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Diverse sources of aeolian sediment revealed in an arid landscape in southeastern Iran using a modified Bayesian un-mixing model

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Diverse sources of aeolian sediment revealed in an arid landscape in southeastern Iran using a Bayesian un-mixing model

3 Abstract

Identifying and quantifying source contributions of aeolian sediment is critical to mitigate 4 local and regional effects of wind erosion in the arid and semi-arid regions of the world. Sediment 5 fingerprinting techniques have great potential in quantifying the source contribution of sediments. 6 7 The purpose of this study is to demonstrate the effectiveness of fingerprinting methods in 8 determining the sources of the aeolian sands of a small erg with varied and complex potential sources upwind. A two-stage statistical processes including a Kruskal-Wallis H-test and a stepwise 9 discriminant function analysis (DFA) were applied to select optimum composite fingerprints to 10 discriminate the potential sources of the aeolian sands from the Jazmurian plain located in Kerman 11 12 Province, southeastern Iran. A Bayesian un-mixing model was applied to quantify uncertainties 13 associate with the source contributions, and the model was evaluated by a goodness of fit (GOF) 14 method. The results suggest that four geochemical properties (Cr, Co, Ni, and Li) were the 15 optimum fingerprints for solving the Bayesian un-mixing model. The results show that there is great diversity in terms of the sources of sand, and that, contrary to expectation, sediments 16 associated with an adjacent large ephemeral lake are the least significant in supplying sediment to 17 18 the erg. Sand-sheet-derived sands and alluvial sediments dominate a majority of the samples, and 19 are likely attributable to relatively short-distance aeolian flux, but substantial contributions from alluvial fans and terraces likely represent longer distance pathways. These results highlight the 20 21 need to consider sediment provenance on a site-by-site basis. The GOF evaluation showed that 22 the Bayesian un-mixing model is an effective method to aid aeolian sediment fingerprinting. This method may be applied to assess aeolian sediment sources in other desert regions with strong 23 24 aeolian activities.

Key words: Sediment Fingerprinting, Aeolian Sediment, Bayesian un-mixing Model,
Uncertainty, Jazmurian Plain.

27

30 **1. Introduction**

31 Desertification, or land degradation in the world's arid regions, is one of the world's most 32 pressing environmental issues (Dregne et al., 1991; UN, 2015). The United Nations Convention to Combat Desertification (UNCCD, 1994) recognized several aspects of desertification leading to 33 34 the loss of productivity of dryland soils including aeolian and water erosion. Desertification resulting from wind erosion and deposition, driven by changing climates (both drought and long-35 36 term climate changes) and human activities has been reported in different climatic regions 37 worldwide (needs citations here). Drylands are typically highly susceptible to aeolian erosion and 38 land degradation, due to interactions between the typically sparse vegetation, lack of moisture to bind the surficial sediments, and the susceptibility of the surface to disturbance and climate change 39 (Ravi et al., 2010). In many arid and semi-arid regions, deflated sand accumulates in dune fields 40 (ergs), including parts of subtropical deserts and rain-shadowed zones of the mid-latitudes (Muhs, 41 42 2017). Although many studies have investigated aeolian dunes worldwide, much of the focus has been on the dune initiation (Luna et al., 2011), sedimentary structures (Yang et al., 2018), and 43 44 palaeoclimatic implications of dated dune deposition (e.g. Lancaster et al., 2016; Thomas and Burrough, 2013; Leighton et al., 2014; Li and Yang, 2015; Du and Wang, 2014). Very little 45 information is available on dune sediment provenance (Muhs, 2017), yet dune fields represent 46 potential archives of information in regional sediment transport pathways, as they are effectively 47 major sinks of the aeolian sediment regime. 48

Aeolian sediment transport fluxes in drylands are frequently complex, multi-directional and 49 may involve multiple sources, sinks and pathways. Furthermore, they are often intimately linked 50 51 to hydrological pathways, which themselves may operate only intermittently and unpredictably, in the form of ephemeral drainages and lakes (playas) (Al-Masrahy & Mountney, 2015; Bullard & 52 53 Livingstone, 2002; Williams, 2015). Although terminal closed basins are often associated with aeolian sediment emissions, often in the form of dust (e.g. Gill, 1996), other studies have 54 55 highlighted the role of dunefields as emission sources (Bullard et al., 2008), and even alluvial fans as sources of nearby dune sands (Howard et al., 1999). Moreover, not all basins may contribute 56 57 equally as aeolian sources, perhaps most notably in the case of Saharan dust emissions, a 58 disproportionate amount of which in now known to originate from the Bodélé Depression in Chad

(Washington and Todd, 2005), and such emissions may also have complex spatio-temporal
dependency on localized hydrology (e.g. Dahmardeh Behrooz *et al.*, 2019). Therefore, identifying
sources of aeolian sediment and quantifying the contribution of different sources represent critical
steps for wind erosion control and management (Wang and Jia, 2013).

