



Physical and chemical properties of deposited airborne particulates over the Arabian Red Sea coastal plain

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Abstract

Mineral dust is the most abundant aerosol, having a profound impact on the Global energy budget. This research continues our previous studies performed on surface soils in the Arabian Peninsula and aims at analyzing mineralogical, physical and chemical composition of dust deposits from the atmosphere. For this purpose, aerosols deposited from the atmosphere are collected during 2015 at six sites on the campus of the King Abdullah University of Science and Technology (KAUST) situated on the Red Sea coastal plain of Saudi Arabia and subjected to the same chemical and mineralogical analysis we conducted on soil samples. Frisbee deposition samplers with foam inserts were used to collect dust and other deposits, for the period December 2014 to December 2015. The average deposition rate measured at KAUST for this period was 14 g m^{-2} per month, with lowest values in winter and increased deposition rates in August to October. XRD analysis of a subset of samples confirms variable amounts of quartz, feldspars, micas, and halite, with lesser amounts of gypsum, calcite, dolomite, hematite, and amphibole. Freeze-dried samples were re-suspended onto the Teflon[®] filters for elemental analysis by XRF, while splits from each sample were analyzed for water soluble cations and anions by Ion Chromatography. It is not possible to explicitly relate the origin of deposition samples to the Arabian Red Sea coastal soils, from the mineralogical and chemical results alone. It is proposed that the dust deposits along the Red Sea coast are a mixture of dust emissions from local soils, and soils imported from distal dust sources. These aerosol data are the first of their kind from the Red Sea region. They will help assess their potential nutrient input into the Red Sea, as well the impact on human health, industry, and solar panel efficiency. These data will also support dust modeling in this important dust belt source area, by better quantifying dust mass balance and optical properties of airborne dust particles.

Keywords

Dust mineralogy, chemistry, particle size distribution
Inverted Frisbee deposition samplers
Freeze-dry dust retrieval
Dust deposition, AOD and visibility



1. Introduction

Dust emission and deposition modeling and measurements are required for the assessment of the dust mass budget. Both emission and deposition are under constrained in atmospheric dust models, leading to large uncertainties (Bergametti and Forêt, 2014). To improve simulations, these authors
5 are, amongst others, suggesting the establishment of dust deposition networks in the vicinity of and away from dust source regions, operating throughout the year. In this paper we are presenting results from a network of dust deposition samplers located on the campus of the King Abdullah University of Science and Technology (KAUST) along the Red Sea coast of Saudi Arabia. This is an important dust source region, the effect of which extends thousands of kilometers downwind.
10 To better characterize optical, microphysical, and health effects of dust aerosols we have conducted detailed chemical and mineralogical analysis of deposition samples collected from atmosphere.

Mineral dust is the most abundant atmospheric aerosol, primarily from suspended soils in arid and semi-arid regions on Earth (Buseck et al., 2000; Washington and Todd, 2005; Goudie, 2006; Muhs
15 et al., 2014), including deserts of the Arabian Peninsula (Edgell, 2006). Dust aerosols profoundly affect climate, biogeochemical cycles in the ocean and over land, air-quality, atmospheric chemistry, cloud formation, visibility, and human activities (Bennett et al., 2006; Bennion et al., 2007; De Longueville et al., 2010; Fryrear, 1981; Hagen and Woodruff, 1973; Haywood and Boucher, 2000; Hsu et al., 2004; Jickells et al., 2005; Kumar et al., 2014; Mahowald, 2009;
20 Menéndez et al., 2017; Nihlen and Lund, 1995; Prospero et al., 2002; Sokolik and Toon, 1999; Twomey et al., 1984; Wang et al., 2010; Huang et al., 2006). The Arabian Peninsula is one of Earth's major sources of atmospheric dust, contributing as much as 11.8% (22–500 Mt a⁻¹) of the total (1,877–4000 Mt a⁻¹) global dust emissions (Tanaka and Chiba, 2006). The Red Sea, being enveloped by the Arabian and African deserts is strongly impacted by windborne mineral dust.
25 Along with profound influence on the surface energy budget over land and the Red Sea (Kalenderski et al., 2013; Osipov et al., 2015; Brindley et al., 2015), dust is an important source of nutrients, more so for the oligotrophic northern Red Sea waters (Acosta et al., 2013). From preliminary assessments it is estimated that 5 to 6 major dust storms per year impact the Red Sea region, depositing about 6 Mt of mineral dust into the Red Sea (Prakash et al., 2015). Simulations
30 and satellite observations suggest that the coastal dust contribution to the total deposition flux into



the Red Sea could be significant, even during fair weather conditions (Jiang et al., 2009; Anisimov et al., 2017). Therefore, the correct representation of the regional dust balance over the Red Sea coastal plain is especially important. Here we specifically focus on the dust deposition in this area, which helps to constrain the dust mass balance, as well as the dust mineralogy and chemical composition. Dust sources impacting on the Arabian Red Sea coastal region were shown to vary by season, coming from local haboobs and low level jets, delivered from the Tokar delta of Sudan in summer (Kalenderski and Stenchikov, 2016), and transported from the west coast of the Arabian Peninsula (Kalenderski et al., 2013).

The mineralogy and chemical composition of dust generated from the Red Sea coastal region remains uncertain. The Red Sea coastal plain is a narrow highly heterogeneous piedmont area, and existing soil databases do not have enough spatial resolution to represent it adequately (Nickovic et al., 2012).

Minerals previously identified in continental soils from Middle East dust generating regions include quartz, feldspars, calcite, dolomite, micas, chlorite, kaolinite, illite, smectite, palygorskite, mixed-layer clays, vermiculite, iron oxides, gypsum, hornblende and halite (Engelbrecht et al., 2009a; Engelbrecht et al., 2016; Goudie, 2006; Prakash et al., 2016; Pye, 1987; Scheuven and Kandler, 2014). It could be expected that similar mineral assemblages would occur in variable proportions in the dust deposition samples collected in the region.

With the exception of the area around Jazan in the south, which is impacted by the Indian Ocean monsoon, the Red Sea coastal region has a desert climate characterized by extreme heat, reaching 43° C during the summer days, with a drop in night-time temperatures on average more than 10° C. Although the extreme temperatures are moderated by the proximity of the Red Sea, summer humidity is often 85 % or higher during periods of the northwesterly *Shamal* winds. Rainfall diminishes from an annual average of 133 mm at Jazan in the south to 56 mm at Jeddah, and 24 mm at Tabuk in the north. Vegetation is sparse, being restricted to semi-desert shrubs, and acacia trees along the ephemeral rivers (wadis), providing forage for small herds of goats, sheep and dromedary camels.

During infrequent but severe rainstorms, run-off from the escarpment along wadis produce flash floods in lowland areas. With such events, fine silt and clay deposits are formed on the coastal



plain, which are transformed into dust sources during dry and windy periods of the year. The resultant dust is transported and deposited along the coastal plain itself and adjacent Red Sea, by prevailing northwesterly to southwesterly winds, with moderate breezes (wind speed $>5.5 \text{ m s}^{-1}$) from the north (<http://www.windfinder.com/weather-maps/report/saudi Arabia#6/22.999/34.980>).

- 5 The importance of dust mineralogy has long been recognized, but only recently the explicit transport of different mineralogical species is implemented in climate models (Perlwitz et al., 2015a, b).

Another important implication of dust emission/deposition processes is associated with the harvesting of the solar renewable energy in the desert areas. However, dust deposits on solar panels
10 are known to have a severe detrimental effect on the efficiency of photovoltaic systems (Goossens and Van Kerschaver, 1999; Hamou et al., 2014; Mejia et al., 2014; Rao et al., 2014; Sulaiman et al., 2014; Ilse et al., 2016), varying with mineral composition and atmospheric conditions (Supplement).

2. Objectives

15 This study is meant to complement the recently published papers by our research group that characterize the effect of dust storms (Prakash et al., 2015; Kalenderski et al., 2013), evaluate radiative effect of dust (Osipov et al., 2015), analyze soils from the Red Sea coastal plain (Prakash et al., 2016) and dust emissions in the same region (Anisimov et al., 2017). It aims to provide mineralogical, physical and chemical compositions of deposition samples collected largely during
20 2015 at six sites on the campus of KAUST, located approximately 80 km north of Jeddah, along the central part of the Red Sea coastal plain of Saudi Arabia, (Fig. 1). The coastal plains of the Arabian Peninsula along the Red Sea and Persian Gulf are among the most populated areas in this region, hosting several major industrial and residential centers. Airborne dust profoundly affects human activities, marine and land ecosystems, climate, air-quality, and human health. Satellite
25 observations suggest that the narrow Red Sea coastal plain to be an important dust source province, augmented by the fine-scale sediment accumulations, scattered vegetation, and variable terrain. Airborne dust inevitably carries the mineralogical and chemical signature of a parent soil. The purpose of a previous study on 13 soil samples from the Arabian Red Sea coastal area (Prakash et al., 2016) was to better characterize their mineralogical, chemical and physical properties, which



in turn improve assessment of dust being deposited in the Red Sea and on land, affecting environmental systems and urban centers. Prakash et al. (2016) found that the Red Sea coastal soils contain major components of quartz and feldspar, as well as lesser but variable amounts of amphibole, pyroxene, carbonate, clays, and micas, with traces of gypsum, halite, chlorite, epidote and oxides. The mineral assemblages in the soil samples was ascribed to the variety of igneous and metamorphic provenance rocks of the Arabian Shield forming the escarpment to the east of the coastal plain.

The specific objective of the present study is to examine mineralogical and chemical information from deposition samples collected on the KAUST campus. This will help to better quantify the ecological impacts, health effects, damage to property, and optical effects of dust blown across this area (Engelbrecht et al., 2009b, a; Weese and Abraham, 2009). The obtained chemical and mineralogical information allows to assess the likelihood that deposited dust at least in part originates from local sources and in part from remotely transported dust. Knowledge of the mineralogy of the dust deposits will provide information on refractive indices, which can be used to calibrate dust radiative transfer models, and help assessing the impact of dust events on the Red Sea and adjacent coastal plain. This research complements our dust studies performed in the Arabian Peninsula (Engelbrecht et al., 2009b; Kalenderski et al., 2013; Prakash et al., 2015; Prakash et al., 2016) as well as globally (Engelbrecht et al., 2016).

3. Sampling and analysis

Anisimov et al. (2017) estimated that the eastern Red Sea coastal plain emits about 5–6 Mt of dust annually. Due to its close proximity, a significant portion of this dust is likely to be deposited into the Red Sea, which could be comparable in amount to the estimated annual deposition rate from remote sources during major dust events (Prakash et al., 2015). Therefore, we expect that the total dust deposition into the Red Sea is of the order of 10 Mt a^{-1} , but this figure still needs to be confirmed.

In the past few decades wind tunnel and field tests to compare their efficiencies, had been performed on different designs of deposition samplers and sand traps, including marble dust collectors (MDCO), inverted Frisbees, and glass surfaces (Goossens and Rajot, 2008; Sow et al., 2006; Goossens et al., 2000; Goossens and Offer, 2000). Most of the experiments performed in



wind tunnels failed to completely mimic the field conditions, which resulted in an underestimation of the dust deposition, more so for the $<10\ \mu\text{m}$ size fraction (Sow et al., 2006). Based on the field evaluations by Vallack (1995) and suggestions by Vallack and Shillito (1998) the decision was taken to deploy inverted Frisbee samplers with foam inserts.

5 At each sampling site the particulate deposits were collected into a 227 mm diameter inverted Frisbee dust deposit sampler, each with a polyester foam insert and bird strike preventers (Hall et al., 1993; Vallack and Chadwick, 1992, 1993; Vallack and Shillito, 1998) (Figure 2). The purpose of the foam insert is to enhance the particulate collection capacity of the dust gauge (Vallack and Shillito, 1998) by better collecting and retaining wet (from fog, dew, rain) and dry, fine and coarse
10 particles being deposited into the inverted Frisbee dish, under stable meteorological conditions, during severe dust events, northwesterly *Shamal* winds, and by daily coastal winds,

For the period December 2014 to March 2015, four Frisbee samplers were located at the New Environmental Oasis (NEO) site, about 50 m apart. The gravimetric information from the four samplers were similar, with small variations amongst them ascribed to the impact from local
15 construction activities. Due to the similarity of these gravimetric results, and to obtain a better representation of dust deposition onto the KAUST campus, two of the samplers (DT1 and DT2) were moved in March, the first (DT1) to a residential area and the other (DT2) to the quay adjacent to the Coastal & Marine Resources Core Lab (CMOR) (Table 1). (Site meta-data provided in the Supplement).

20 The deposition samples were collected for intervals of a calendar month, starting in December 2014 and ending December 2015. At the end of each month, the samples are retrieved by flushing the dust deposit from the foam insert and collection dish into the downpipe and plastic bottle, with distilled water. Both the insoluble particles and dissolved salts in the water suspension are retrieved in the laboratory by a freeze-drying (sublimation) procedure.

