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Southern African dust aerosols are rich in micronutrients, K-feldspar and carbonate minerals

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List of Abbreviations

AMMA = African Monsoon Multidisciplinary Analysis (2006), special observation period 0 (SOP0), Niger (Rajot et al., 2008); special observation periods 1 and 2 (SOP1-2), West Africa (Reeves et al., 2010).

DABEX = Dust And Biomass-burning Experiment (2006), Niger (Haywood et al., 2008)

DODO = Dust Outflow and Deposition to the Oceans (2006), Senegal (McConnell et al., 2008)

FENNEC = The Saharan Climate System (2010−2012), West Africa (Washington et al., 2012)

GERBILS = Geostationary Earth Radiation Budget Intercomparisons of Longwave and Short−wave radiation (2007), Mauritania, Mali, and Niger (Haywood et al., 2011)

CESAM = Multiphase Atmospheric Experimental Simulation Chamber (Wang et al., 2011)

GAMEL = Générateur d'Aérosol Minéral En Laboratoire (Lafon et al., 2014)

Aus = Australia

NAf = Northern Africa

SAf = Southern Africa

SAm = Southern America

ICP-AES = Inductively Coupled Plasma–Atomic Emission Spectroscopy

ICP-MS = Inductively Coupled Plasma–Mass Spectrometry

XRF = X-ray Fluorescence

XRD = X-ray Diffraction

PIXE = Particle-Induced X-ray Emission

PIGE = Particle-Induced Gamma-ray Emission

SEM = Scanning Electron Microscopy

PM_{10} = Particles with an aerodynamic diameter less than 10 µm

$PM_{2.6}$ = Particles with an aerodynamic diameter less than 2.6 µm

PM_9 = Particles with an aerodynamic diameter less than 9 µm

TSP = Total Suspended Particles

Table S1. Summary of dust aerosol samples and analyses in this study. For the sample collected along riverbed transects at ~100 m intervals, the reported coordinate represents an approximate central location of the transect.

Sample ID	Location	Latitude	Longitude	Generation	Available analyses
Kuiseb	Kuiseb River	-23.563063	15.039235	GAMEL	XRF, XRD
Hope-Mine	Hope Mine	-23.5713	15.25013	GAMEL	XRF, XRD
GB-WF	Namib GP	-23.4509	15.03569	GAMEL	XRF, XRD
Etosha-West	Etosha Pan	-19.1249	15.97	GAMEL	XRF, XRD
233-TRP	Skukuza	-24.9948	31.5887	GAMEL	XRF, XRD
232-TRP	Skukuza	-24.9948	31.5887	GAMEL	XRF, XRD
199-KAL	Kalahari BOT	-26.8248	20.67703	GAMEL	XRF, XRD
184-BSW	Kalahari BOT	-18.3642	21.84194	GAMEL	XRF, XRD
179-BSW	Kalahari BOT	-20.9767	22.48	GAMEL	XRF, XRD
MS-AGR	Free State	-28.21	26.15	GAMEL	XRF, XRD
HUAB_H123	Huab River transect	-20.86	13.65	CESAM	XRF
HUAB_H125	Huab River transect	-20.86	13.65	CESAM	XRF
HUAB_H127B	Huab River transect	-20.86	13.65	CESAM	XRF
HUAB_H127A	Huab River transect	-20.86	13.65	CESAM	XRF, XRD
HUAB_H129	Huab River transect	-20.86	13.65	CESAM	XRF, XRD
HUAB_H130	Huab River transect	-20.86	13.65	CESAM	XRF
HUAB_H131	Huab River transect	-20.86	13.65	CESAM	XRF, XRD
HUAB_H132	Huab River transect	-20.86	13.65	CESAM	XRF
HUAB_H133	Huab River transect	-20.86	13.65	CESAM	XRF, XRD
HUAB_H135	Huab River transect	-20.86	13.65	CESAM	XRF, XRD
HUAB_H139	Huab River transect	-20.86	13.65	CESAM	XRF
HUAB_H141	Huab River transect	-20.86	13.65	CESAM	XRF
HUAB_H143	Huab River transect	-20.86	13.65	CESAM	XRF
K89_AERO	Kuiseb River transect	-23.18	14.65	CESAM	XRF
K99_AERO	Kuiseb River transect	-23.18	14.65	CESAM	XRF
K103_AERO	Kuiseb River transect	-23.18	14.65	CESAM	XRF
K105_AERO	Kuiseb River transect	-23.18	14.65	CESAM	XRF
K109_AERO	Kuiseb River transect	-23.18	14.65	CESAM	XRF
K111_AERO	Kuiseb River transect	-23.18	14.65	CESAM	XRF
K113_AERO	Kuiseb River transect	-23.18	14.65	CESAM	XRF
K115_AERO	Kuiseb River transect	-23.18	14.65	CESAM	XRF
OMANN_O40	Omaruru River transect	-22.03	14.35	CESAM	XRF
OMANN_O44	Omaruru River transect	-22.03	14.35	CESAM	XRF
O46_AERO	Omaruru River transect	-22.03	14.35	CESAM	XRF
OMANN_O46	Omaruru River transect	-22.03	14.35	CESAM	XRF
OMANN_O51	Omaruru River transect	-22.03	14.35	CESAM	XRF
O51_AERO	Omaruru River transect	-22.03	14.35	CESAM	XRF

OMANN_O65	Omaruru River transect	-22.03	14.35	CESAM	XRF
OMANN_O67	Omaruru River transect	-22.03	14.35	CESAM	XRF
O67_AERO	Omaruru River transect	-22.03	14.35	CESAM	XRF
OMANN_O69	Omaruru River transect	-22.03	14.35	CESAM	XRF
OMANN_O71	Omaruru River transect	-22.03	14.35	CESAM	XRF
OMANN_O73	Omaruru River transect	-22.03	14.35	CESAM	XRF
OMANN_O75	Omaruru River transect	-22.03	14.35	CESAM	XRF

Table S2. Summary of data sources included in the integrated dataset of elemental composition and mineralogy of mineral dust.