For the first time, Collins et al. (1997) applied a sediment fingerprinting method to quantify 63 contribution sources of fluvial sediments. Consequently, many researchers applied this technique 64 to quantify source contributions of fluvial sediments at various locations worldwide (e.g. Walling, 65 2005; Collins et al., 2010; Zhang et al., 2012; Smith and Blake, 2014; Le Gall et al., 2017; Tiecher 66 et al., 2018; Habibi et al., 2019). Sediment fingerprinting is well-developed in the context of 67 fluvial sediments, but only recently has this approach has been introduced to quantifying source 68 contribution of aeolian sediments (Gholami et al., 2017a, b; Liu et al., 2016a; Wang et al., 2017; 69 Dahmardeh Behrooz et al., 2019). The successful development of sediment fingerprinting methods 70 for aeolian sediment deposits is important as it provides quantitative estimates of aeolian sediment 71 with constrained uncertainties which can be applied to diverse dryland regions and environmental 72 problems, especially where such transport fluxes may be complex and other methods of 73 74 provenancing (e.g. detrital zircon U-Pb dating) may be difficult to apply (Gholami et al., 2017b). The effectiveness of multiple composite fingerprints to quantify the provenance of aeolian 75 sediments reported by Liu et al., (2016a) suggested that these methods could be useful in other 76 locations for studying provenance of aeolian sediments. 77

78 Geochemical characteristics of aeolian sediments deposited far from their source regions have been used as proxies for their potential sources (Wang et al. 2017). Criteria to determine sources 79 80 are based on comparing the different geochemical properties of sediment samples and potential source samples. In recent years, numerous different sediment fingerprinting techniques have been 81 82 developed to quantify sediment provenance, with hydrological applications most common at present (Walling, 2013; Wang et al., 2017). A wide range of properties have been employed in 83 sediment fingerprinting studies including geochemical elements (Collins et al., 2012; Lamba et al., 84 2015; Liu et al., 2016a; Gholami et al., 2017a; Gholami et al., 2019), geochemical indicators (Vale 85 et al., 2016), isotopic ratios (Douglas et al., 1995), radionuclides (Walling et al., 1999; Olley et al., 86 2012), organic elements (Walling et al., 1999; Gellis et al., 2009), magnetic properties (Russell et 87 al., 2001) and physical signatures (Kouhpeima et al., 2010). 88

89 Results produced by sediment fingerprinting studies, however, may have various uncertainties (Walling, 2013). In recent years, techniques such as Bayesian models and Monte Carlo simulation 90 were developed to evaluate uncertainties associate with sediment fingerprinting results (Collins et 91 al., 2012; Cooper et al., 2014; Pulley et al., 2015; Lamba et al., 2015; Liu et al., 2016b; Abban et 92 al., 2016; Cooper and Krueger, 2017; Nosrati et al., 2018; Habibi et al., 2019; Gholami et al., 93 2019). However, most of these studies focused on fluvial systems and the application of these 94 modelling techniques to quantify source contribution of aeolian sediments is rare. Recently, 95 Gholami et al. (2017b) successfully applied a Bayesian mixing model to assess uncertainties 96 associated with results of aeolian sediment fingerprinting in the Yazd-Ardekan plain, Iran. Large 97 parts of Iran (an area of about 24 million ha) are arid or semi-arid areas where wind erosion acts 98 as an important geomorphological process over (Gholami et al., 2017a). About 25% of this area is 99 occupied by dune fields, including the Yazd, Ashkzar, Kashan and Jazmurian ergs (Figure 1). 100 Jazmurian erg and its surrounding areas at the southern border of Kerman and Sistan-Baluchestan 101 Provinces, Iran, experience severe wind erosion (Rashki et al, 2017). The aim of this research is 102 to test and evaluate the fingerprinting method to quantify sources of aeolian sediment in a dune 103 104 field with a complex potential range of sand sources (a large playa, associated terminal fluvial channels, sand sheets and more distal alluvial fans), and to incorporate robust estimates of the 105 106 uncertainties associated with the fingerprinting results using a Bayesian un-mixing model.

