0.22	1.4±	0.22±
	7.3	45.12		3.54	0.51	0.16	0.79	0.08	1.04	0.18	0.4		0.54	0.06

 206
 207
 Note: Superscripts M and C correspond to average measured and consensus values of reference material mentioned in earlier tables.

208 **Table 5.** Calculated percent osmium contribution in cryoconite from individual sources: Local

209 Moraine (LM), Less Radiogenic with low Os concentration mineral phase (LR) and Ultramafic 210 Rock (UR).

Sample	LM	LR	UR	
C1	66.7	31.8	1.5	
C3	30.7	69.2	0.2	
C5	40.7	59.1	0.2	
C9	70.5	28.0	1.6	
C11	69.9	24.1	6.1	
C13	92.4	4.6	3.1	
C14	74.4	23.5	2.1	
C17	74.6	23.1	2.3	