Region	Reference	Study Area	Aerosol Collection	size	Data Type	Analytical technique
SAf	This study	Central Namib Gravel Plain; Western Kalahari; Etosha Pan, Huab, Omaruru, and Kuiseb riverbeds; savannah soils in South Africa; agricultural soils in the Free State; mining dust from Namibia	Laboratory soil-derived	PM_{10}	Elemental composition, Mineralogy	XRF; XRD
	Di Biagio et al. (2017)	Central Namib Gravel Plain	Laboratory soil-derived	PM_{10}	Elemental composition, Mineralogy	XRF; XRD
	Eltayeb et al. (1993)	Central Namib Gravel Plain	Laboratory soil-derived	$PM_{2.6}$	Elemental composition	XRF
	Engelbrecht et al. (2016)	Etosha Pan; Makgadikgadi Pans; Nxai Pan	Laboratory soil-derived	PM_{10}	Elemental composition	XRF
	Humphries et al. (2014)	Okavango Delta	Ground-based, near source	TSP	Elemental composition	XRF
	Qu (2016)	Central Namib Gravel Plain; Western Kalahari	Laboratory soil-derived	PM_{10}	Elemental composition	XRF
Aus	Box et al. (Jan 27-29 2010)	Lake Eyre Basin	Ground-based, transported	TSP	Elemental composition	PIXE and PIGE
	Di Biagio et al. (2017)	Lake Eyre Basin	Laboratory soil-derived	PM_{10}	Elemental composition, Mineralogy	XRF; XRD
	Engelbrecht et al. (2016)	Lake Eyre Basin	Laboratory soil-derived	PM_{10}	Elemental composition	XRF
	Moreno et al. (2008)	Lake Eyre Basin	Laboratory soil-derived	PM_{10}	Elemental composition	ICP-AES; ICP-MS
	Radhi et al. (2010a, 2010b)	Lake Eyre Basin	Ground-based, near source	TSP	Elemental composition	PIXE and PIGE
	Karlson et al. (2014)	Lake Eyre Basin; Northwestern Australia	Ground-based, near source and transported	TSP	Elemental composition	PIXE and PIGE
SAm	Demasy et al. (2024)	Patagonia	Laboratory soil-derived	PM_{10}	Elemental composition	ICP-MS
	Di Biagio et al. (2017)	Patagonia; Atacama Desert	Laboratory soil-derived	PM_{10}	Elemental composition, Mineralogy	XRF; XRD
	Engelbrecht et al. (2016)	Atacama Desert	Laboratory soil-derived	PM_{10}	Elemental composition	XRF
	Gaiero et al. (2007); (2003)	Patagonia	Ground-based, transported	TSP	Elemental composition	ICP-AES; ICP-MS
	Qu (2016)	Patagonia	Laboratory soil-derived	PM_{10}	Elemental composition	XRF

	Rojas et al. (1990)	Atacama Desert; Remote sites across Argentina, Bolivia, and Brazil	Ground-based, near source	TSP	Elemental composition	XRF
NAf	Di Biagio et al. (2017)	Sahara Desert; Sahel; Bodélé Depression	Laboratory soil-derived	PM_{10}	Elemental composition, Mineralogy	XRF; XRD
	Engelbrecht et al. (2016)	Sahel; Bodélé Depression; Lake Iriki	Laboratory soil-derived	PM_{10}	Elemental composition	XRF
	Formenti et al. (2014)	West Africa (AMMA-SOP-1/2); Niger (AMMA-SOP0; DABEX); Senegal (DODO); Mauritania, Mali, Niger (GERBLIS)	Aircraft, near source; Ground-based, near source	PM_9; PM_{10}	Elemental composition, Mineralogy	PIXE; XRD
	Formenti et al. (2011)	West Africa (AMMA-SOP-1)	Ground-based, near source	PM_9	Elemental composition	XRF
	Formenti et al. (2008)	Niger (AMMA-SOP0, DABEX); Senegal (DODO)	Aircraft, near source; Ground-based, near source	PM_{10}	Elemental composition, Mineralogy	PIXE; XRD
	Klaver et al. (2011)	Mauritania, Mali, Niger (GERBLIS)	Aircraft, near source	PM_{10}	Elemental composition, Mineralogy	PIXE; XRD
	(Ryder et al., 2015)	West Africa (FENNEC)	Aircraft, near source	PM_{10}	Elemental composition	SEM

Table S3. Location and references to the integrated dataset on SAf dust chemical tracers. Atmospheric observations are included for comparison.

Location ID	Description	References
Namib GP	Central Namib Gravel Plain, western Namibia.	This study; Di Biagio et al. (2017); Qu (2016)
Kalahari NAM	Western Kalahari, central Namibia	Qu (2016)
Kalahari BOT	Southwestern Kalahari, southwestern Botswana. Areas of the Kalahari north and south of the Okavango Delta, northwestern Botswana	This study
Salt Pans	Etosha Pan, northern Namibia. Makgadikgadi and Nxai Pans, northeastern Botswana	This study (Etosha Pan only); (Engelbrecht et al., 2016).
Coastal rivers	Ephemeral riverbeds on the Namibian coast, including Huab, Omaruru, and Kuiseb rivers	This Study
Skukuza	Savannah soils at Skukuza in the Kruger National Park, South Africa	This Study
Hope Mine	Abandoned copper mine, central western Namibia	This Study
Free State	Agricultural soils in the Free State	This Study
Henties Bay – Dust mixed aerosols	Atmospheric aerosols over the Namibian coast	Desboeufs et al. (2024); Formenti et al. (2025); Klopper et al. (2020)
SA Highveld – Dust mixed aerosols	Atmospheric aerosols over the South African Highveld, an inland urban-industrial environment	Baldo et al. (2025)

Table S4. Summary statistics of elemental enrichment factors in mineral dust across Southern Africa, Australia, Southern America, and Northern Africa. Data source references are provided in Table S2.