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108 2. Material and methods

110 The study area is located in the Jazmurian Basin, in the Kerman Province of southeastern Iran (Figure 1). With the Jabal Albarez mountains to the north, and separated from the Gulf of Oman 111 by the Makran mountains to the south, the Jazmurian Basin is a closed basin fed by the Bampur 112 113 River from the east, and the longer Halil (Haliri) River to the west. The region is arid, receiving 114 100-200 mm rainfall annually, but with evapotranspiration of up to 2500 mm year⁻¹ (Rashki, Arjmand & Kaskaoutis, 2017). Geologically, this area is covered by five Quaternary geological 115 formations: (1) sand sheets (Q_s unit); (2) alluvial fine-grain sediments and dry river bed sediments 116 $(Q_{al} \text{ unit})$; (3) alluvial fans and terraces $(Q_t \text{ unit})$; (4) mixtures of clay and salt (the dried lake-bed 117 of Jazmurian lake, or Q_c unit) and (5) dune fields (Q_{sd} unit) (Figure 1, part B). The Q_s , Q_{al} , Q_t and 118 Q_c geological units are assumed to be the potential sources of aeolian sediments for the small erg 119

^{109 2.1} Study area

representing the deposition region, the Q_{sd} geological unit (Liu et al., 2016a; Gholami et al., 2017a, b). The area of the case study is 8050 km² and it consists of 1754 km² Q_t unit, 1443 km² Q_s unit, 1667 km² Q_c unit, 1887 km² Q_{al} unit and 199 km² Q_{sd} unit.

Jazmurian lake covers, at its maximum extent, about 1100 km² of the study area, but the lake is rarely inundated, and frequently completely dry; this has been the case since at least the earlier half of the 20th century (Harrison, 1943). The lake has recently yielded sedimentological evidence of palaeoclimatic change since the Last Glacial Maximum, revealing a complex aridity history, with markedly wetter conditions during the early Holocene, with more minor excursions in moisture availability throughout the last 20 ka (Vaezi *et al.*, 2019).

Dominant winds in the western Jazmurian region are mainly from the southwestern, southern 129 and southeastern directions (Figure 1, part E), though to the north and east they are more varied. 130 Extensive droughts in the early 2000s caused the Jazmurian lake to completely dry and resulted in 131 an increased frequency of dust events observed during 2001-2003. Dusty days in the Jazmurian 132 Basin ranged from 91 in 1996 to 203 in 2003 (Rashki et al., 2017). Increasing in frequency and 133 intensity of dust storms resulting from the desiccation of the lakes may raise serious problems for 134 the regional climate, ecosystems and human health (e.g. Rashki et al., 2013b). The Jazmurian 135 region is a main source of dust storms, and atmospheric dusts emitted from this area affect mostly 136 137 both sides of the Sea of Oman, including the southeastern Arabian Peninsula and western Pakistan (Rashki et al., 2017). 138



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Figure 1. Location and geological map of the Jazmurian region, south of Kerman, Iran and sampling sites. a) Location of study area (with red color) at the map of Iran and south of Kerman province (Yellow color); b) Geological map of study area. Different colors represent different geological sites in the study area; c) Landsat image (February 2017) of study area; and d) Annual wind rose from Kahnouj station. Number of sampling points = 72.

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146 2.2 Sampling and laboratory analysis

A total of 72 sediment and soil samples were collected from the upper 0-5 cm depth of the potential sources and deposition regions (Figure 1, part B) in winter 2017. Among these samples, 7 were collected from Q_s , 25 from Q_{al} , 5 from Q_t , 21 from Q_c source areas. Additionally, 14 samples were collected from the dune fields (Q_{sd}) as aeolian sediments (Figure 1, part C). Source samples collected from points that were: (*a*) clearly derived from the geological unit; (*b*) within the spatial coverage of the source area, broadly; and (*c*) influenced by wind erosion (Gholami etal., 2017b).