25 A total of 52 deposition samples were collected at the six sampling sites on the KAUST campus (Fig. 2) over a period of 13 months, largely in 2015. Representative subsets of these were selected for X-ray diffraction (XRD), (27 samples) and chemical analysis (29 samples).



Freeze-dried sample splits were re-suspended in the laboratory onto Teflon[®] filters, for elemental analysis by X-ray Fluorescence (XRF) spectrometry by using a miniaturized version of a dust entrainment facility (Engelbrecht et al., 2016) <http://www.dri.edu/atmospheric-sciences/atms-laboratories/4185-dust-entrainment-and-characterization-facility>). With this modified system the
5 dust sample is drawn into a vertically mounted tubular dilution chamber, and the re-suspended dust collected onto a 47 mm diameter Teflon[®] filter, for chemical analysis.

The samples re-suspended onto the Teflon[®] filters were chemically analyzed for elemental content by XRF, including for Si, Ti, Al, Fe, Mn, Ca, K, P, V, Cr, Ni, Cu, Zn, Rb, Sr, Y, Zr, and Pb (US EPA, 1999). Splits of about 2 mg from each freeze-dried sample was analyzed for water soluble
10 cations of sodium (Na⁺), potassium (K⁺), calcium (Ca²⁺) and magnesium (Mg²⁺), and anions of sulfate (SO₄²⁻), chloride (Cl⁻), phosphate (PO₄³⁻) and nitrate (NO₃⁻), by Ion Chromatography (IC) (Chow and Watson, 1999).

A subset of 27 samples from the total of 52 samples, representing all months of the year, was selected for X-ray diffraction (XRD) analysis. XRD is a non-destructive technique particularly
15 suited to identifying and characterizing minerals such as quartz, feldspars, calcite, dolomite, clay minerals and iron oxides, in fine soils and dusts. Dust reactivity in seawater as well as optical properties depend on its mineralogy, e.g. carbonates and sulfates are generally more soluble in water than silicates such as feldspars, amphiboles, pyroxenes or quartz. A Bruker D8[®] X-ray powder diffraction system was used to analyze the mineral content of the dust deposition samples.
20 The diffractometer was operated at 40 kV and 40 mA, with Cu K α radiation, scanning over a range of 4-50° 2 θ . The Bruker Topas[®] software and relative intensity ratios (RIRs) were applied for semi-quantitative XRD analyses of the dust deposition samples (Rietveld, 1969; Chung, 1974; Esteve et al., 1997; Caquineau et al., 1997; Sturges et al., 1989).

4. Results

25 4.1 Meteorology

Northwesterly *Shamal* winds prevailed during all twelve months of 2015 (Fig. 3). Four to five severe dust storms lasting three to five days each, contributed to hot humid conditions during the summer months. Also, weaker north-easterly winds were experienced in October and November of that year.



The first four months in the second half of 2015 experienced the highest ambient temperatures (Table 2), with an average temperature of 35° C for August followed by 34° C for September, bracketed by 33° C for both July and October. The highest single temperature was 43° C, recorded in October, with the coolest temperature of 17° C in January of that year. The range of temperatures
5 was the greatest through fall, winter and spring, with large diurnal temperature fluctuations during these seasons. The humidity at KAUST is consistently high (Table 2), with averages varying from 57 % for December and 61% for January, to as high as 82 % for August and 80% for September. Dewpoints were calculated for each set of hourly measurements, applying the August-Roche-Magnus approximation (Alduchov and Eskridge, 1996; August, 1828; Magnus, 1844). The highest
10 dewpoint temperatures were calculated in August (31° C) and September (30° C) while the month with the greatest frequency of humidity measurements (96) in excess of 90 % was also recorded in August (Table 2, Fig. 4). The lowest monthly frequency (4) for humidity exceeding 90 % was December.

4.2 Gravimetric analysis

15 With a few exceptions, the monthly gravimetric measurements from the four samplers (DT1 – DT4) are comparable (Fig. 5), fluctuating similarly by month and season. The deposition rates were at their lowest for December 2014 (avg. 4 g m⁻²), increasing steadily for four months to a peak value for March, 2015 (avg. 20 g m⁻²) before decreasing over the subsequent four months to a low for July (avg. 5 g m⁻²). The deposition rates increased sharply for August (28 g m⁻²),
20 September (23 g m⁻²) and October (28 g m⁻²), before diminishing in November (14 g m⁻²) and December (11 g m⁻²). The NEO terrain is close to several building construction sites, about 400 m to the east and southeast of the installed deposition samplers, which periodically created substantial amounts of local airborne dust. This, together with the windy conditions are held responsible for elevated dust concentrations measured at the two NEO sites (DT3, DT4). Wind-blown sea spray
25 during stormy conditions was responsible for elevated deposition levels of sea salt at the CMOR (DT2) quay-side site, for the months of September and October 2015.

Bearing in mind that the dust deposition samplers, sampling procedures, as well as conditions and sampling periods were different to those of this study, some comparisons to similar studies in desert regions are listed in Table 3. The deposition rates from this study, both on average (14 g m⁻² month⁻¹) and in range (4-28 g m⁻² month⁻¹), were found to be similar to those previously recorded
30



by Offer and Goossens (2001) in the Negev Desert, Israel (average $17 \text{ g m}^{-2} \text{ month}^{-1}$, range $10\text{-}25 \text{ g m}^{-2} \text{ month}^{-1}$), and West Niger (Goossens and Rajot, 2008) (average $13 \text{ g m}^{-2} \text{ month}^{-1}$, range $6\text{-}21 \text{ g m}^{-2} \text{ month}^{-1}$). A campaign in the Saudi Arabian capital of Riyadh (Modaihsh, 1997; Modaihsha and Mahjoub, 2013) during the dusty months of January to March showed average
5 monthly deposition rates of 42 g m^{-2} , and a range of $20\text{-}140 \text{ g m}^{-2}$. The dust deposition measured in Kuwait on the other hand, varied substantially by sampling district, being impacted to a variable extent by the disturbed soils from the Mesopotamian lowlands and the northwesterly *Shamal* winds. For these reasons the dust loadings varied during the campaigns in the N-E Bay area of Kuwait during the 2002/3 period (Al-Awadhi, 2005) (average $28 \text{ g m}^{-2} \text{ month}^{-1}$, range $3\text{-}58 \text{ g m}^{-2}$
10 month^{-1}) to samples collected in Kuwait City during the 2011/12 period (Al-Awadhi and AlShuaibi, 2013) (average $53 \text{ g m}^{-2} \text{ month}^{-1}$, range $2\text{-}320 \text{ g m}^{-2} \text{ month}^{-1}$) and samples collected during the 1979/80 campaign in the N-W Gulf area of Kuwait (Khalaf and Al-Hashash, 1983) (average $191 \text{ g m}^{-2} \text{ month}^{-1}$, range $10\text{-}1003 \text{ g m}^{-2} \text{ month}^{-1}$).

4.3 AERONET and visibility measurements

15 An CIMEL Robotic Sun Photometer is installed on the rooftop of the CMOR building on the campus of the KAUST and operated by our group since 2012, as a part of the NASA- AERONET, providing aerosol optical depth (AOD) and aerosol retrieved characteristics (<https://aeronet.gsfc.nasa.gov/>). Figure 6 compares the monthly averaged AOD at 500 nm with the
20 dust deposition rate for 2015. In a general sense the AOD and the deposition rates show comparable trends, both with maxima in spring and larger maxima in fall. However, the AOD reaches a first maximum in April, being one month later than that of the deposition rate. Also, the larger second AOD maximum occurred in August while the maximum deposition rate is broadly distributed over a three-month period, from August to October. The photometer measures light
25 attenuation by all aerosols along a column in the atmosphere, while deposition rate depends on dust at ground level only, the latter generally containing a relatively coarser dust fraction. The low-level dust particles are predominantly from local dust sources while the higher altitude dust could be transported from distal sources and chemically transformed, i.e., aged. As was pointed out by Yu et al. (2013) the differences between the deposition and AOD time series can in part be
30 attributed to modifications of the natural dust aerosol by anthropogenic activities, including petrochemical and other large industries along the Red Sea coast, as well as by entrainment of



construction and road dust. The linear correlation coefficient between the monthly deposition rates and the monthly averaged AOD of 0.40 suggests a causal interrelationship between these two quantities.

Furthermore, a comparison between the deposition samples and the visibility is made with
5 measurements taken in 2015 at the Jeddah airport meteorological station, approximately 70 km to the south of KAUST. Visibility is expressed as the frequency of dust events with reported weather codes 06-09, or 30–35, grouped as dusty or non-dusty days, for each month (Notaro et al., 2013; Anisimov et al., 2017), expressed as percentages. The bimodal monthly distributions seen with the deposition rates and AERONET monitoring are also mirrored by the visibility measurements
10 collected at Jeddah (Figure 7). The linear correlation coefficient between the monthly deposition rates and monthly averaged visibility measurements is 0.48, clearly suggesting a causal relationship between the two variables. It has been suggested that visibility and visibility frequency be used as a metric of dust emission flux and near surface dust concentrations (Cowie et al., 2014; Anisimov et al., 2017; Yu et al., 2013; Norris et al., 2014; Shao and Dong, 2006; Notaro et al.,
15 2013).

4.4 Mineral analysis by XRD

XRD analysis of the 27 samples (Fig. 8) show variable amounts of quartz (6–38 %, avg. 22 %) and feldspars (plagioclase, K-feldspar) (5-34 %, avg. 20 %), clays (10-18 %, avg. 13 %), micas (6-31 %, avg. 13 %), halite (1-53 %, avg. 7 %) with lesser amounts of gypsum (1-8 %, avg. 4 %),
20 calcite (0-8 %, avg. 2 %), dolomite (0-7 %, avg. 3 %), hematite (0-8 %, avg. 3 %), and amphibole (and pyroxene) (0-4%, avg. 1 %).

From the XRD, four broad mineral assemblages can be distinguished, the first and major assemblage is comprised of feldspars, clays and micas as well as hematite and gypsum, the second group is of quartz, the third of halite, and the fourth of calcite.

25 There is an increase in the halite concentrations at sites DT1-DT3, from about 2 % (DT1) in December 2014 to about 53 % (DT2) in July 2015 (Fig. 8). From August onwards there is an abrupt decrease in halite content to less than 5 %, except for samples collected at the DT2 (CMOR, quay-side) site alongside the ocean. There was a simultaneous increase in the proportion of quartz to a maximum of 38 % in April (DT3), and decreasing to less than 25 % at all sites after July,



2015. The silicate mineral group decreased systematically from about 72 % (DT1) in December
2014 to about 25 % (DT2) in July. Except for two samples from the DT3 site collected in
September and October 2015, the dominant minerals after July, 2015 included the silicate
assemblage, with concentrations of up to 80 %. The variation in the proportions of the four mineral
5 assemblages, especially the halite, is ascribed to seasonal fluctuations in wind, humidity and
precipitation, as well as the proximity of the sea to the samplers.

4.5 Particle size distribution

Dust deposition rates are dependent on both the meteorological conditions and dust properties such
as particle size distribution. The size distributions of surface soils from potential dust source
10 regions along the Red Sea coastal plain were previously documented (Prakash et al., 2016). The
size distribution as measured on one deposition sample (DT1) (Fig. 9a) by SEM differs marginally
from the size distributions of the soils from the coastal dusts (Fig. 9b). The deposition sample with
a geometric mean particle diameter of 2.9 μm is slightly coarser than the average $<38 \mu\text{m}$ sieved
soils with a geometric mean diameter of 2.5 μm . The deposition sample also shows a broader
15 distribution towards the larger particle sizes. This marginal difference can be ascribed to a
predominant deposition of a coarser particles (Prakash et al., 2016). In addition the Frisbee sampler
is biased towards the sampling of the coarser particles, as previously documented (Bergametti and
Forêt, 2014; Goossens, 2005).

The deposition samplers collect the total suspended particulates (TSP) but the bin aerosol models
20 usually calculate only PM_{10} . So they simulate deposition rates that should be lower than that we
observed. However, the size distribution of deposited particles shown in Figure 9 could be used to
distinguish the contribution of PM_{10} in deposited mass and reconcile models with observations.

4.6 Chemistry (XRF and IC)

As expected, the chemically analyzed deposition samples contain major amounts of SiO_2
25 (Appendix A, Fig. 10a, b), varying between 12–53 % (avg. 31 %) in the sample subset, occurring
as quartz, and together with Al_2O_3 , (avg. 4 %) and CaO , (avg. 2.3 %) in plagioclase, and K_2O (avg.
0.6 %) in potassium feldspars. SiO_2 together with Al_2O_3 , Fe_2O_3 , TiO_2 , MnO , MgO , and some K_2O
are also contained in the clays, micas and amphiboles, previously identified in these samples by
optical microscopy and XRD. Lesser amounts of CaO are contained in gypsum and calcite, and



together with MgO, in dolomite. The iron expressed here as Fe₂O₃ can be contained in hematite (Fe₂O₃), goethite FeO(OH) or in clay minerals such as illite, each with different solubility. It has been suggested that a large fraction of iron in soils and dusts is contained as amorphous colloidal coatings on quartz and feldspars (Engelbrecht et al., 2016).