Region	Element	N total	Mean	Median	sd	25th percentile	75th percentile	Min	Max
SAf	Si	72	1.39	0.74	2.64	0.67	1.00	0.45	18.36
	Mg	70	7.20	1.98	18.45	1.16	4.71	0.31	109.52
	K	70	1.80	1.17	1.99	1.06	1.78	0.00	12.49
	Ca	72	7.02	1.27	16.13	0.82	4.61	0.00	96.39
	Fe	72	1.69	1.62	0.92	1.20	1.71	0.93	7.03
	Mn	63	2.82	1.88	3.67	0.95	3.13	0.00	18.33
	P	63	2.55	1.70	1.87	1.11	3.34	0.64	7.34
	Na	63	0.62	0.35	2.06	0.17	0.57	0.00	16.55
	Ti	70	2.11	1.54	1.20	1.37	2.89	0.00	6.16
Aus	Si	49	1.25	0.82	1.85	0.67	0.97	0.37	12.54
	Mg	12	0.62	0.53	0.40	0.36	0.64	0.28	1.74
	K	16	0.75	0.82	0.41	0.38	0.92	0.23	1.75
	Ca	21	0.56	0.46	0.52	0.30	0.63	0.09	2.38
	Fe	57	1.87	1.75	0.75	1.35	2.24	0.52	4.74
	Mn	49	2.73	1.66	2.98	1.16	3.16	0.12	18.22
	P	9	0.89	0.83	0.21	0.77	0.98	0.60	1.28
	Na	13	0.37	0.12	0.63	0.05	0.19	0.03	2.25
	Ti	52	1.59	1.19	1.02	0.82	2.33	0.32	4.09
NAf	Si	508	0.65	0.64	0.12	0.60	0.70	0.15	1.49
	Mg	508	0.70	0.63	0.39	0.42	0.88	0.00	2.63
	K	508	0.60	0.60	0.27	0.46	0.71	0.00	1.88
	Ca	508	1.00	0.75	1.37	0.28	1.30	0.00	18.87
	Fe	508	1.25	1.24	0.33	1.15	1.35	0.00	4.72
	Mn	10	2.40	1.72	1.69	1.57	2.53	0.96	6.46
	P	501	1.20	1.23	0.61	1.00	1.47	0.00	6.64
	Na	501	0.16	0.02	0.49	0.00	0.16	0.00	8.89
	Ti	508	1.95	1.92	0.81	1.62	2.24	0.00	9.26
SAm	Si	160	1.05	1.00	0.25	0.91	1.22	0.29	2.11
	Mg	152	1.54	1.30	1.01	0.94	2.14	0.00	5.76
	K	152	1.37	1.37	0.44	1.11	1.51	0.51	3.23
	Ca	160	1.89	1.44	1.75	1.07	1.91	0.15	12.43
	Fe	161	1.26	1.19	0.72	1.05	1.32	0.43	9.65
	Mn	151	2.36	1.30	3.42	0.47	2.96	0.00	26.39
	P	137	6.74	5.82	4.86	4.86	6.96	1.40	53.89

	Na	151	0.77	0.78	0.41	0.58	0.95	0.00	2.21
	Ti	152	4.12	4.06	1.59	3.44	4.89	1.06	16.57

Table S5. Summary statistics of key mineral components in mineral dust across Southern Africa, Australia, Southern America, and Northern Africa. Data source references are provided in Table S2.

Region	Mineral	N total	Mean	Median	sd	25th percentile	75th percentile	Min	Max
SAf	Quartz	18	13	10	10	7	14	0	37
	Clays	18	62	61	14	57	70	21	87
	Carbonates	18	8	4	18	0	4	0	78
	Feldspars	18	15	16	13	2	26	0	34
Aus	Quartz	1	34	34	-	34	34	34	34
	Clays	1	57	57	-	57	57	57	57
	Carbonates	1	0	0	-	0	0	0	0
	Feldspars	1	6	6	-	6	6	6	6
NAf	Quartz	61	12	10	8	7	13	1	41
	Clays	61	84	87	11	84	91	49	96
	Carbonates	61	2	1	5	0	2	0	26
	Feldspars	61	1	1	2	0	1	0	14
SAm	Quartz	2	26	26	22	18	34	11	42
	Clays	2	60	60	13	56	65	51	69
	Carbonates	2	6	6	9	3	9	0	12
	Feldspars	2	6	6	0	6	6	6	6

S1. Data processing of aerosol size distribution measurements.

The experiments conducted with GAMEL and CESAM employ different generation methods and instrumentation setups, necessitating distinct data-processing approaches.

For GAMEL experiments, the size-distribution data were converted into volume distributions ($\pi/6 \cdot D^3 \cdot dN/dlogD$), where D is the particle diameter measured by the instrument. To allow comparison between samples while accounting for differences in dust-generation efficiency among soils, data were retained only for the first 3 minutes of dust generation, normalised so that the integral equals 1 over a common diameter range (the full diameter range measured by the GRIMM), and averaged. Repeated experiments on the same soil samples under the same shaking conditions were averaged.