154 The grain size distribution of the samples was determined using the dry sieve method. The geochemical analysis of fingerprint properties focused on the 125-410 µm fraction of the samples. 155 This is the predominant range of grain size in the aeolian sediment deposition area, and sediments 156 in this range are susceptible to aeolian transport (Field et al., 2010). The samples were digested 157 158 with aqua regia (Collins et al., 2012) and analyzed for Ni, Cu, Co, Cr, Ga, Mn, P, Ba, Sr and Li 159 using inductively coupled plasma optical emission spectroscopy (ICP-OES; Varian 730-ES model). The relative standard deviation (% RSD), based on three replicates for each determinant 160 on each sample, was consistently $\leq 5\%$. 161

162 2.3 Potential sources of aeolian sediments

Selection of the optimum fingerprint involves quantitative assessment of the power of 163 individual properties to identify the potential sources of sediment (Collins et al., 2010). A two-164 165 stage statistical procedure, which was introduced by Collins et al. (1997), was used to identify optimum composite fingerprints to discriminate potential sources of aeolian sediments. At the first 166 step, the ability of potential sources' properties was investigated using the Kruskal-Wallis H test. 167 At the second step, optimum composite fingerprints were selected by a stepwise discriminant 168 function analysis (DFA). Wilks' lambda was used as the primary factor of discrimination in the 169 stepwise DFA, which determined the optimum fingerprints as input parameters to the model. This 170 two-stage procedure has been successfully applied by many studies for source fingerprinting of 171 fluvial sediments (Walling et al., 1999; Stone et al., 2014; Zhou et al., 2016; Chen et al., 2016; Liu 172 173 et al., 2016b) and more details of this method and its application to aeolian sediments may be 174 found in Gholami et al. (2017a, b).

175 2.4 Bayesian un-mixing model

In this study, we used a Bayesian un-mixing model, developed by Gholami et al. (2017b), to quantify source contributions of aeolian sediments. It is a full Bayesian model in that all hyperparameters are not fixed at a specific value and a prior distribution was selected for each hyperparameter. Compared to an empirical Bayesian approach, a full Bayesian model is more flexible and more complicated (Cooper et al., 2014). Further details of modelling procedure are given in Gholami et al. (2017b) and Habibi et al. (2019). Compared to the model used in Gholami et al. (2017b) and Habibi et al. (2019), which used a Centered Log Ratio (CLR) transformation, in this study, we used the Dirichlet distribution for source contributions (Fox and Papanicolaou, 2008). The Dirichlet distribution is a multivariate generalization of the beta distribution which satisfies the necessary boundaries constraints directly (that is, that all sources should sum to unity, and that all contribute between 0 and 1). It is thus simpler than the CLR transformation approach.

187 If $P = \{p_i, ..., p_n\}$ follows the Dirichlet distribution with hyper-parameters $a_1, ..., a_n > 0$, its 188 density function is

189
$$f(P) = \frac{\Gamma(\sum_{i=1}^{n} a_i)}{\prod_{i=1}^{n} \Gamma(a_i)} \prod_{i=1}^{n} p_i^{a_i - 1}$$
(eq. 1)

Here, $p_i, ..., p_n \ge 0$ and $\sum_{i=1}^n p_i = 1$. Because there is no assumed prior information for the source contributions, we set hyper-parameters $a_1, ..., a_n$ equal to one. Similarly, in this study, weakly or non-informative hyper-parameters were used as prior distributions.

Because of the structure of the model, directly sampling from the Dirichlet distribution was not possible. Therefore, a beta distribution was used according to the following steps to sample $P = \{p_i, ..., p_n\}$ values from Dirichlet distribution (Gelman et al., 2004). First using $Beta(a_1, \sum_{i=2}^k a_i)$ distribution p1 was generated, then $p_2, ..., p_{n-1}$ were simulated using $p_j =$ $(1 - \sum_{i=1}^{j-1} \theta_i)\phi_j$, where ϕ_j was sampled from $Beta(a_j, \sum_{i=j+1}^n a_i)$ distribution. Finally, p_n was calculated as $p_k = 1 - \sum_{i=1}^{n-1} p_i$.

It is not possible to obtain posterior distribution functions directly, as the joint posterior of all parameters is complex and high-dimensional. However, the Bayesian un-mixing model defined above can be analyzed using Markov Chain Monte Carlo (MCMC) modelling, and the parameters can be derived using the WinBUGS package (Lunn et al., 2000). The model was run 20,000,000 times from the posterior distribution and the first 5,000,000 runs were considered as burn in. The model convergence during the runs was assessed by monitoring the trace plots of generated values (Gholami et al., 2017b).