- 5 The water-soluble cations (Appendix A, Fig. 11a, b) account for 1-19 % and the anions for 1-30 % of the total mass, respectively. These account for variable amounts of halite (1-32 %), and gypsum (1-9 %), with lesser amounts of other chlorides and carbonates. Of importance as dust borne nutrients likely to be deposited in the Red Sea, are the low concentrations of both water soluble NO₃⁻ (avg. 0.8 %), and water soluble PO₄³⁻ (avg. 0.2 %) compared to the total P₂O₅ (avg. 10 0.3 %) in the dust deposits. The phosphorus is contained in the largely insoluble mineral apatite (francolite), found in the sedimentary rocks underlying large parts of the Arabian Peninsula (Notholt et al., 2005).

The sum of chemical species, including elements expressed as oxides, and ion concentrations, vary from 35–78 %, with an average of 56 % of the measured chemical mass. The shortfall from 100 15 % is attributed in part to components not analyzed for, including H₂O, OH, carbon (CO₃²⁻, organic carbon, elemental carbon) and artifacts of debris deposited onto the samplers.

The chemical abundances were recalculated as normative minerals (Fig. 12a, b), comparable in composition to those identified by XRD (Fig. 8) and optical microscopy. The relative normative mineral abundances (Fig. 12b) show variable amounts of quartz (avg. 52.4 %) feldspar (avg. 3.9 20 %), kaolinite (2.6 %), calcite (8.8 %) dolomite (0.2 %), hematite (8.0 %), as well as the evaporate minerals gypsum (12.1 %), halite (12.1 %), sylvite (0.2 %), and bischofite (0.2 %). There is also, as shown by XRD, an increase in halite content from about 7.8 % in January to about 25.9 % in July, followed by a sharp drop to about 4.6 % in August, with greater abundances in September (51.0 %) and October (31.6 %) at the CMOR quayside site, ascribed to sea spray from stormy 25 conditions during those two months (Fig. 12b).

Elemental mass ratios of the Frisbee deposition samples are compared to the <38 μm sieved soil samples from the Arabian Red Sea coastal plain (Prakash et al., 2016), and total suspended particulate (TSP) samples collected at other sites in the Middle East (Engelbrecht et al., 2009b) are compared in Table 4. The average Si/Al ratio of 6.86 of the Frisbee deposition samplers is



intermediate to the 13.60 of the Arabian Red Sea coastal soils and the approximately unity of the Middle East samples. The Fe/Al ratios of the sample sets show similar relationships as the Si/Al ratios, being intermediate to the Red Sea coastal soils and four of the five other Middle East countries, excluding UAE, to which it is similar. The difference is ascribed to the greater
5 abundance of the minerals such as quartz in the coarser sieved soil samples, and less thereof in the finer TSP fractions. The Ca/Al ratio of 2.17 is similar to those of TSP samples from samples of Qatar (2.07) and UAE (2.16), ascribed to the regional carbonate-bearing soils in all three countries. The average Ti/Al, Mg/Al and K/Al ratios of the Frisbee deposition samples are substantially lower than those of the Red Sea coastal soils, which may be related to mineralogical differences in the
10 dust source regions. Differences can also be ascribed to larger percentages of Al bearing minerals such as clays in the deposition samples from this study.

5. Summary and conclusions

This paper has as its goal the provision of mineralogical, physical and chemical information on deposition samples collected at the KAUST campus during 2015. The study provides an
15 assessment of the seasonal variability of the regional dust deposition rates onto Saudi Arabian coastal plain, and is meant to be used for validating dust mass balance in the meteorological models with the dust component.

Inverted Frisbee samplers with foam inserts are found to be robust, easy to use, and provided comparable results, for the collection of wet and dry deposits. Once a month the samples are
20 retrieved by flushing the deposits into plastic flasks followed by freeze-drying of the slurry and recovery of all suspended particles and dissolved salts. The average deposition rate at KAUST in 2015 was 14 g m^{-2} , fluctuating from 4 g m^{-2} in December, to 20 g m^{-2} in March, 5 g m^{-2} in July, 28 g m^{-2} in September and October, and down to 11 g m^{-2} the following December. The fluctuations are ascribed to variable meteorological conditions, including high humidity prevailing along the
25 Arabian Red Sea coastal plain during the autumn months. The particle size distribution patterns point to a marginal bias towards the coarser size fractions in comparison with the $<38 \mu\text{m}$ sieved soil samples.

Chemical analysis, confirmed by XRD, point to a consistent silicate mineral fractions for the deposition samples, at all sampling sites for the entire sampling period. The Si/Al, Fe/Al, and



Ca/Al ratios of the deposition samples fall within the range of the soil samples previously collected along the Arabian Red Sea coastal plain as well as the TSP size fractions collected at several sites in the Middle East. It is therefore not feasible to explicitly relate the deposition samples to the coastal soils from chemical and mineralogical results on their own. It is proposed that the dust deposits along the Red Sea coast are a mixture of dust emissions from local soils, and those soils imported from distal dust sources.

For 2015, there are marked similarities between monthly distribution patterns of the deposition samples and AOD measured at KAUST, as well as visibility measurements from Jeddah airport, 70 km to the south. This shows that both the AOD and visibility measurements mirror fluctuations in dust deposition, although it may not be justified to calculate quantitative interrelationships without further research.

Except for the variable halite fractions, there are small variations in the mineralogical content of the dust samples collected on the KAUST campus. To better represent the dust being deposited in Red Sea, and coastal plain, the sampling campaign should be extended to sites beyond the KAUST campus. Such a sampling site was recently set up on an island off the coast from KAUST.

6. Data availability

The gravimetric, mineralogical and chemical data from this study are available upon request from Georgiy Stenchikov (Georgiy.Stenchikov@kaust.edu.sa).

Author Contributions. Johann Engelbrecht was responsible for the sample analysis and data compilation; Georgiy Stenchikov formulated the problem, designed the research project, and supported experimental activities; Jish Prakash collected, and conducted the freeze-drying of the samples, and performed part of the XRD analysis. Anatolii Anisimov assembled the meteorological and visibility data; Illia Shevchenko assembled the AERONET optical data; Engelbrecht, Stenchikov, Jish Prakash, Anisimov, and Shevchenko compiled different parts of the manuscript.

Acknowledgements. This research, including the chemical and mineralogical analysis is supported by internal funding from the King Abdullah University of Science and Technology (KAUST). We acknowledge the contributions from the collaborating Core Labs at KAUST and



the Desert Research Institute. This research is supported by the Supercomputing Laboratory at KAUST.

References

- 5 Acosta, F., Ngugi, D. K., and Stingl, U.: Diversity of picoeukaryotes at an oligotrophic site off the Northeastern Red Sea Coast, *Aquatic Biosystems*, 9, 16, doi: 10.1186/2046-9063-9-16, 2013.
- Al-Awadhi, J. M.: Dust fallout characteristics in Kuwait: a case study, *Kuwait Journal of Science and Engineering*, 32, 2, 135-151, 2005.
- Al-Awadhi, J. M., and AlShuaibi, A. A.: Dust fallout in Kuwait city: Deposition and
10 characterization, *Science of the Total Environment*, 461-462, 139–148, doi: 10.1016/j.scitotenv.2013.03.052, 2013.
- Alduchov, O. A., and Eskridge, R. E.: Improved Magnus Form Approximation of saturation vapor pressure, *Journal of Applied Meteorology*, 35, 4, 601-609, 1996.
- Anisimov, A., Tao, W., Stenchikov, G., Kalenderski, S., Prakash, P. J., Yang, Z., and Shi, M.:
15 Quantifying local-scale dust emission from the Arabian Red Sea coastal plain, *Atmospheric Chemistry and Physics*, 17, 993-1015, doi:10.5194/acp-17-993-2017, 2017.
- August, E. F.: Ueber die Berechnung der Expansivkraft des Wasserdunstes, *Annalen der Physik und Chemie*, 13, 122-137, 1828.
- Bennett, C. M., McKendry, I. G., Kelly, S., Denike, K., and Koch, T.: Impact of the 1998 Gobi
20 dust event on hospital admissions in the Lower Fraser Valley, British Columbia, *Science of the Total Environment*, 366, 2-3, 918-925, doi: 10.1016/j.scitotenv.2005.12.025, 2006.
- Bennion, P., Hubbard, R., O'Hara, S., Wiggs, G., Wegerdt, J., Lewis, S., Small, I., van der Meer, J., and Upshur, R.: The impact of airborne dust on respiratory health in children living in the Aral Sea region, *International Journal of Epidemiology*, 36, 5, 1103-1110, doi:
25 10.1093/ije/dym195, 2007.



- Bergametti, G., and Forêt, G.: Dust Deposition, in: Mineral Dust. A Key Player in the Earth System, edited by: Knippertz, P., and Stuut, J.-B. W., Springer, Dordrecht, 179-200, 2014.
- Brindley, H., Osipov, S., Bantges, R., Smirnov, A., Banks, J., Levy, R., Prakash, P. J., and Stenchikov, G.: An assessment of the quality of aerosol retrievals over the Red Sea and
5 evaluation of the climatological cloud-free dust direct radiative effect in the region, *Journal of Geophysical Research: Atmospheres*, 120, 20, 1086210878, doi: 10.1002/2015JD023282, 2015.
- Buseck, P. R., Jacob, D. J., Pósfai, M., Li, J., and Anderson, J. R.: Minerals in the air: An environmental perspective, *International Geology Review*, 42, 7, 577-593, doi: 10.1080/00206810009465101, 2000.
- 10 Caquineau, S., Magonthier, M.-C., Gaudichet, A., and Gomes, L.: An improved procedure for the X-ray diffraction analysis of low-mass atmospheric dust samples, *European Journal of Mineralogy*, 9, 157-166, 1997.
- Chow, J. C., and Watson, J. G.: Ion Chromatography in elemental analysis of airborne particles, *Elemental Analysis of Airborne Particles*, edited by: Landsberger, S., and Creatchman, M.,
15 Gordon and Breach Science, Amsterdam, 1999.
- Chung, F. H.: Quantitative interpretation of X-ray diffraction patterns of mixtures. I. Matrix-flushing method for quantitative multicomponent analysis, *J. Appl. Crystallogr.*, 7, 519-525, doi:10.1107/S0021889874010375 1974.
- Cowie, S. M., Knippertz, P., and Marsham, J. H.: A climatology of dust emission events from
20 northern Africa using long-term surface observations, *Atmospheric Chemistry and Physics*, 14, 8579–8597, doi:10.5194/acp-14-8579-2014, 2014.
- De Longueville, F., Hountondji, Y. C., Henry, S., and Ozer, P.: What do we know about effects of desert dust on air quality and human health in West Africa compared to other regions?, *Science of the Total Environment*, 409, 1, 1-8, doi: 10.1016/j.scitotenv.2010.09.025, 2010.
- 25 Edgell, H. S.: *Arabian Deserts. Nature, Origin and Evolution*, Springer, Dordrecht, Netherlands, 592 pp., 2006.



- Engelbrecht, J. P., McDonald, E. V., Gillies, J. A., Jayanty, R. K. M., Casuccio, G., and Gertler, A. W.: Characterizing mineral dusts and other aerosols from the Middle East – Part 2: Grab samples and re-suspensions, *Inhalation Toxicology*, 21, 327-336, doi: 10.1080/08958370802464299, 2009a.
- 5 Engelbrecht, J. P., McDonald, E. V., Gillies, J. A., Jayanty, R. K. M., Casuccio, G., and Gertler, A. W.: Characterizing mineral dusts and other aerosols from the Middle East – Part 1: Ambient sampling, *Inhalation Toxicology*, 21, 4, 297-326, doi: 10.1080/08958370802464273, 2009b.
- Engelbrecht, J. P., Moosmüller, H., Pincock, S., Jayanty, R. K. M., Lersch, T., and Casuccio, G.: Technical Note: Mineralogical, chemical, morphological, and optical interrelationships of
10 mineral dust re-suspensions, *Atmospheric Chemistry and Physics*, 16, 10809-10830, doi:10.5194/acp-16-10809-2016, 2016.
- Esteve, V., Rius, J., Ochando, L. E., and Amigó, J. M.: Quantitative x-ray diffraction phase analysis of coarse airborne particulate collected by cascade impactor sampling, *Atmospheric Environment*, 31, 23, 3963-3967, doi: 10.1016/S1352-2310(97)00257-4, 1997.
- 15 Fryrear, D. W.: Long-term effect of erosion and cropping on soil productivity, *Special Paper - Geological Society of America*, 186, 253-260, doi: 10.1130/SPE186-p253, 1981.
- Goossens, D., and Van Kerschaever, E.: Aeolian dust deposition on photovoltaic solar cells: The effects of wind velocity and airborne dust concentration on cell performance, *Solar Energy*, 66, 4, 277-289, 1999.
- 20 Goossens, D., Offer, Z., and London, G.: Wind tunnel and field calibration of five aeolian sand traps, *Geomorphology*, 35, 233-252, [http://doi.org/10.1016/S0169-555X\(00\)00041-6](http://doi.org/10.1016/S0169-555X(00)00041-6), 2000.
- Goossens, D., and Offer, Z. Y.: Wind tunnel and field calibration of six aeolian dust samplers, *Atmospheric Environment*, 34, 1043-1057, [http://doi.org/10.1016/S1352-2310\(99\)00376-3](http://doi.org/10.1016/S1352-2310(99)00376-3), 2000.
- 25 Goossens, D.: Quantification of the dry aeolian deposition of dust on horizontal surfaces: an experimental comparison of theory and measurements, *Sedimentology*, 52, 859-873, doi: 10.1111/j.1365-3091.2005.00719.x, 2005.