For the CESAM experiments, the protocol for data reduction to obtain the aerosol dust size distribution is established as part of the CESAM procedures and is described in detail elsewhere (Di Biagio et al., 2019; Di Biagio et al., 2017). The first step of the procedure converts the working diameters of the SMPS, GRIMM, and WELAS instruments (which are, respectively, electrical mobility and optical diameters) into a sphere-equivalent geometric diameter (D_g). Di Biagio et al. (2019) have shown that the correction factor for the optical particle counters (OPCs, WELAS and GRIMM) is less sensitive to the complex refractive index in the range of values expected for mineral dust in the visible and near-infrared. In this study, we assume an average refractive index of 1.53 + 0.004i for both the WELAS and the GRIMM, yielding estimated Dg values of 0.65-73.0 µm for the WELAS and 0.29-68.2 µm for the GRIMM. The average dry aerodynamic shape factor required to convert the electrical mobility diameter measured by the SMPS to geometric diameter is 1.2, which best matches the SMPS number size distribution with those of the GRIMM or WELAS in their overlap range. The aerosol dust number size distribution between 10 nm and 73 µm can then be obtained by combining the number size distributions measured by the different probes. For these experiments, the GRIMM is preferred over the WELAS for particles smaller than approximately 800 nm due to its higher counting efficiency. Due to size-dependent particle losses in the sampling lines, the measured number size distributions are reduced in size range from 0.01 to 23.7 µm, which is consistent with previous work (Baldo et al., 2023; Caponi et al., 2017; Di Biagio et al., 2019). For comparison with GAMEL, only measurements collected shortly after the dust injection peak in CESAM were retained, as larger particles are rapidly lost by gravitational settling. The data were converted to volume distributions, normalised so that the integral equals 1 over a common diameter range, averaged, and interpolated using the "smooth.spline" function from the core CRAN R software to obtain values over a consistent diameter range, matching the GAMEL experimental data.

S2. Data source for the rainfall map of Southern Africa

The rainfall map of Southern Africa is derived from the Climate Hazard Group InfraRed Precipitation with Stations dataset version 3 (CHIRPS3, 2025). This dataset integrates satellite-based thermal infrared rainfall estimates with ground-based observations, at a spatial resolution of 0.05° by 0.05°, covering the global domain and including additional sub-domain datasets. It contains long-term rainfall records from 1981 to the near present, with temporal resolutions ranging from daily to annual. For our analysis, we used ten years of annual rainfall data for the Africa sub-domain product from 2015 to 2024.

S3. Principal component analysis of key elemental ratios

We conducted a Principal Component Analysis (PCA) of our integrated dataset, which included the elemental ratios (Ca+Mg)/Al, K/Al, Si/Al, and Fe/Al measured in this study, as well as data from the literature. Observations from salt pans with distinctive features were excluded because they dominated the PCA and reduced variation among other samples. PCA was conducted using the prcomp() function from core CRAN R software.

The results are shown in Fig. S7. The first two principal components account for around 75% of the variance. Principal Component 1 (PC1) was predominantly associated with the ratios K/Al and (Ca+Mg)/Al, which are nearly orthogonal to Si/Al and Fe/Al, the latter primarily associated with Principal Component 2 (PC2).

Source regions occupy distinct positions in PCA space. The Namib GP and Kalahari NAM clusters intersect and are distributed across quadrants I and IV, near the (Mg+Ca)/Al and K/Al vectors, suggesting these samples have higher (Mg+Ca)/Al and K/Al ratios and may be associated with weakly weathered material rich in carbonate and primary aluminosilicate minerals, as represented by PC1. The Kalahari BOT sample, agricultural dust from the Free State, and savannah samples from Skukuza, grouped as Eastern source areas, cluster in quadrant II, near the Si/Al and Fe/Al vectors, indicating higher Si/Al and Fe/Al ratios, which could be linked to more weathered source soils rich in silica and Fe oxide, as represented by PC2. Hope Mine shows characteristics similar to those of the Eastern source cluster. The riverbed samples are concentrated in a narrow group within quadrant III, showing minimal variation along PC1 but a wider distribution along PC2 in the opposite direction to the Si/Al and Fe/Al vectors. This indicates lower Si/Al and Fe/Al ratios, suggesting weaker weathering compared to Eastern source areas.

Overall, these results further confirm that Si/Al, (Ca+Mg)/Al, and K/Al ratios can be used as mineral dust source tracers in southern Africa and can separate arid coastal sources from more humid, inland eastern source areas. Note that all anthropogenic sources are predominantly associated with PC2, which we attribute to more weathered source soil. Most of the source areas, except for Hope Mine, are located in more humid regions that have experienced greater weathering in the past and current climates. However, anthropogenic activities are concurrent and can also contribute to the processing of source soil and enhance weathering.