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208 2.5 Performance assessment of Bayesian un-mixing model

The goodness of fit (GOF) was used to evaluate the Bayesian un-mixing model performance according to Collins et al, (2012), and was calculated as follows:

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$$GOF = 1 - \frac{1}{n} * \sum_{i=1}^{n} \left[\frac{(B_i - \sum_{i=1}^{m} A_j \cdot X_{j.i})}{B_i} \right]^2$$
 (eq. 2)

Where B_i indicates concentration of optimum fingerprint property (*i*) in the dune field samples; A_j is mean concentration of optimum fingerprint property (*i*) in source category (*s*); X_{j,i} indicates optimized percentage contribution from potential source category (*s*); *n* is number of optimum fingerprints (in this research, *n*=4); and *m* is number of potential sources for dune field samples (in this study, *m*=4).

217 **3. Results**

218 3.1 Discrimination sources of aeolian sediments

Results of the two-stage statistical procedure are showed in Tables 1 and 2. Table 1 presents the results of the Kruskal-Wallis *H*-test, which was used to assess the ability of the tracer properties to discriminate the four potential sources including Q_s , Q_{ab} , Q_t and Q_c . The Kruskal-Wallis *H*-test (stage 1) showed that all of the 10 tracer properties could discriminate four potential sources at the 99% level of confidence (Table 1).

Table 1. Kruskal-Wallis *H*-test results for selecting fingerprints to distinguish potential aeolian
 sediment sources in the Jazmurian plain.

Tracers	Ni	Cu	Co	Cr	Ga	Mn	Р	Ba	Sr	Li
Chi-Square	40.9	40.6	39.3	40.8	40.2	34.4	39.3	18.3	39.7	41.7
Sig	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*

226 * Statistically significant at p < 0.01

complex which lies unconformably to the south of the Jazmurian plain, whereas the commonlyassociated nickel and cobalt are more likely attributable in origin to the metamorphic Deyader complex, also to the south (McCall, 2002). Lithium, meanwhile, is most abundant at the earth's surface as evaporite minerals associated with closed basins such as the Jazmurian plain, and its significance as a tracer probably relates to its ability to discriminate more local contributions.

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Table 2. Stepwise DFA results for selecting the optimum fingerprints.

Step	Optimum fingerprint	Wilks lambda	<i>p</i> -value
1	Cr	178.9	< 0.001
2	Li	55.1	< 0.001
3	Ni	37.8	< 0.001
4	Со	30.2	< 0.001

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The stepwise DFA was able to correctly classify 81% of the variance between the potential source samples. Although stepwise DFA results suggested that good source discrimination was achieved, samples collected from Q_s shown slightly overlap with the Q_{al} source samples when the first and second functions were plotted (Figure 2).



Figure 2. Two-dimensional scatter plot constructed from the first and second discriminant functions calculated using the stepwise DFA in association with the stepwise selection of the optimum fingerprints for discriminating potential sources of aeolian sediments in the Jazmurian plain, south of Kerman, Iran. Scatter plot shows distribution of samples collected from four

potential sources including Q_s , Q_{al} , Q_t and Q_c in the Jazmurian Plain. The stepwise DFA selected four optimum fingerprints (Cr, Li, Ni and Co) that provided a good discrimination between potential sources with 81% samples correctly classified in the four sources.

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268 3.2 Apportionment source of aeolian sediments by the Bayesian un-mixing model

Uncertainty ranges of main source contribution of aeolian sediments were estimated by the 269 Bayesian un-mixing model with 95% confidence limits (Table 3, Figure 4). The Q_{al} unit (alluvial 270 271 and dry river-bed sources) was recognized as the main source to supply materials for sediment samples 1, 2, 3 and 6, with mean contributions of 37%, 36%, 29%, and 36%, respectively. For 272 273 sediment sample 4, Q_s is the main source with mean contributions of 29%. For sediment sample 5, Q_t was recognized as main source and contribution ranged between 1-72% (with mean 29%). 274 For sediment sample 7, about 33% of the materials came from the Q_{al} source (with contribution 275 range 2-78%). The mean contributions from Q_s as main source for sediment samples 8, 9 and 10 276 277 were 38% (with contribution range 2-82%); 35% (with contribution range 2-79%); and 27% (with contribution range 1-68%), respectively. For sediment samples 11 and 12, the Q_s was the main 278 source and its contribution ranges were 2-78% (with mean 34%) and 1-73% (with mean 31%), 279 280 respectively. For sediment samples 13 and 14, the Q_c was recognized as the main source and its contribution ranges were 6-65% (with mean 37%) and 7-64% (with mean 37%), respectively. In 281 282 the Bayesian model, the MC errors for all of aeolian sediment samples were less than 0.1% (Table 3), and the goodness of fit (GOF) values for 14 sediment samples ranged from 79% to 100% 283 (Figure 3). The level of the MC error deviation is within the range proposed by Ntzoufras (2009). 284