- Goossens, D., and Rajot, J. L.: Techniques to measure the dry aeolian deposition of dust in arid and semi-arid landscapes: a comparative study in West Niger, *Earth Surface Processes and Landforms*, 33, 178-195, doi: 10.1002/esp.1533, 2008.
- Goudie, A. S., and Middleton, N.J.: *Desert Dust in the Global System*, Springer, 287 pp., 2006.
- 5 Hagen, L. J., and Woodruff, N. P.: Air pollution in the Great Plains, *Atmospheric Environment*, 7, 323-332, 1973.
- Hall, D. J., Upton, S. L., and Marsland, G. W.: Improvements in dust gauge design, in: *Measurements of Airborne Pollutants*, edited by: Couling, S., Butterworth, Heinemann, 1993.
- Hamou, S., Zine, S., and Abdellah, R.: Efficiency of PV module under real working conditions,
10 *Energy Procedia*, 50, 553-558, 2014.
- Haywood, J., and Boucher, O.: Estimates of the direct and indirect radiative forcing due to tropospheric aerosols: A review, *Reviews of Geophysics*, 38, 4, 513-543, doi: 10.1029/1999RG000078, 2000.
- Hsu, N. C., Tsay, S. C., King, M. D., and Herman, J. R.: Aerosol properties over bright-
15 reflecting source regions, *IEEE Transactions on Geoscience and Remote Sensing*, 42, 3, 557-569, doi: 10.1109/TGRS.2004.824067, 2004.
- Huang, J., Minnis, P., Lin, B., Wang, T., Yi, Y., Hu, Y., Sun-Mack, S., and Ayers, K.: Possible influences of Asian dust aerosols on cloud properties and radiative forcing observed from MODIS and CERES, *Geophysical Research Letters*, 33, L06824, doi: 10.1029/2005GL024724,
20 2006.
- Ilse, K., Werner, M., Naumann, V., Figgis, B. W., Hagedorf, C., and Bagdahn, J.: Microstructural analysis of the cementation process during soiling on glass surfaces in arid and semi-arid climates, *Physica Status Solidi RRL*, 1-5, doi: 10.1002/pssr.201600152, 2016.
- Jiang, H., Farrar, J. T., Beardsley, R. C., Chen, R., and Chen, C.: Zonal surface wind jets across
25 the Red Sea due to mountain gap forcing along both sides of the Red Sea, *Geophys. Res. Lett.*, 36, 19, L19605, 10.1029/2009GL040008, 2009.



- Jickells, T. D., An, Z. S., Andersen, K. K., Baker, A. R., Bergametti, G., Brooks, N., Cao, J. J., Boyd, P. W., Duce, R. A., Hunter, K. A., Kawahata, H., Kubilay, N., laRoche, J., Liss, P. S., Mahowald, N., Prospero, J. M., Ridgwell, A. J., Tegen, I., and Torres, R.: Global iron connections between desert dust, ocean biogeochemistry, and climate, *Science*, 308, 5718, 67-71, doi: 10.1126/science.1105959, 2005.
- 5
- Kalenderski, S., Stenchikov, G., and Zhao, C.: Modeling a typical winter-time dust event over the Arabian Peninsula and the Red Sea, *Atmospheric Chemistry and Physics*, 13, 1999-2014, doi:10.5194/acp-13-1999-2013, 2013.
- Kalenderski, S., and Stenchikov, G.: High-resolution regional modeling of summertime transport and impact of African dust over the Red Sea and Arabian Peninsula, *Journal of Geophysical Research: Atmospheres*, 121, 6435–6458, doi:10.1002/2015JD024480, 2016.
- 10
- Khalaf, F., and Al-Hashash, M.: Aeolian sedimentation in the north-western part of the Arabian Gulf, *Journal of Arid Environments*, 6, 319-332, 1983.
- Kumar, R., Barth, M. C., Pfister, G. G., Naja, M., and Brasseur, G. P.: WRF-Chem simulations of a typical pre-monsoon dust storm in northern India: influences on aerosol optical properties and radiation budget, *Atmospheric Chemistry and Physics*, 14, 2431-2446, doi: 10.5194/acp-14-2431-2014, 2014.
- 15
- Magnus, G.: Versuche über die Spannkkräfte des Wasserdampfs, *Annalen der Physik und Chemie*, 61, 2, 225-247, 10.1002/andp.18441370202, 1844.
- Mahowald, N., S. Engelstaedter, C. Luo, A. Sealy, P. Artaxo, C. Benitez-Nelson, S. Bonnet, Y. Chen, P.Y. Chuang, D.D. Cohen, F. Dulac, B. Herut, A.M. Johansen, N. Kubilay, R. Losno, W. Maenhaut, A. Paytan, J.M. Prospero, L.M. Shank, and R.L. Siefert: Atmospheric iron deposition: Global distribution, variability and human perturbations, *Annual Review of Marine Science*, 1, 245-278, doi: 10.1146/annurev.marine.010908.163727, 2009.
- 20
- Mejia, F., Kleissl, J., and Bosch, J. L.: The effect of dust on solar photovoltaic systems, *Energy Procedia*, 49, 2370-2376, doi: 10.1016/j.egypro.2014.03.251, 2014.
- 25



- Menéndez, I., Derbyshire, E., Carrillo, T., Caballero, E., Engelbrecht, J. P., Romero, L. E., Mayer, P. L., de_Castro, F. R., and Mangas, J.: Saharan dust and the impact on adult and elderly allergic patients: the effect of threshold values in the northern sector of Gran Canaria, Spain, *International Journal of Environmental Health Research*, 27, 2, 144-160, doi: 10.1080/09603123.2017.1292496, 2017.
- Modaihsh, A. S.: Characteristics and composition of the falling dust sediments on Riyadh City, Saudi Arabia, *Journal of Arid Environments*, 36, 2, 211-223, <http://dx.doi.org/10.1006/jare.1996.0225>, 1997.
- Modaihsha, A. S., and Mahjoub, M. O.: Falling dust characteristics in Riyadh City, Saudi Arabia during winter months, *Asia-Pacific Chemical, Biological & Engineering Society Procedia*, 5, 50-58, doi: 10.1016/j.apcbee.2013.05.010, 2013.
- Muhs, D. R., Prospero, J. M., Baddock, M. C., and Gill, T. E.: Identifying sources of aeolian mineral dust: Present and past, in: *Mineral Dust, A Key Player in the Earth System*, edited by: Knippertz, P., and Stuut, J.-B. W., Springer Science+Business Media Dordrecht, 51-74, 2014.
- Nickovic, S., Vukovic, A., Vujadinovic, M., Djurdjevic, V., and Pejanovic, G.: Technical Note: High-resolution mineralogical database of dust-productive soils for atmospheric dust modeling, *Atmospheric Chemistry and Physics*, 12, 845-855, doi:10.5194/acp-12-845-2012, 2012.
- Nihlen, T., and Lund, S. O.: Influence of aeolian dust on soil Formation in the Aegean area, *Zeitschrift fur Geomorphologie*, 393, 341-361, 1995.
- Norris, G., Duvall, R., Brown, S., and Bai, S.: *EPA Positive Matrix Factorization (PMF) 5.0 Fundamentals and User Guide*, U.S. Environmental Protection Agency, 1-124, 2014.
- Notaro, M., Alkolibi, F., Fadda, E., and Bakhrjy, F.: Trajectory analysis of Saudi Arabian dust storms, *Journal of Geophysical Research: Atmospheres*, 118, 6028-6043, doi:10.1002/jgrd.50346, 2013.
- Notholt, A. J. G., Sheldon, R. P., and Davidson, D. F.: *Phosphate deposits of the world, Volume 2, Phosphate rock resources*, Cambridge University Press, New York, 600 pp., 2005.



- Offer, Z. Y., and Goossens, D.: Ten years of aeolian dust dynamics in a desert region (Negev Desert, Israel): analysis of airborne dust concentration, dust accumulation and the high-magnitude dust events, *Journal of Arid Environments* 47, 2, 211-249, <http://dx.doi.org/10.1006/jare.2000.0706>, 2001.
- 5 Osipov, S., Stenchikov, G., Brindley, H., and Banks, J.: Diurnal cycle of the dust instantaneous direct radiative forcing over the Arabian Peninsula, *Atmospheric Chemistry and Physics*, 15, 9537–9553, doi:10.5194/acp-15-9537-2015, 2015.
- Perlwitz, J. P., Pérez García-Pando, C., and Miller, R. L.: Predicting the mineral composition of dust aerosols – Part 1: Representing key processes, *Atmospheric Chemistry and Physics*, 15, 20, 11593–11627, doi: 10.5194/acp-15-11593-2015, 2015a.
- 10
- Perlwitz, J. P., Pérez García-Pando, C., and Miller, R. L.: Predicting the mineral composition of dust aerosols – Part 2: Model evaluation and identification of key processes with observations, *Atmospheric Chemistry and Physics*, 15, 20, 11629-11652, doi: 10.5194/acp-15-11629-2015, 2015b.
- 15 Prakash, P. J., Stenchikov, G., Kalenderski, S., Osipov, S., and Bangalath, H.: The impact of dust storms on the Arabian Peninsula and the Red Sea, *Atmospheric Chemistry and Physics*, 15, 199-222, doi: 10.5194/acp-15-199-2015, 2015.
- Prakash, P. J., Stenchikov, G., Tao, W., Yapici, T., Warsama, B., and Engelbrecht, J. P.: Arabian Red Sea coastal soils as potential mineral dust sources, *Atmospheric Chemistry and Physics*, 16, 18, 11991-12004, doi:10.5194/acp-16-11991-2016, 2016.
- 20
- Prospero, J. M., Ginoux, P., Torres, O., Nicholson, S. E., and Gill, T. E.: Environmental characterization of global sources of atmospheric soil dust identified with the Nimbus 7 Total Ozone Mapping Spectrometer (TOMS) absorbing aerosol product, *Reviews of Geophysics*, 40, 1, doi:10.1029/2000RG000095, 2002.
- 25 Pye, K.: *Aeolian dust and dust deposits*, Academic Press, London, 1987.
- Rao, A., Pillai, R., Mani, M., and Ramamurthy, P.: Influence of dust deposition on photovoltaic panel performance, *Energy Procedia*, 54, 690-700, doi: 10.1016/j.egypro.2014.07.310, 2014.



- Rietveld, H. M.: A profile refinement method for nuclear and magnetic structures, *Journal of Applied Crystallography*, 2, 65-71, dx.doi.org/10.1107/S0021889869006558, 1969.
- Scheuvens, D., and Kandler, K.: On composition, morphology, and size distribution of airborne mineral dust, in: *Mineral Dust, a Key Player in the Earth System*, edited by: Knippertz, P., and Stuut, J.-B. W., Springer Science+Business Media Dordrecht, 15-49, 2014.
- Shao, Y., and Dong, C. H.: A review on East Asian dust storm climate, modelling and monitoring, *Global and Planetary Change*, 52, 1-22, doi:10.1016/j.gloplacha.2006.02.011, 2006.
- Sokolik, I. N., and Toon, O. B.: Incorporation of mineralogical composition into models of the radiative properties of mineral aerosol from UV to IR wavelengths, *Journal of Geophysical Research - Atmospheres*, 104, D8, 9423-9444, doi: 10.1029/1998JD200048, 1999.
- Sow, M., Goossens, D., and Rajot, J. L.: Calibration of the MDCO dust collector and of four versions of the inverted frisbee dust deposition sampler, *Geomorphology*, 82, 3, 360-375, doi: 10.1016/j.geomorph.2006.05.013, 2006.
- Sturges, W. T., Harrison, R. M., and Barrie, L. A.: Semi-quantitative X-ray diffraction analysis of size fractionated atmospheric particles, *Atmos. Env.*, 23, 5, 1083-1098, 1989.
- Sulaiman, S. A., Singh, A. K., Mokhtar, M. M. M., and Bou-Rabee, M. A.: Influence of dirt accumulation on performance of PV panels, *Energy Procedia*, 50, 50-56, doi: 10.1016/j.egypro.2014.06.006, 2014.
- Tanaka, T. Y., and Chiba, M.: A numerical study of the contributions of dust source regions to the global dust budget, *Global and Planetary Change*, 52, 1-4, 88-104, doi:10.1016/j.gloplacha.2006.02.002, 2006.
- Twomey, S. A., Piepgrass, M., and Wolfe, T. L.: An assessment of the impact of pollution on global cloud albedo, *Tellus B*, 36B, 5, 356-366, doi: 10.1111/j.1600-0889.1984.tb00254.x, 1984.
- US EPA: Compendium of Methods for the Determination of Inorganic Compounds in Ambient Air, Compendium Method IO-3.3, Determination of metals in ambient particulate matter using X-ray fluorescence (XRF) spectroscopy, EPA/625/R-96/010, 3.3-1 - 3.3-32, 1999.