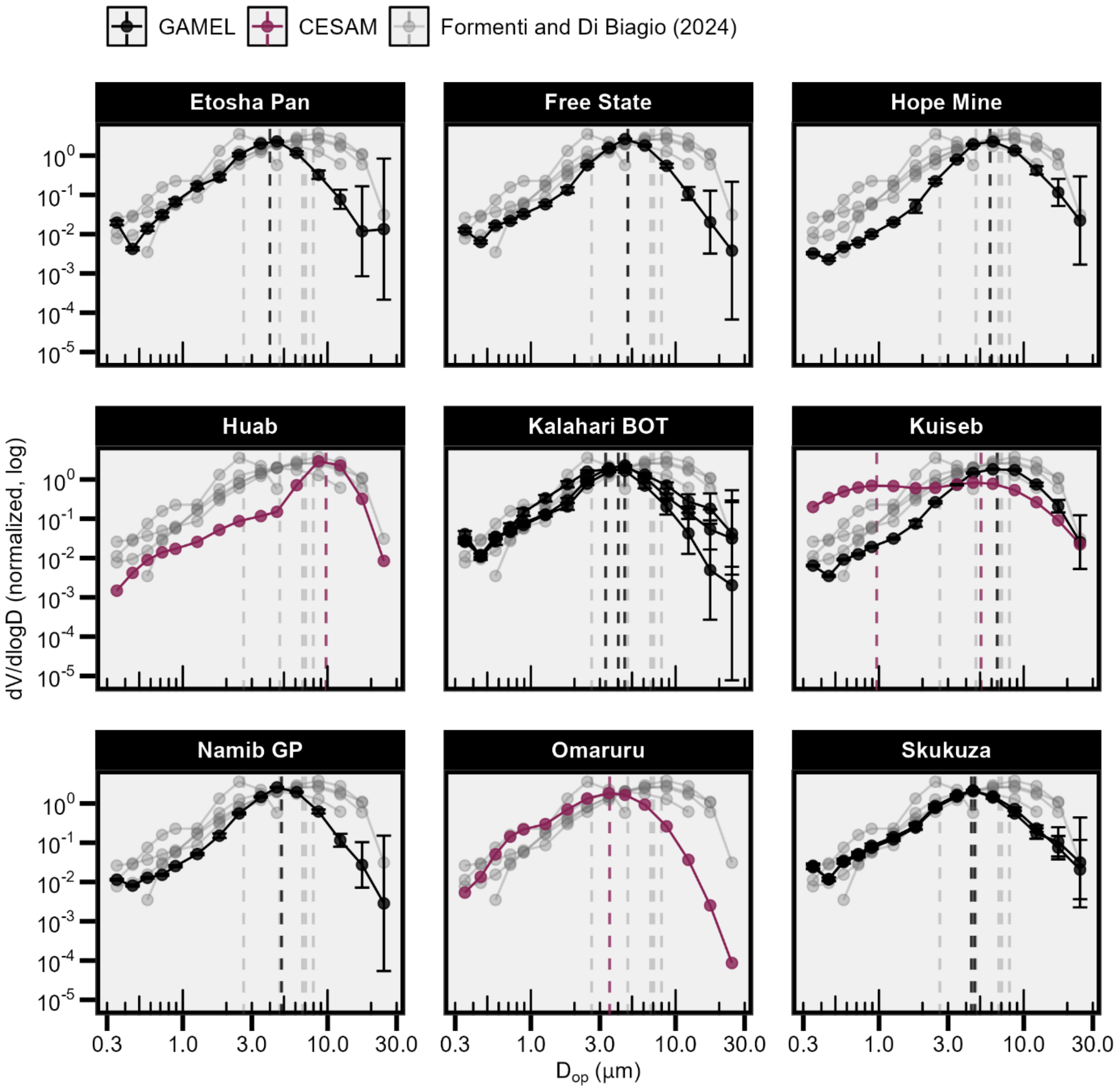

Figure S1. Size distribution data obtained during the laboratory generation of dust aerosols using GAMEL aerosol generator and the CESAM multiphase simulation chambers. Observations of PM_{10} and PM_{20} aerosols collected near source regions from the integrated dataset compiled by Formenti and Di Biagio (2024) (including Fratini et al., 2007; Gillette et al., 1974; Rajot et al., 2008; Shao et al., 2011; Sow et al., 2009) are shown for comparison. Data are reported as volume distributions (μm^3 cm^{-3}) normalised so that the integral equals 1 over a common diameter range. The dashed lines indicate the peaks of the single-mode log-normal fitted distributions. Only the aerosol sample generated in CESAM from Kuiseb River sediments exhibits an additional peak at 1 µm.

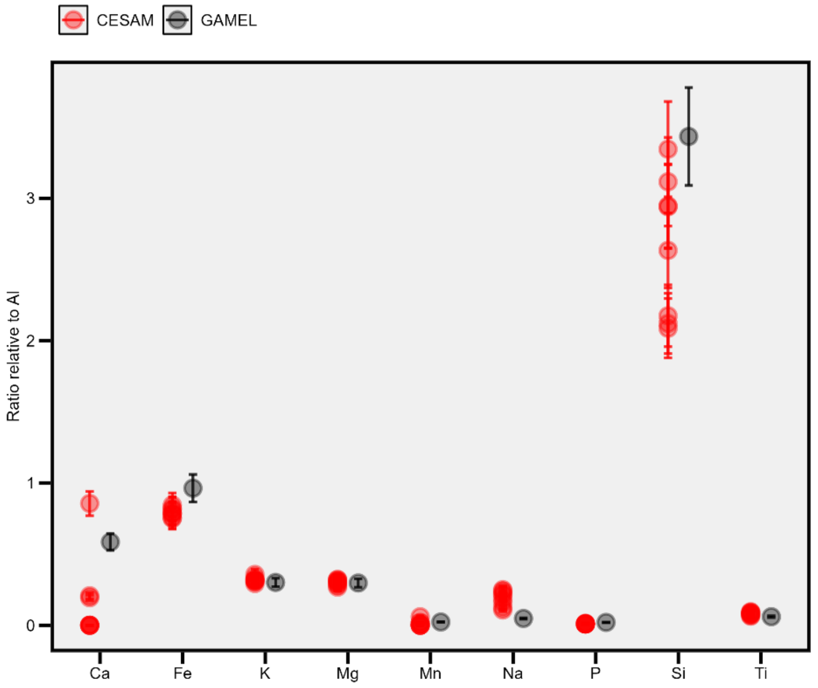

Figure S2. Elemental compositions of dust aerosols generated by CESAM and GAMEL from a similar soil type, using the Kuiseb riverbed sample. In red, the chemical composition of Kuiseb dust generated by CESAM, using different samples collected from a riverbed transect in the terminal reach, while in black, that of Kuiseb dust generated by GAMEL, using a riverbed sample collected at the Gobabeb Namib Research Centre. The elemental concentrations were normalised to Al to account for variations in the mass generated. The error bars represent a 10% uncertainty in XRF measurements