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Figure 3. Goodness of fit (GOF) calculated for solutions of the Bayesian un-mixing model for theaeolian sediment samples



Figure 4. Source contributions for the fourteen samples from Jazmurian erg, expressed as 95% confidence intervals around a median. Note the general homogeneity of the sediment, with only Jazmurian lake-bed sediments (Q_c) typically less common, although locally abundant; especially in samples at the northern margin of the erg. Background imagery courtesy of Google EarthTM.

			Standard	MC error			
Sediment	source	Mean %	deviation	(×10 ⁻⁴)	2.5%	median	97.5%
1	Qs	27	0.20	3.03	1	23	74
	Qal	36	0.23	3.29	2	33	82
	Qt	26	0.20	2.91	1	22	73
	Qc	11	0.10	1.43	0	8	38
2	Qs	22	0.18	2.60	1	18	65
	Qal	33	0.22	3.19	1	31	79
	Qt	26	0.20	2.84	1	21	71
	Qc	19	0.14	2.08	1	16	53
3	Qs	20	0.16	2.32	1	16	60
	Qal	29	0.20	2.79	1	26	72
	Qt	23	0.18	2.53	1	19	67
	Qc	28	0.17	2.42	2	27	64
4	Qs	29	0.20	2.84	1	27	72
	Qal	26	0.19	2.58	1	22	69
	Qt	27	0.19	2.74	1	23	71
	Qc	18	0.12	1.70	1	16	46
5	Qs	23	0.17	2.45	1	20	64
	Qal	25	0.18	2.46	1	21	66
	Qt	26	0.19	2.54	1	23	69
	Qc	26	0.15	2.02	2	26	57
6	Qs	25	0.19	2.77	1	21	70
	Qal	36	0.23	3.23	2	34	81
	Qt	26	0.20	2.83	1	22	72
	Qc	13	0.11	1.58	0	10	41
7	Qs	27	0.19	2.79	1	24	71
	Qal	33	0.21	2.92	2	31	78
	Qt	26	0.19	2.73	1	22	71
	Qc	14	0.11	1.48	1	12	41
8	Qs	36	0.23	3.38	2	34	81
	Qal	26	0.20	2.83	1	22	73
	Qt	28	0.21	2.99	1	24	75
	Qc	10	0.10	1.27	0	7	35
9	Qs	35	0.22	2.97	2	33	80
	Qal	26	0.20	2.77	1	22	72
	Qt	27	0.20	2.77	1	23	73
	Qc	12	0.10	1.39	0	9	37
10	Qs	28	0.19	2.77	1	25	69

Table 3: Uncertainty ranges (with 95% confidence limits) of source contributions for 14 aeolian
sediment samples analyzed by the Bayesian un-mixing model.

	Qal	25	0.19	2.69	1	22	68
	Qt	26	0.19	2.67	1	22	69
	Qc	21	0.13	1.92	1	20	50
11	Qs	34	0.22	3.13	1	32	79
	Qal	28	0.20	2.74	1	24	73
	Qt	27	0.20	2.79	1	24	73
	Qc	11	0.10	1.37	0	8	36
12	Qs	31	0.21	3.01	1	29	75
	Qal	26	0.19	2.85	1	22	70
	Qt	27	0.19	2.86	1	23	71
	Qc	16	0.11	1.64	1	14	43
13	Qs	22	0.16	2.31	1	20	61
	Qal	20	0.16	2.32	1	16	59
	Qt	23	0.17	2.37	1	19	64
	Qc	35	0.16	2.20	4	35	66
14	Qs	20	0.15	2.21	1	16	57
	Qal	25	0.18	2.62	1	22	65
	Qt	22	0.17	2.41	1	18	63
	Qc	33	0.16	2.26	4	34	64

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308 **4. Discussion**

The results of our study show that the 10 tracer properties were able to identify aeolian 309 sediment sources at the 99% level of confidence. By using the stepwise discriminant function 310 analysis, the number of tracers was reduced to four (Cr, Co, Ni and Li), yet these can still explain 311 312 up to 81% of the variance between the sediment sources. Based on these four fingerprinting tracers, 313 we applied a Bayesian un-mixing model to identify the relative contribution of the four potential sources to the aeolian sediment in the Jazmurian Plain, southeastern Iran. The performance of this 314 model, evaluated by using the GOF, ranged from 78% to 100%. The fact that a majority of the 315 316 GOF values was well above 80% suggested that the Bayesian model performed well in assessing 317 the sediment sources in our study area (Zhou et al., 2016; Haddadchi et al., 2013).