- Vallack, H. W., and Chadwick, M. J.: A field comparison of dust deposit gauge performance at two sites in Yorkshire, *Atmospheric Environment Part A*, 26, 8, 1445-1451, [https://doi.org/10.1016/0960-1686\(92\)90129-9](https://doi.org/10.1016/0960-1686(92)90129-9), 1992.
- Vallack, H. W., and Chadwick, M. J.: Monitoring airborne dust in a high density coal-fired power station region in North Yorkshire, *Environmental Pollution*, 80, 2, 177-183, [https://doi.org/10.1016/0269-7491\(93\)90145-E](https://doi.org/10.1016/0269-7491(93)90145-E), 1993.
- Vallack, H. W.: A field evaluation of Frisbee-type dust deposit gauges, *Atmospheric Environment*, 29, 12, 1465-1469, [https://doi.org/10.1016/1352-2310\(95\)00079-E](https://doi.org/10.1016/1352-2310(95)00079-E), 1995.
- Vallack, H. W., and Shillito, D. E.: Suggested guidelines for deposited ambient dust, *Atmospheric Environment*, 32, 16, 2737-2744, [http://doi.org/10.1016/S1352-2310\(98\)00037-5](http://doi.org/10.1016/S1352-2310(98)00037-5), 1998.
- Wang, W., Huang, J., Minnis, P., Hu, Y., Li, J., Huang, Z., Ayers, J. K., and Wang, T.: Dusty cloud properties and radiative forcing over dust source and downwind regions derived from A-Train data during the Pacific Dust Experiment, *Journal of Geophysical Research*, 115, D00H35, doi: 10.1029/2010JD014109, 2010.
- Washington, R., and Todd, M. C.: Atmospheric controls on mineral dust emission from the Bodélé depression, Chad: The role of the low level jet, *Geophysical Research Letters*, 32, L17701., doi:10.1029/2005GL023597, 2005.
- Weese, C. B., and Abraham, J. H.: Potential health implications associated with particulate matter exposure in deployed settings in southwest Asia, *Inhalation Toxicology*, 21, 291-296, doi: 10.1080/08958370802672891, 2009.
- Yu, Y., Notaro, M., Liu, Z., Kalashnikova, O., Alkolibi, F., Fadda, E., and Bakhrjy, F.: Assessing temporal and spatial variations in atmospheric dust over Saudi Arabia through satellite, radiometric, and station data, *Journal of Geophysical Research, Atmospheres*, 118, 13, 253–213, 264, doi:10.1002/2013JD020677, 2013.



FIGURES

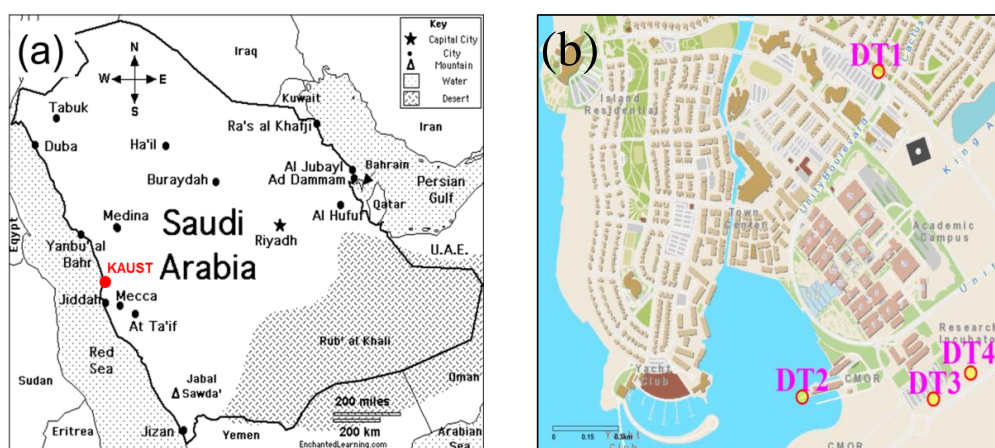


Figure 1. Locality of (a) the King Abdullah University of Science and Technology (KAUST) campus, north of the coastal city of Jeddah, along the Saudi Arabian Red Sea coast and (b) the Frisbee deposition sites (DT1-DT4) on the KAUST campus.

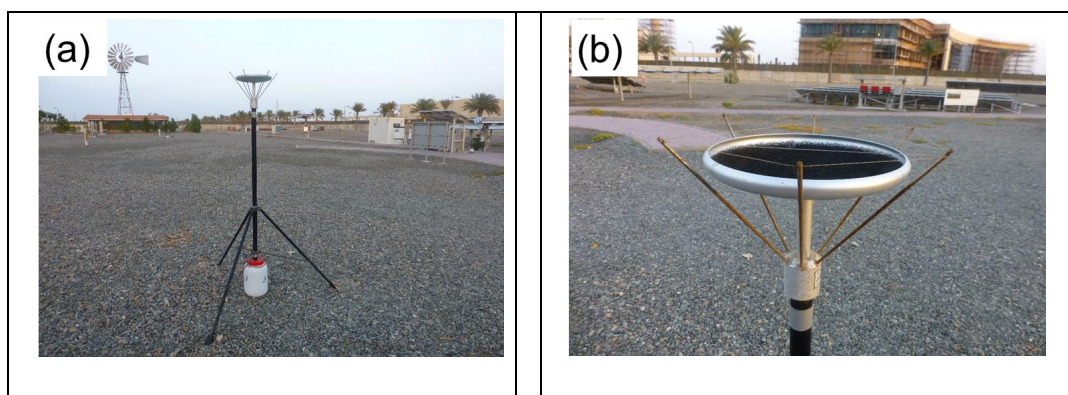


Figure 2. Inverted Frisbee type deposition sampler (a) on tripod and white plastic drainage bottle, (b) showing the foam insert in the collection dish to help retain the deposited dust particles, as well as the spikes with nylon thread to prevent birds from readily perching on the dish.

5

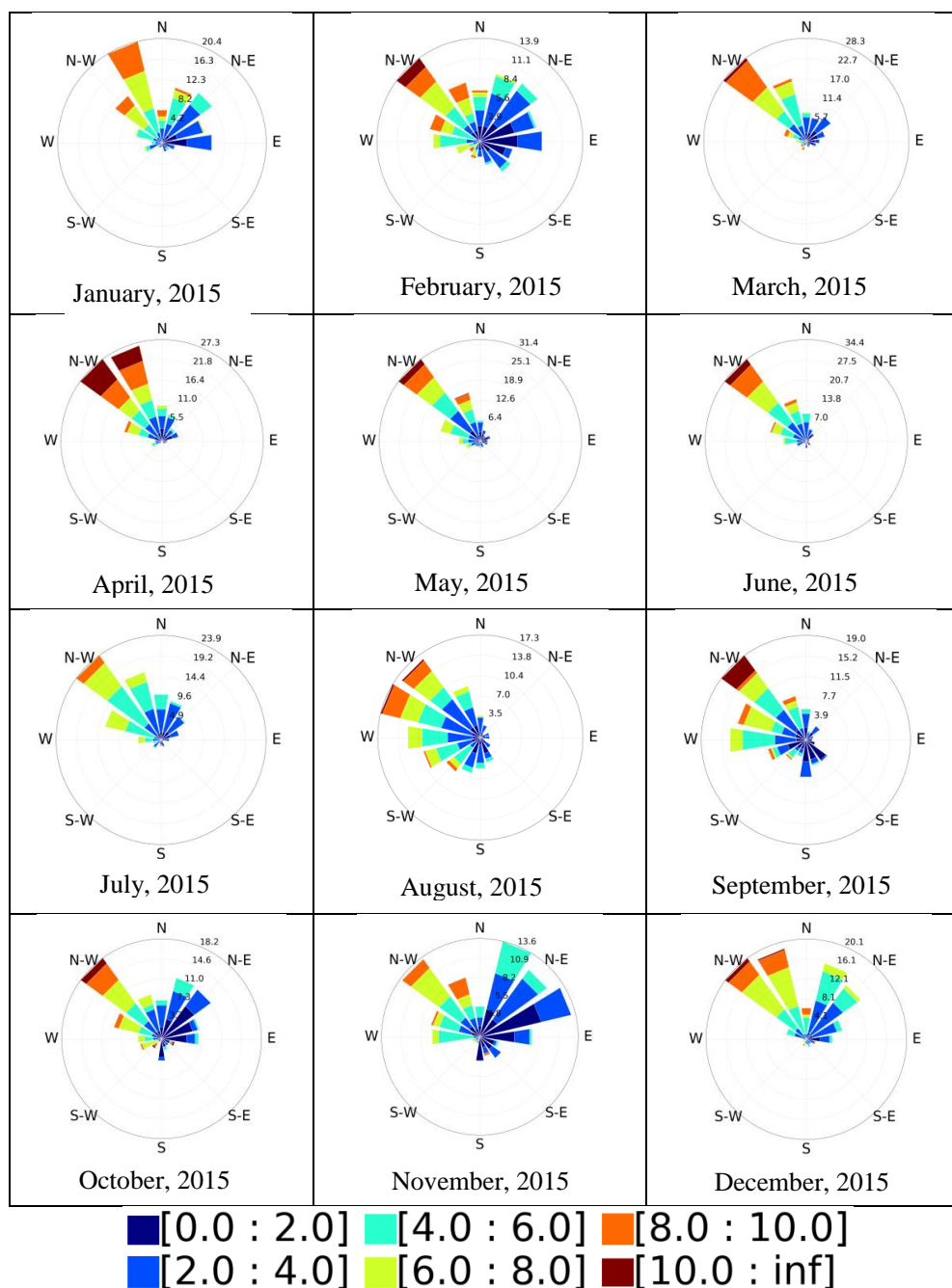


Figure 3. Wind roses show prevailing north-westerly *Shamal* winds at KAUST for all months of the 2015 year with north-easterly winds (windspeed in m s^{-1}) in the winter months of October through February.

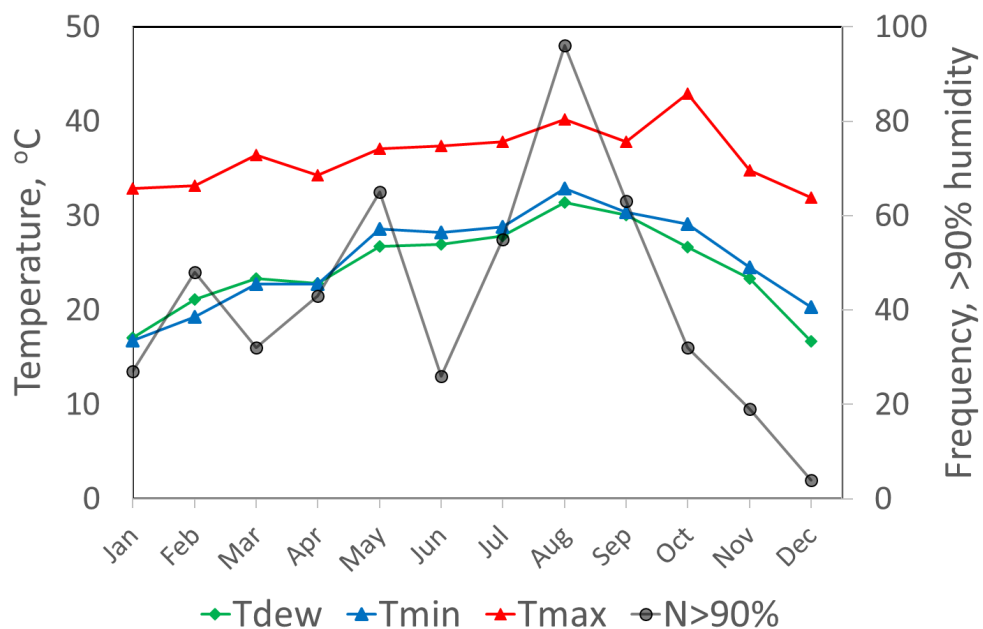


Figure 4. Monthly averaged minimum and maximum ambient temperatures as well as dewpoint variations for KAUST during 2015. Also shown for each month is the frequency of hourly humidity measurements exceeding 90%.
5

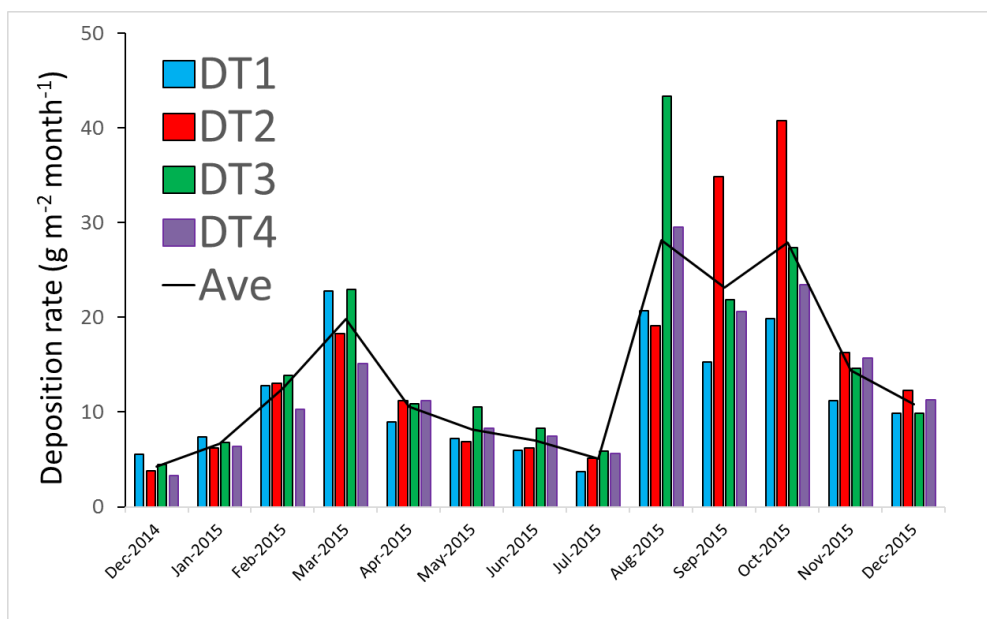


Figure 5. Monthly deposition rates (g m^{-2}) from Frisbee samplers (DT1-DT4) at the KAUST
5 campus. Also shown are the monthly averages for the four samplers.