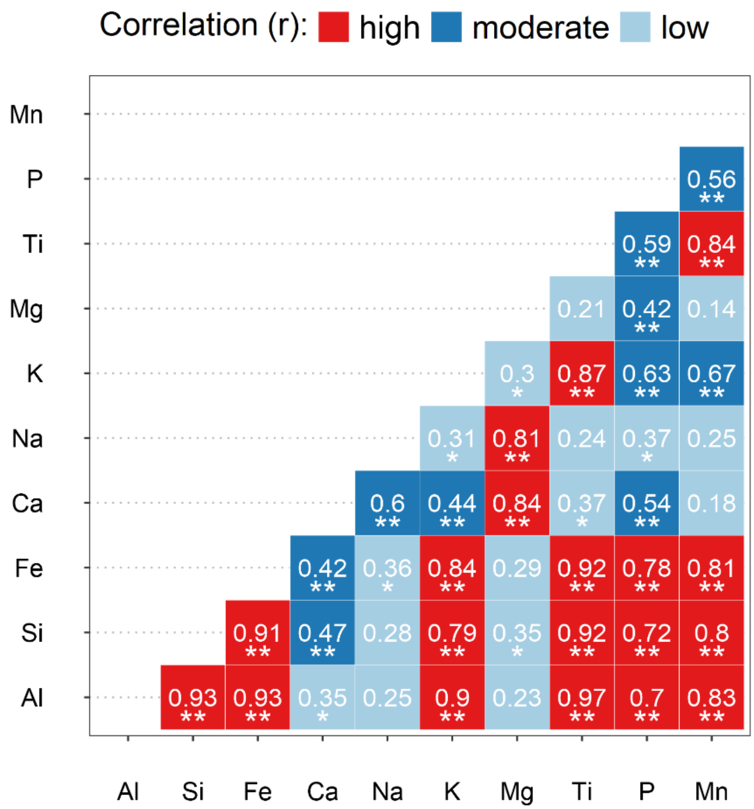

Figure S3. Correlations between crustal elements. The correlation matrix reports estimated r values from linear regression. Note that * indicates p-values ≤ 0.05, while ** indicates p-values ≤ 0.01.

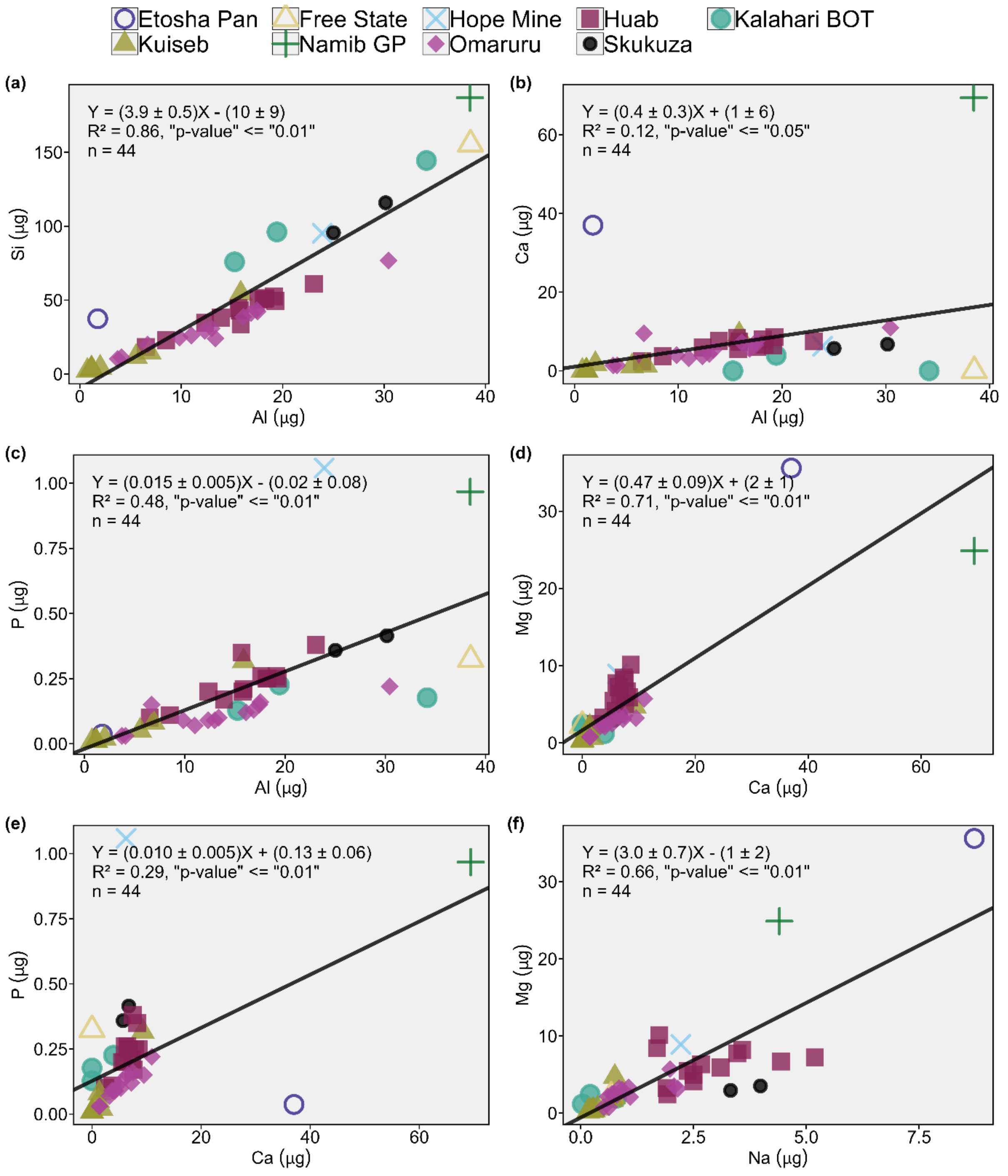

Figure S4. Key element correlations supporting the correlation matrix in Figure S2. The analysis includes all data points. Uncertainty in XRF measurements is 10%.