The results of this study are in sharp contrast to studies which identified both marked spatial variability in the contributions of sources (e.g. Dahmardeh Behrooz *et al.*, 2019), and spatial variability of provenance in depositional environments, even at a localized scale (Gholami et al 2017b). At Jazmurian, the sources of the aeolian sediment in our study area are very diverse and no single source area had a contribution >40%. Desiccation of lakes in arid and semiarid areas 323 may affect the frequency and intensity of aeolian sediment transport at local to global scales, and 324 numerous studies have associated lake-beds with sources of aeolian emissions. These are reported 325 from locations as diverse as Owens Lake, USA (Reheis et al, 2009), Hamoun lakes, Iran (Rashki et al, 2012; 2013a, b; Dahmardeh Behrooz et al., 2019), the Aral sea, Uzbekistan (Breckle et al, 326 2012), southern Africa (Prospero et al, 2002; and Mahowald et al, 2003), and Lake Eyre, Australia 327 (Baddock et al, 2009). Here, however, materials for only two or three sand field samples come 328 predominantly from the dried-bed of Jazmurian Lake (Q_c unit or mixture of clay and salt 329 materials), despite its extensive outcropping upwind of the erg (samples 13 and 14; sample 5 has 330 almost equal contributions from Q_c and Q_t). 331

Instead, this study shows the dunefield is supplied by a complex and diverse range of sources 332 333 (Figure 4), and that most samples, fluvial and alluvial sediments (Q_{al} unit), alluvial fan and terrace sediments (Q_t unit), and sand sheets (Q_s unit), often contributing almost equally within the bounds 334 335 of uncertainty, are the predominant sources for twelve of the samples studied. Sediments from the source area to Jazmurian erg are transported by winds that blow from the south and southeast 336 337 (Figure 1), where the sources are represented by a more proximal mixture of alluvial (Q_{al}) , lakebed sediments (Q_c) and sand sheets (Q_s) , with a more distal (~40 km) bajada of alluvial fans (Q_t) 338 339 bordering the Makran mountains to the south. Spatial patterning of sediment sources within the dunefield sediment sources is limited (Figures 4 and 5), and only the sediment associated with the 340 341 Jazmurian lake units (Q_c) show strong variance, being more abundant at the northern/western end of the erg. However, if the single largest mean contributions are considered (Figure 4), there is a 342 weak trend in the data for samples in the eastern edge of the erg to have alluvially-derived material 343 as the most abundant component, those to the center to have a more substantial component of sand-344 345 sheet derived sediments, and only those to the west containing larger contributions of lake-bed contributions. This observation likely reflects relatively local (km-scale) sediment sources and 346 pathways, as this pattern mirrors the nature of the substrate surrounding the erg, with outcropping 347 of lake-bed clays to the south-west, sand sheets to the south, and fluvial deposits to the south and 348 east (Figure 5a). However, the presence of a considerable alluvial fan (Qt) component in all 349 samples probably highlights the importance of a longer-distance transport component, over scales 350 of 10 - 100 km (Figure 1), as local outcroppings of such deposits are very rare. 351

The aeolian sediment system in this region is a complex and interlinked interplay of sediment pathways and stores, affected by periodic fluvial events, and not simply a case of sediment 354 deflating from an extensive ephemeral lake complex. Whilst the significance of dry fluvial and 355 alluvial materials as an aeolian sediment source is well reported (e.g. Cohen *et al.*, 2010; Du, Wu 356 & Tan, 2018), and Gholami et al., (2017b) revealed that Quaternary alluvial fans and terraces (alluvial sediments) are the main source of materials for sand fields in Yazd-Ardekan plain in 357 Central Iran. Here it is clear that almost all components of the landscape have the capacity for 358 aeolian sand mobilization at a range of scales. These findings are also in agreement with a recent 359 360 study by Ahmady-Birgani et al. (2018), which reported that simultaneous actions of alluvial, fluvial and aeolian processes provide the majority of materials to the newly-formed sand fields 361 associated with the desiccation of Lake Urmia in northwestern Iran. 362