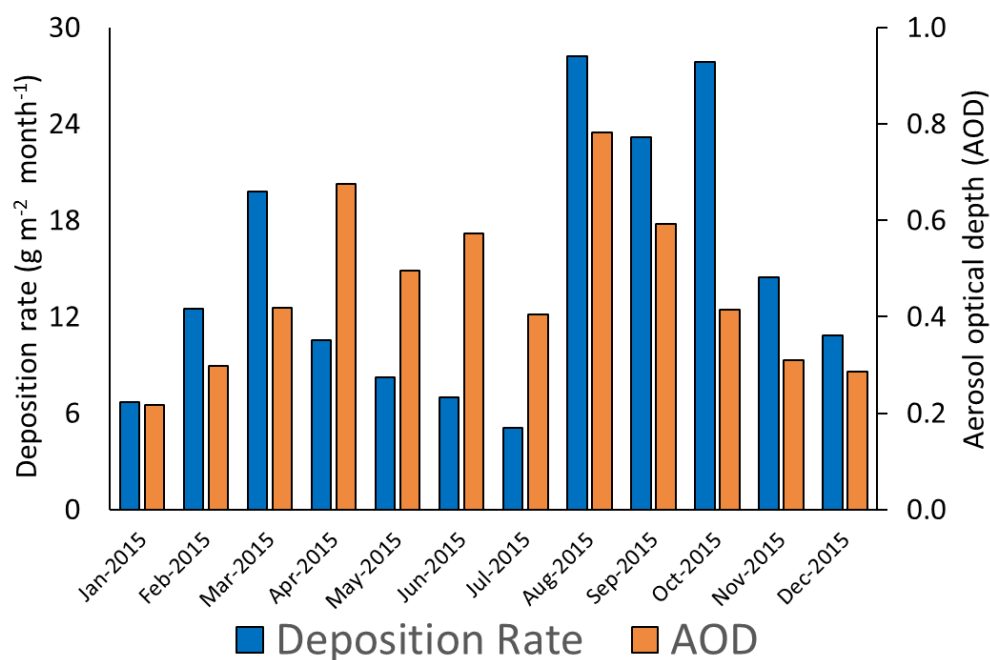


Figure 6. Average monthly deposition rate for all four samplers (DT1- DT4) on the KAUST
5 campus, and the monthly averaged AOD measurements from the KAUST AERONET site, for
2015.

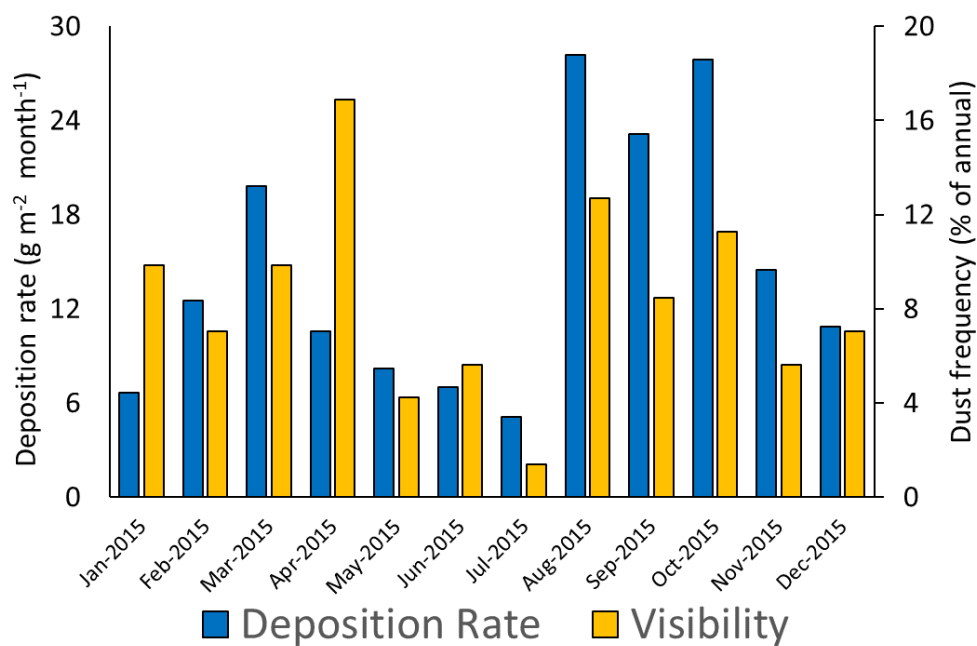


Figure 7. Average monthly deposition rate for all four samplers (DT1-DT4) on the KAUST
5 campus, and the monthly averaged visibility measurements collected from the Jeddah airport in
2015.

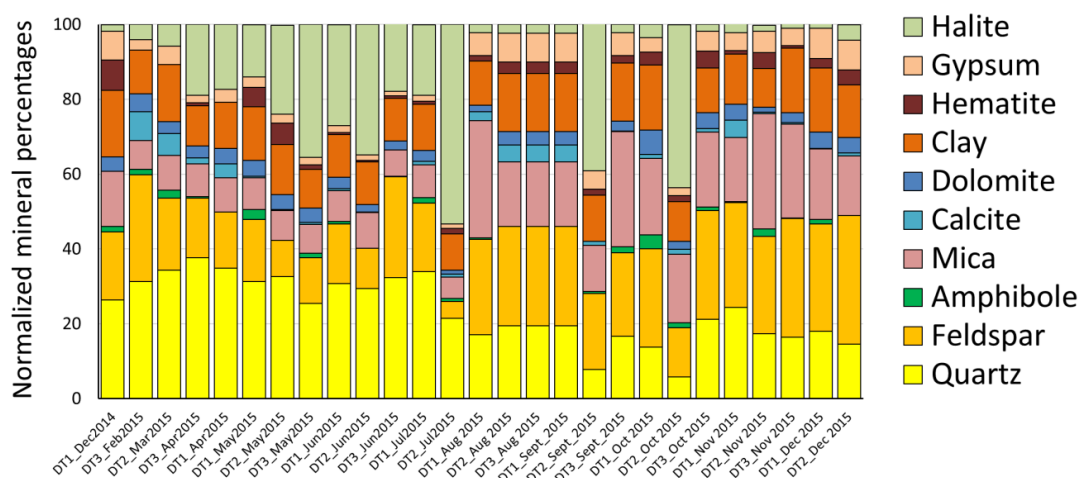


Figure 8. Semi-quantitative XRD mineral analyses of monthly Frisbee samples collected at the
5 three sites DT1–DT3, for the period December, 2014 to December2015.

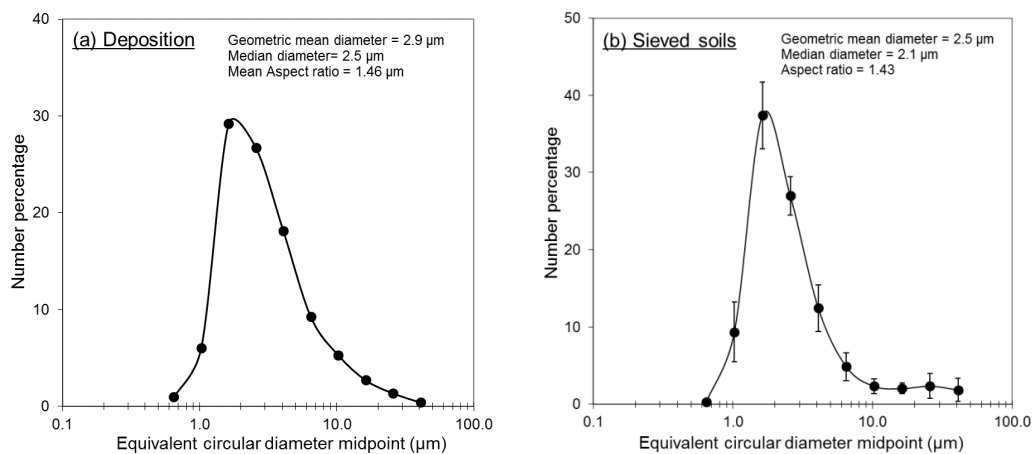


Figure 9. Particle size distributions of (a) deposition sample (DT1) collected by Frisbee sampler on KAUST campus, and (b) average of thirteen <math><38\ \mu\text{m}</math> sieved soil samples (Prakash et al., 2016), both measured by SEM.

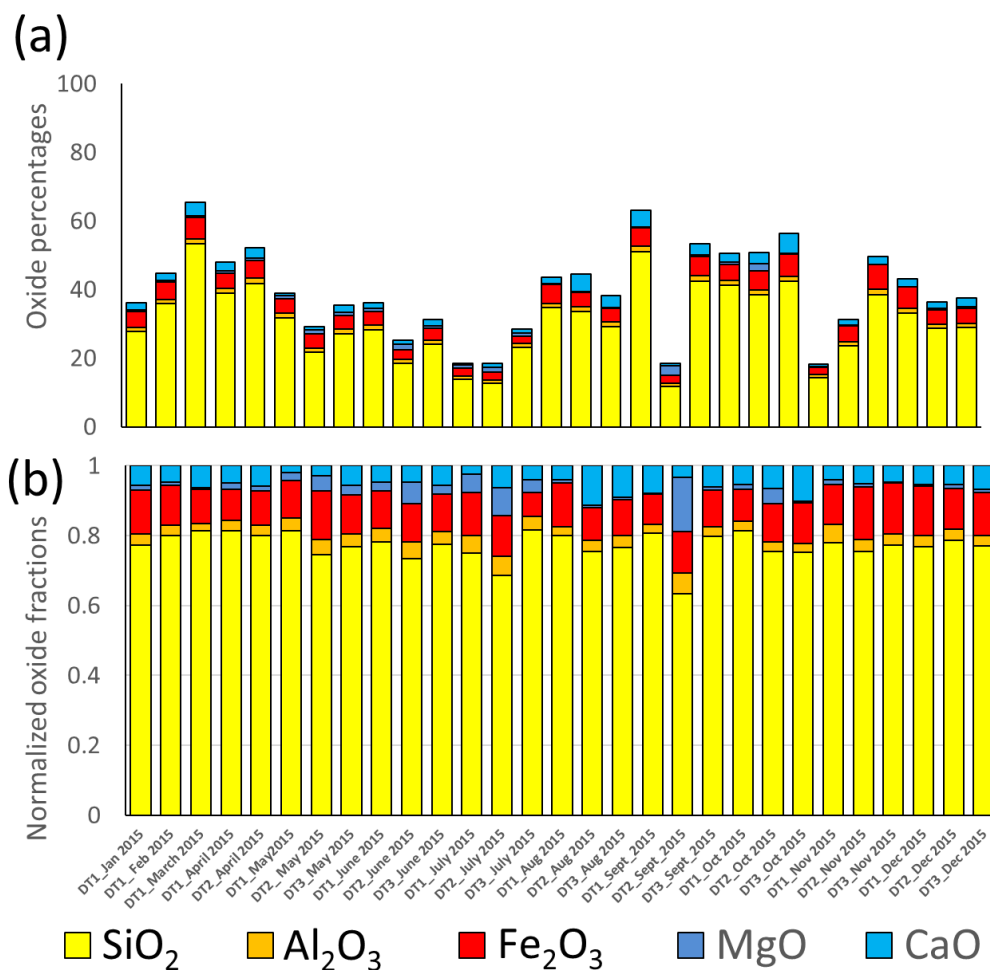


Figure 10(a). Deposition sample elemental compositions, expressed as oxides and (b) fractions
5 normalized to unity.