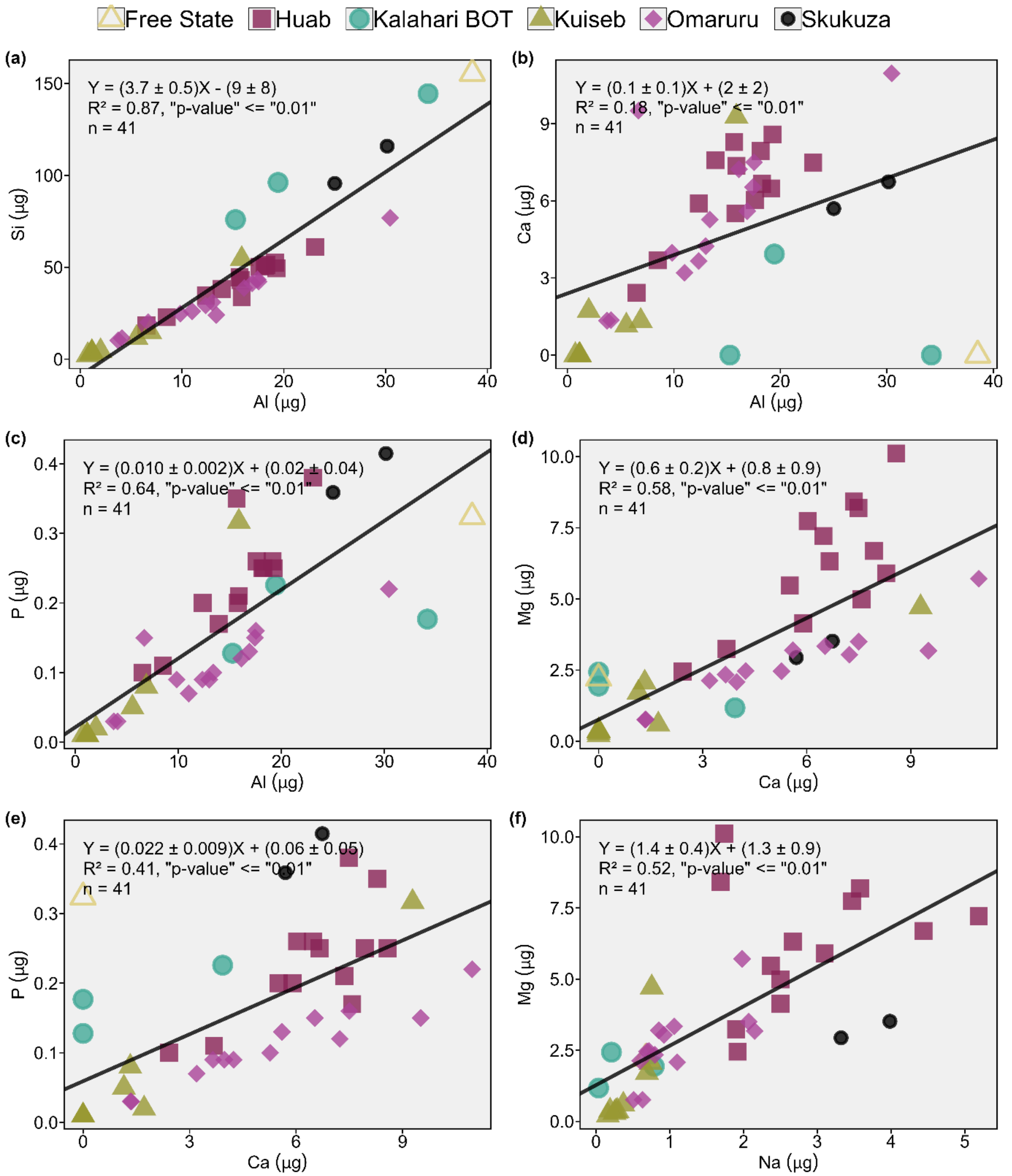

Figure S5. Key element correlations supporting the correlation matrix in Figure S2. Namib GB, Etosha Pan, and Hope Mine are not included. Key correlations are maintained even after removing extreme values. Uncertainty in XRF measurements is 10%.