It is worth considering noting that the age of the dunes at Jazmurian erg is unknown, and that 363 absolute ages of Quaternary sediments from southern Iran are in general sparse. However, the 364 dunes remain active within recent years (Figure 5b and 5c), with at least surficial mobilization of 365 sands reshaping the surface of the dunes and interdunes. Where such longer records do exist, either 366 in terms of dated terrestrial sequences (Kehl, Frechen & Skowronek, 2005; Kehl, Frechen & 367 Skowronek, 2009; Rashidi et al., 2019), or the recent lacustrine sequence from Jazmurian (Vaezi 368 et al., 2019), they reveal multiple periods of varying climate during the Late Quaternary, with 369 likely periods of increased hydrological stress even during the Holocene. It is thus possible that 370 371 not all source areas contribute equally to the dunefield contemporaneously, and that changing wind patterns on longer timescale may also contribute to the varied nature of the sands' origins. 372



Figure 5. Localized variance in the major source contributions to the sands of the dune field are 374 likely associated with spatio-temporal variance in local sources. a) The dominant component of 375 the target samples, whilst never markedly more than other contributions, does seem to relate to 376 377 shorter distance transport with some east-west variance evident across the erg. b) The dunefield's modern activity is evident by comparison with an image (courtesy of Google EarthTM) from March 378 2011, revealing bright interdunes, presumably rich with evaporites, with c) a comparable image 379 from March 2012, showing the interdunes buried beneath blown sand. To the west of this image, 380 fields are similarly covered, and dune crests in the southeast corner have moved on the order of 381 ~10 m. 382

383 384 In terms of managing land degradation, this study highlights the potential for using sediment provenancing studies to better inform potential land management of aeolian desertification, and 385 crucially, highlights the need to make such assessments on a site-by-site basis. The Jazmurian erg 386 387 is adjacent to a large dryland lake system, which serves as the terminal basin for local hydrological 388 activity across a sand-rich landscape, and which varies in extent on a range of timescales and is 389 thus associated with extensive deposition of lacustrine sediments and evaporites. It might seem 390 tempting to immediately ascribe that as the dominant source of aeolian sediments for Jazmurian erg (e.g., Gill, 1996). Yet establishing the provenance of the sediments of Jazmurian erg has 391 392 revealed that the sands of the dunes are from a wide range of local sources, with substantial contributions from all major local landscape elements. This includes both short (km-scale) and 393

longer (10-100 km scale) contributions; focusing on managing the lake-bed's contribution would
be to overlook the majority of actual source material. Mitigation efforts to minimize aeolian
desertification at Jazmurian need to focus on a holistic approach to sand stabilization.

397 5. Conclusions

Sediment fingerprinting is an effective tool to quantify source contribution of aeolian 398 399 sediments. Results of our study show that aeolian, fluvial and alluvial processes are the main sediment supplier's for dune fields in the Jazmurian plain of Iran. Like other modeling methods, 400 401 results produced by fingerprinting method are associated with uncertainties. Therefore, quantifying uncertainty related to source contribution of aeolian sediment is essential for 402 403 environmental management. Here, we introduced a novel Bayesian un-mixing model to quantify uncertainties associated with source contribution of aeolian sediments. The performance of the 404 revised model was satisfactory, as suggested by GOF. 405

Our study found that the sediment sources for the Jazmurian erg are diverse and likely 406 407 represent complex, multiphase sediment pathways, with evidence for sand transport at a range of spatial scales. This finding, in contrast to other studies which have revealed sometimes singular 408 409 dominant landscape elements in terms of aeolian emissions, highlights the need investigate aeolian transport pathways on a site-by-site basis, as there is marked spatial and temporal variability in the 410 consistency of sediment pathways. This knowledge can inform mitigation strategies for the 411 protection of agricultural and other land uses. The fingerprinting method and the uncertainty 412 evaluation approach proposed by this study has the potential to be applied to other arid and 413 semiarid systems, where aeolian sediment transport is a concern for aeolian desertification, air 414 quality, human health, and nutrient cycling. 415

416 **Conflict of Interest**

417 The authors declare that there is no conflict of interests regarding the publication of this418 article.

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