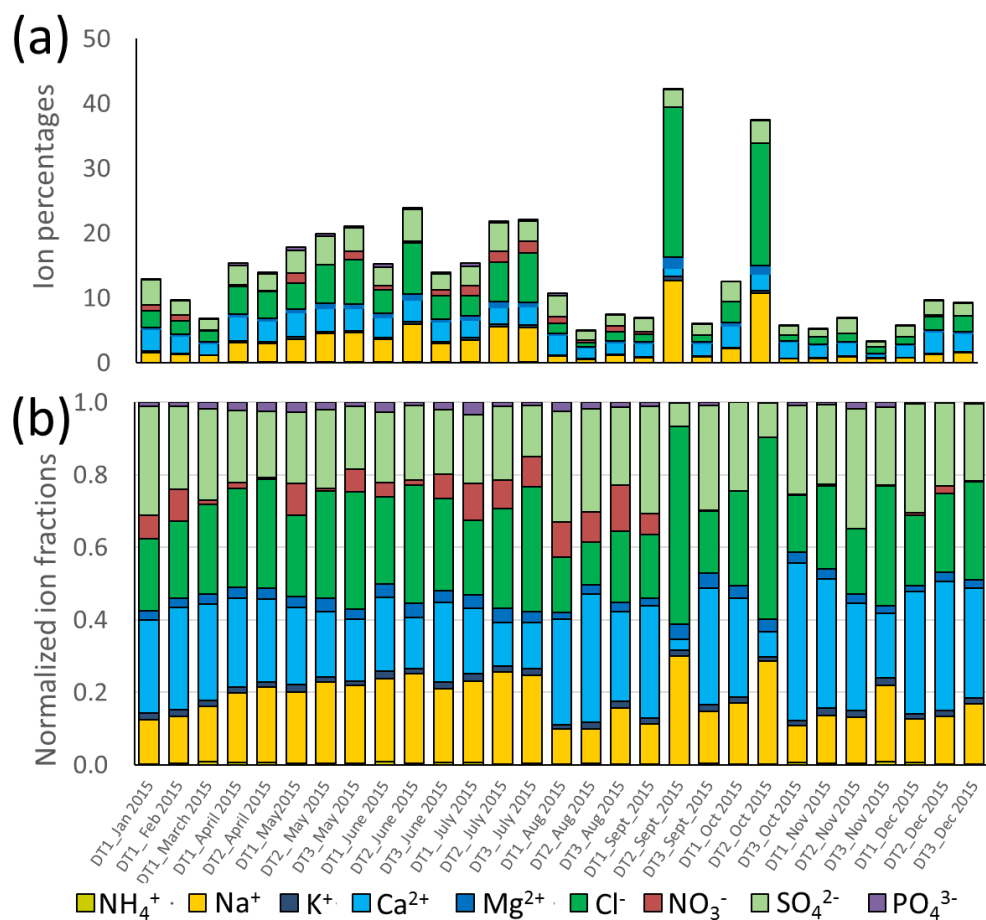


Figure 11 (a). Ion concentrations and (b) fractions totaled to unity.

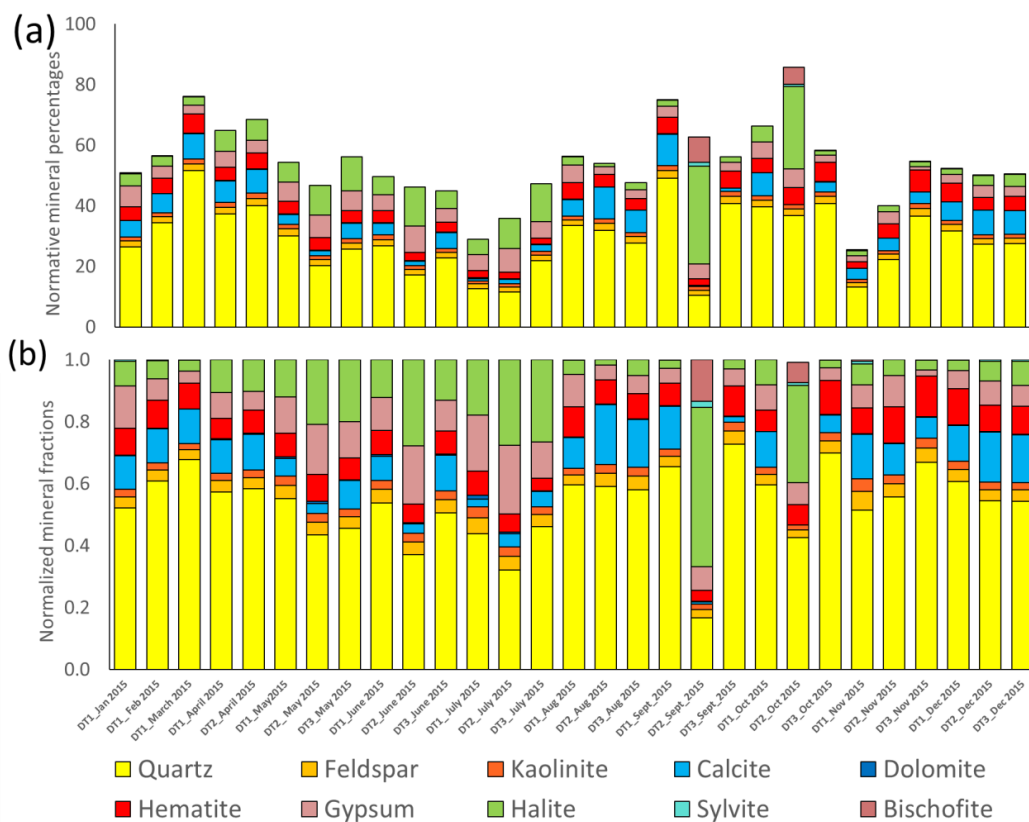


Figure 12 (a). Chemical abundances combined as normative minerals, (b) normalized to 100%.



TABLES

Table 1. Locality of deposition samplers at six sites on the campus of KAUST.

Site	Latitude	Longitude	Elev. m.a.s.l.	Start	End	
DT1	NEO 1	22°18'16.12"N	39°06'28.46"E	1	Dec14	Mar15
	Res G3705	22°18'59.06"N	39°06'21.32"E	12	Apr15	Dec15
DT2	NEO 2	22°18'16.84"N	39° 6'29.33"E	1	Dec14	Mar15
	CMOR	22°18'16.60"N	39° 6'7.91"E	1	Apr15	Dec15
DT3	NEO 3	22°18'17.31"N	39° 6'30.51"E	1	Dec14	Dec15
DT4	NEO 4	22°18'18.10"N	39° 6'31.52"E	1	Dec14	Dec15



Table 2. Monthly averaged temperatures, humidity measurements, and calculated dewpoints at KAUST during 2015.

Month	Temperature				Humidity				Dewpoint
	Avg. °C	Min. °C	Max. °C	Range °C	Avg. %	Min. %	Max. %	N>90% Count	Avg. °C
Jan	25	17	33	16	61	10	99	27	17
Feb	27	19	33	14	74	15	99	48	21
Mar	28	23	36	14	76	29	99	32	23
Apr	28	23	34	12	74	23	99	43	23
May	32	29	37	9	77	21	99	65	27
Jun	32	28	37	9	76	22	99	26	27
Jul	33	29	38	9	75	26	99	55	28
Aug	35	33	40	7	82	36	99	96	31
Sep	34	30	38	8	80	26	99	63	30
Oct	33	29	43	14	72	9	96	32	27
Nov	30	25	35	10	69	25	99	19	23
Dec	27	20	32	12	57	15	94	4	17

5



Table 3. Dust deposition measurements from the Middle East and other Global dust regions.

Study	Locality	Sampler type	Sampling period	Average deposition rate ($\text{g m}^{-2} \text{month}^{-1}$)	Range deposition rate ($\text{g m}^{-2} \text{month}^{-1}$)
(a) This study (2017)	Saudi Arabia, KAUST	Frisbee with foam insert	Dec 2014 - Dec 2015	14	4 - 28
(b) Modaihsh and Mahjoub (2013)	Saudi Arabia, Riyadh	Dish with marbles	Jan - Mar ?	42	20 - 140
(c) Khalaf and Al-Hashash (1983)	Kuwait, N-W Gulf	Polyethelene cylinders with water	Apr 1979 - Mar 1980	191	10 - 1003
(d) Al-Awadhi (2005)	Kuwait, N-E Bay	PVC bucket with marbles	May 2002 - Apr 2003	28	3 - 58
(e) Al-Awadhi and AlShuaibi (2013)	Kuwait, City	PVC bucket with marbles	Mar 2011 - Feb 2012	53	2 - 320
(f) Offer and Goossens (2001)	Israel, Negev	Marble collectors	1988 - 1997	17	10 - 25
(g) Goossens and Rajot (2008)	Niger, Banizoumbou	Frisbee with marbles, original data	8 periods in 2005	13	6 - 21
(h) Smith and Twiss (1965)	USA, Kansas	Cylindrical rain gauge with screens	June 1963 - June 1964	6	3 - 14



5 Table 4. Elemental mass ratios for the deposition samples from this study, compared to those of soils from the Red Sea coastal plain (Prakash et al., 2016) and TSP samples from other countries of the Middle East (Engelbrecht et al., 2009b). The TSP filter samples were collected by low-volume aerosol samplers without size selective inlets, for 24-hr sampling periods.

		Si/Al	Ti/Al	Fe/Al	Mg/Al	Ca/Al	K/Al
Frisbee	Deposition	6.86	0.14	1.47	0.11	2.17	0.34
Saudi Soils	Sieved <38 μ m	13.60	0.44	2.52	0.65	0.36	0.43
Djibouti	TSP	0.92	2.19	1.12	0.88	0.74	1.14
Afghanistan	TSP	1.05	1.25	1.00	0.94	0.69	1.96
Qatar	TSP	1.02	0.24	0.98	1.40	2.07	0.93
UAE	TSP	1.29	0.28	1.52	2.85	2.16	1.02
Iraq	TSP	1.03	0.72	0.99	1.11	1.31	1.04
Kuwait	TSP	1.07	0.65	0.99	1.25	1.23	0.94



Appendix A

Sample	DT1_Jan 2015	DT1_Feb 2015	DT1_March 2015	DT1_April 2015	DT2_April 2015	DT1_May2015	DT2_May 2015
Major and minor elements as oxides (%)							
SiO ₂	27.890 ± 0.050	35.886 ± 0.065	53.301 ± 0.089	38.965 ± 0.063	41.802 ± 0.073	31.729 ± 0.055	21.772 ± 0.039
TiO ₂	0.466 ± 0.001	0.530 ± 0.001	0.679 ± 0.002	0.464 ± 0.002	0.599 ± 0.002	0.486 ± 0.002	0.451 ± 0.001
Al ₂ O ₃	3.505 ± 0.035	4.464 ± 0.050	5.421 ± 0.097	4.257 ± 0.115	4.824 ± 0.081	3.817 ± 0.079	3.033 ± 0.026
Fe ₂ O ₃	4.480 ± 0.007	5.119 ± 0.008	6.312 ± 0.013	4.309 ± 0.013	5.091 ± 0.011	4.150 ± 0.010	4.104 ± 0.006
MnO	0.080 ± 0.001	0.082 ± 0.002	0.109 ± 0.004	0.075 ± 0.005	0.091 ± 0.003	0.077 ± 0.003	0.066 ± 0.001
CaO*	1.989 ± 0.015	2.097 ± 0.013	4.157 ± 0.016	2.369 ± 0.018	3.066 ± 0.017	0.753 ± 0.014	0.847 ± 0.013
K ₂ O*	0.484 ± 0.005	0.604 ± 0.004	0.864 ± 0.003	0.705 ± 0.006	0.798 ± 0.005	0.542 ± 0.008	0.432 ± 0.007
P ₂ O ₅	0.417 ± 0.001	0.150 ± 0.001	0.010 ± 0.003	0.332 ± 0.004	0.306 ± 0.002	0.474 ± 0.003	0.429 ± 0.001
Total (oxides)	39.311	48.932	70.852	51.475	56.579	42.028	31.134
Trace elements (ppm)							
V	107 ± 1	76 ± 1	85 ± 3	106 ± 4	93 ± 3	116 ± 3	99 ± 1
Cr	92 ± 3	115 ± 5	113 ± 12	101 ± 15	108 ± 10	113 ± 10	120 ± 2
Ni	78 ± 2	71 ± 3	84 ± 6	68 ± 8	71 ± 5	77 ± 5	57 ± 1
Cu	81 ± 3	57 ± 4	134 ± 10	125 ± 13	99 ± 9	206 ± 9	64 ± 2
Zn	223 ± 5	247 ± 8	293 ± 18	287 ± 23	258 ± 15	467 ± 16	219 ± 4
As	0 ± 3	0 ± 5	6 ± 12	0 ± 15	0 ± 10	0 ± 10	0 ± 2
Br	29 ± 3	26 ± 4	42 ± 10	59 ± 13	45 ± 9	34 ± 9	76 ± 2
Rb	28 ± 1	24 ± 1	16 ± 3	28 ± 4	34 ± 3	30 ± 3	27 ± 1
Sr	333 ± 3	392 ± 5	514 ± 11	386 ± 13	422 ± 9	303 ± 9	341 ± 2
Y	1071 ± 4	36 ± 4	26 ± 10	125 ± 13	46 ± 9	36 ± 9	24 ± 2
Zr	103 ± 4	98 ± 6	84 ± 14	57 ± 17	139 ± 12	133 ± 12	134 ± 3
Mo	0 ± 5	0 ± 7	12 ± 17	4 ± 21	8 ± 14	0 ± 14	0 ± 3
Pb	15 ± 5	28 ± 8	32 ± 18	66 ± 23	28 ± 15	19 ± 15	28 ± 3
Water soluble ions (%)							
NH ₄ ⁺	0.027 ± 0.003	0.033 ± 0.004	0.055 ± 0.006	0.105 ± 0.012	0.095 ± 0.011	0.076 ± 0.009	0.079 ± 0.009
Na ⁺	1.585 ± 0.012	1.267 ± 0.010	1.053 ± 0.009	2.952 ± 0.021	2.897 ± 0.021	3.519 ± 0.025	4.473 ± 0.031
K ⁺	0.230 ± 0.009	0.170 ± 0.006	0.114 ± 0.004	0.262 ± 0.010	0.207 ± 0.008	0.371 ± 0.014	0.296 ± 0.011
Mg ²⁺	0.338 ± 0.005	0.265 ± 0.004	0.188 ± 0.003	0.488 ± 0.007	0.400 ± 0.005	0.558 ± 0.008	0.744 ± 0.010
Ca ²⁺	3.311 ± 0.028	2.718 ± 0.023	1.813 ± 0.015	3.745 ± 0.032	3.220 ± 0.027	3.780 ± 0.032	3.560 ± 0.030
Cl ⁻	2.563 ± 0.014	2.054 ± 0.011	1.695 ± 0.009	4.177 ± 0.022	4.227 ± 0.023	3.963 ± 0.021	5.927 ± 0.032
NO ₃ ⁻	0.830 ± 0.030	0.843 ± 0.031	0.082 ± 0.004	0.269 ± 0.010	0.051 ± 0.004	1.578 ± 0.057	0.107 ± 0.005
SO ₄ ²⁻	3.877 ± 0.034	2.199 ± 0.019	1.718 ± 0.015	3.055 ± 0.027	2.549 ± 0.022	3.527 ± 0.031	4.327 ± 0.038
Total (ions)	12.761	9.548	6.719	15.052	13.647	17.372	19.513
Total (oxides + ions)	52.072	58.479	77.571	66.527	70.226	59.400	50.647
Note: CaO* and K ₂ O* are water insoluble, P ₂ O ₅ calculated from total P							