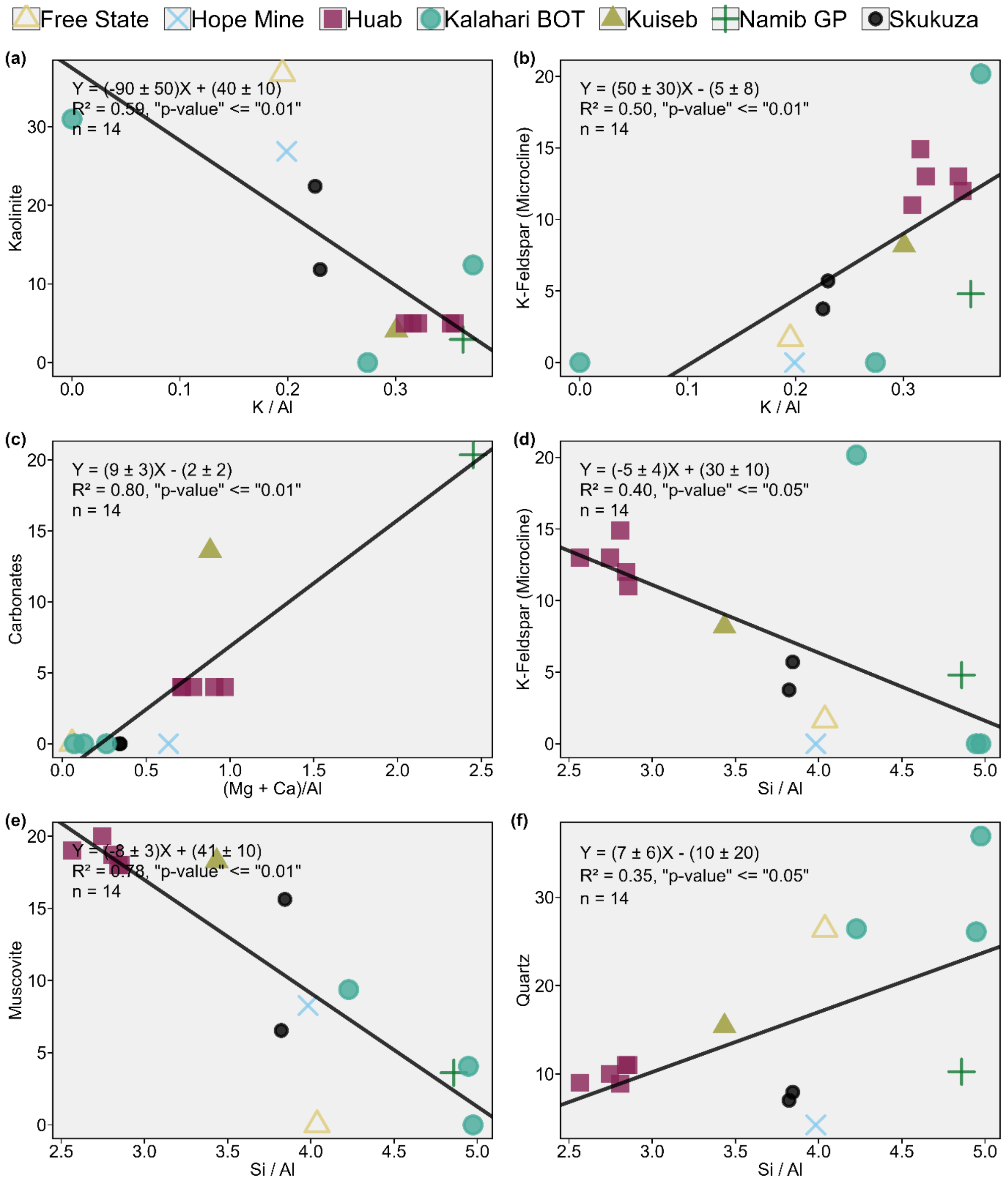

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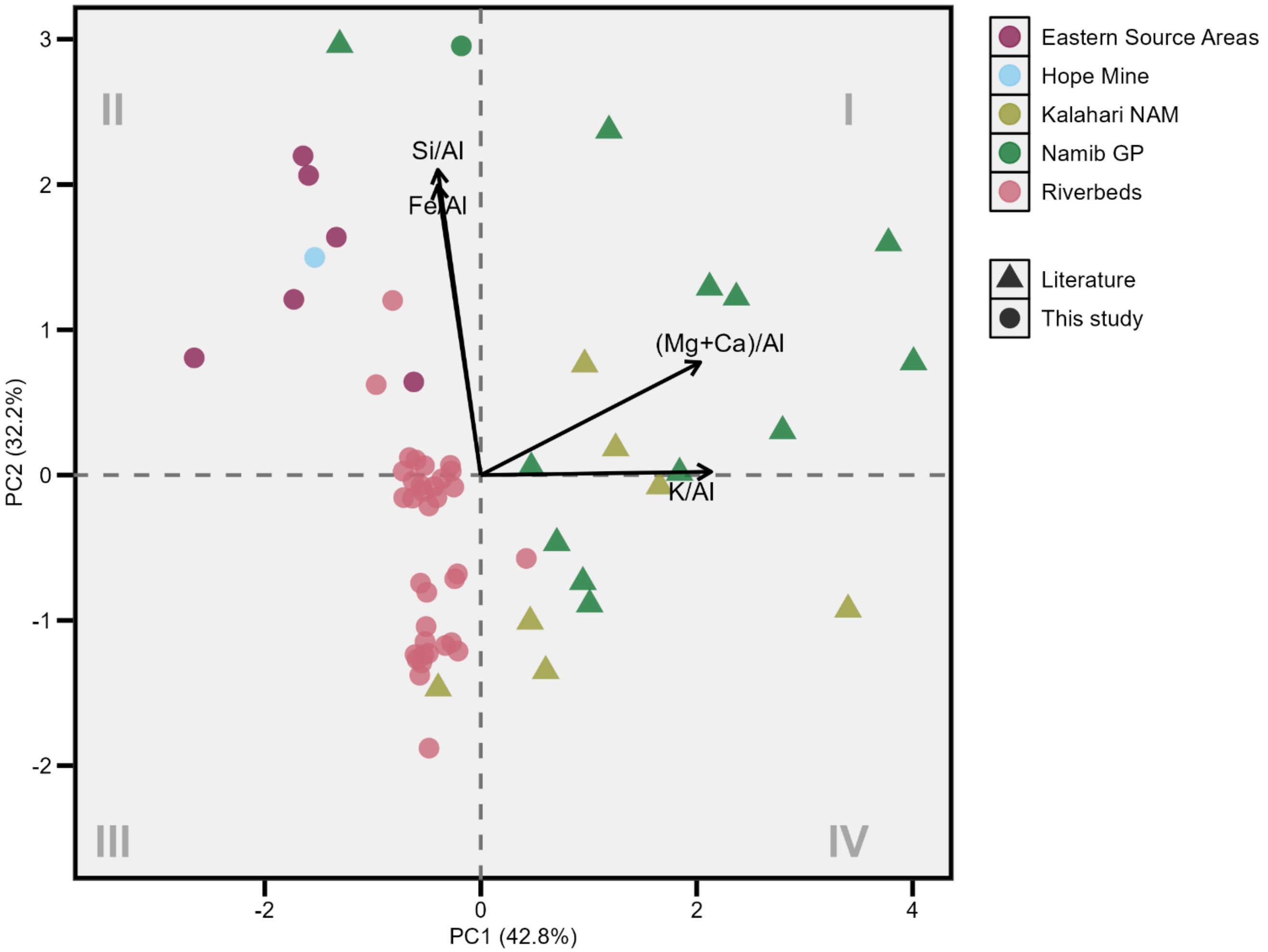
Figure S6. Correlations between key crustal element ratios and minerals. Note that Etosha Pan was excluded from the analysis because its composition significantly differs from the other dust samples. Uncertainty in XRF and XRD measurements is 10%.



140 **Figure S7. Principal Component Analysis (PCA) of key elemental ratios observed in Southern African dust aerosols. Namib GP data include this study, Di Biagio et al. (2017), and Qu (2016). Kalahari NAM data are from Qu (2016). The Kalahari BOT sample, agricultural dust from the Free State, and savannah samples from Skukuza were grouped as Eastern source areas. The PCA results are discussed in Sect. S3.**

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