Appendix A

Sample	DT3_May 2015	DT1_June 2015	DT2_June 2015	DT3_June 2015	DT1_July 2015	DT2_July 2015	DT3_July 2015
Major and minor elements as oxides (%)							
SiO ₂	27.167 ± 0.051	28.318 ± 0.053	18.530 ± 0.035	24.158 ± 0.045	13.820 ± 0.027	12.693 ± 0.025	23.221 ± 0.037
TiO ₂	0.448 ± 0.001	0.478 ± 0.002	0.306 ± 0.001	0.370 ± 0.001	0.261 ± 0.001	0.241 ± 0.001	0.200 ± 0.002
Al ₂ O ₃	3.777 ± 0.059	3.692 ± 0.062	2.919 ± 0.050	3.067 ± 0.045	1.886 ± 0.041	2.030 ± 0.037	2.694 ± 0.148
Fe ₂ O ₃	3.972 ± 0.008	3.906 ± 0.008	2.782 ± 0.006	3.346 ± 0.006	2.287 ± 0.005	2.154 ± 0.005	1.935 ± 0.014
MnO	0.083 ± 0.002	0.077 ± 0.002	0.050 ± 0.002	0.068 ± 0.002	0.050 ± 0.002	0.044 ± 0.002	0.050 ± 0.007
CaO*	1.983 ± 0.016	1.681 ± 0.014	1.179 ± 0.013	1.745 ± 0.014	0.427 ± 0.010	1.179 ± 0.011	1.148 ± 0.013
K ₂ O*	0.508 ± 0.006	0.513 ± 0.007	0.366 ± 0.008	0.467 ± 0.006	0.208 ± 0.008	0.226 ± 0.008	0.359 ± 0.009
P ₂ O ₅	0.170 ± 0.002	0.590 ± 0.002	0.383 ± 0.002	0.389 ± 0.001	0.753 ± 0.002	0.457 ± 0.001	0.288 ± 0.005
Total (oxides)	38.108	39.254	26.514	33.609	19.692	19.024	29.895
Trace elements (ppm)							
V	88 ± 2	111 ± 2	86 ± 2	91 ± 1	115 ± 1	111 ± 1	77 ± 5
Cr	71 ± 7	96 ± 7	65 ± 6	82 ± 5	160 ± 5	60 ± 5	67 ± 21
Ni	62 ± 3	84 ± 4	49 ± 3	72 ± 3	133 ± 3	71 ± 2	91 ± 11
Cu	56 ± 6	134 ± 7	59 ± 5	49 ± 5	209 ± 5	62 ± 4	25 ± 19
Zn	251 ± 11	430 ± 12	297 ± 9	255 ± 8	515 ± 9	244 ± 7	180 ± 32
As	0 ± 7	0 ± 7	0 ± 6	0 ± 5	0 ± 5	0 ± 5	0 ± 21
Br	58 ± 6	62 ± 7	100 ± 5	64 ± 5	62 ± 5	88 ± 4	37 ± 19
Rb	24 ± 2	35 ± 2	16 ± 2	23 ± 1	17 ± 1	12 ± 1	8 ± 5
Sr	392 ± 7	322 ± 7	276 ± 6	291 ± 5	233 ± 5	268 ± 4	284 ± 19
Y	14 ± 6	23 ± 7	14 ± 5	19 ± 5	7 ± 5	12 ± 4	23 ± 19
Zr	123 ± 8	149 ± 9	112 ± 7	82 ± 6	76 ± 6	83 ± 6	88 ± 24
Mo	0 ± 10	0 ± 10	0 ± 8	0 ± 7	0 ± 7	0 ± 6	0 ± 29
Pb	18 ± 10	12 ± 11	15 ± 9	17 ± 8	22 ± 8	30 ± 7	45 ± 32
Water soluble ions (%)							
NH ₄ ⁺	0.091 ± 0.010	0.125 ± 0.014	0.120 ± 0.013	0.100 ± 0.011	0.088 ± 0.010	0.032 ± 0.004	0.109 ± 0.012
Na ⁺	4.509 ± 0.031	3.505 ± 0.025	5.875 ± 0.041	2.834 ± 0.020	3.466 ± 0.024	5.538 ± 0.038	5.360 ± 0.037
K ⁺	0.276 ± 0.010	0.312 ± 0.012	0.352 ± 0.013	0.256 ± 0.010	0.339 ± 0.013	0.360 ± 0.013	0.390 ± 0.015
Mg ²⁺	0.572 ± 0.008	0.559 ± 0.008	0.947 ± 0.013	0.453 ± 0.006	0.582 ± 0.008	0.878 ± 0.012	0.628 ± 0.009
Ca ²⁺	3.582 ± 0.030	3.094 ± 0.026	3.341 ± 0.028	3.092 ± 0.026	2.767 ± 0.024	2.642 ± 0.022	2.833 ± 0.024
Cl ⁻	6.828 ± 0.037	3.648 ± 0.020	7.799 ± 0.042	3.562 ± 0.019	3.141 ± 0.017	6.005 ± 0.032	7.612 ± 0.041
NO ₃ ⁻	1.328 ± 0.048	0.595 ± 0.022	0.349 ± 0.013	0.939 ± 0.034	1.573 ± 0.057	1.702 ± 0.061	1.864 ± 0.067
SO ₄ ²⁻	3.649 ± 0.032	2.965 ± 0.026	4.878 ± 0.043	2.483 ± 0.022	2.923 ± 0.026	4.424 ± 0.039	3.087 ± 0.027
Total (ions)	20.836	14.804	23.663	13.719	14.879	21.580	21.882
Total (oxides + ions)	58.944	54.058	50.177	47.328	34.571	40.605	51.777
Note: CaO* and K ₂ O* are water insoluble, P ₂ O ₅ calculated from total P							



Appendix A

Sample	DT1_Aug 2015	DT2_Aug 2015	DT3_Aug 2015	DT1_Sept_2015	DT2_Sept_2015	DT3_Sept_2015	DT1_Oct 2015
Major and minor elements as oxides (%)							
SiO ₂	34.862 ± 0.061	33.619 ± 0.058	29.244 ± 0.054	50.971 ± 0.083	11.690 ± 0.024	42.544 ± 0.074	41.270 ± 0.067
TiO ₂	0.591 ± 0.001	0.469 ± 0.002	0.422 ± 0.002	0.605 ± 0.003	0.206 ± 0.001	0.609 ± 0.002	0.496 ± 0.002
Al ₂ O ₃	4.021 ± 0.033	3.773 ± 0.078	3.514 ± 0.068	5.057 ± 0.124	3.628 ± 0.053	5.114 ± 0.081	4.374 ± 0.115
Fe ₂ O ₃	5.488 ± 0.008	4.186 ± 0.010	3.878 ± 0.009	5.479 ± 0.015	2.206 ± 0.006	5.540 ± 0.011	4.592 ± 0.013
MnO	0.095 ± 0.001	0.082 ± 0.003	0.068 ± 0.003	0.102 ± 0.005	0.048 ± 0.002	0.096 ± 0.003	0.081 ± 0.005
CaO*	1.772 ± 0.014	5.067 ± 0.017	3.423 ± 0.014	4.909 ± 0.019	3.273 ± 0.006	0.598 ± 0.014	2.690 ± 0.018
K ₂ O*	0.598 ± 0.003	0.850 ± 0.002	0.709 ± 0.003	0.988 ± 0.002	0.000 ± 0.014	0.853 ± 0.003	0.756 ± 0.004
P ₂ O ₅	0.249 ± 0.001	0.158 ± 0.002	0.076 ± 0.002	0.000 ± 0.004	0.000 ± 0.001	0.194 ± 0.002	0.047 ± 0.003
Total (oxides)	47.676	48.204	41.334	68.110	21.051	55.547	54.306
Trace elements (ppm)							
V	122 ± 1	110 ± 3	42 ± 2	51 ± 4	19 ± 2	93 ± 2	0 ± 4
Cr	116 ± 3	59 ± 10	76 ± 9	96 ± 16	46 ± 6	93 ± 10	152 ± 15
Ni	91 ± 1	71 ± 5	54 ± 4	61 ± 8	29 ± 3	76 ± 5	73 ± 8
Cu	55 ± 2	76 ± 9	41 ± 7	55 ± 14	32 ± 5	86 ± 8	40 ± 13
Zn	194 ± 4	226 ± 15	127 ± 13	157 ± 24	107 ± 9	339 ± 15	185 ± 23
As	0 ± 3	0 ± 10	0 ± 9	0 ± 16	0 ± 6	0 ± 10	0 ± 15
Br	20 ± 2	16 ± 9	34 ± 7	17 ± 14	715 ± 7	58 ± 8	64 ± 13
Rb	22 ± 1	43 ± 3	12 ± 2	47 ± 4	18 ± 2	38 ± 2	24 ± 4
Sr	441 ± 3	369 ± 9	257 ± 7	394 ± 14	179 ± 5	345 ± 9	331 ± 13
Y	18 ± 2	9 ± 9	25 ± 7	23 ± 14	8 ± 5	14 ± 8	18 ± 13
Zr	141 ± 3	133 ± 12	125 ± 10	123 ± 20	62 ± 7	127 ± 12	99 ± 17
Mo	0 ± 4	0 ± 14	0 ± 12	0 ± 23	1 ± 8	3 ± 13	17 ± 21
Pb	4 ± 4	58 ± 15	63 ± 13	36 ± 24	12 ± 9	28 ± 14	46 ± 23
Water soluble ions (%)							
NH ₄ ⁺	0.025 ± 0.003	0.018 ± 0.002	0.021 ± 0.002	0.021 ± 0.003	0.027 ± 0.003	0.024 ± 0.003	0.013 ± 0.002
Na ⁺	1.044 ± 0.009	0.481 ± 0.006	1.144 ± 0.009	0.756 ± 0.007	12.685 ± 0.087	0.862 ± 0.008	2.134 ± 0.016
K ⁺	0.116 ± 0.004	0.094 ± 0.004	0.133 ± 0.005	0.106 ± 0.004	0.625 ± 0.023	0.123 ± 0.005	0.192 ± 0.007
Mg ²⁺	0.213 ± 0.003	0.133 ± 0.002	0.193 ± 0.003	0.146 ± 0.002	1.732 ± 0.024	0.261 ± 0.004	0.425 ± 0.006
Ca ²⁺	3.101 ± 0.026	1.772 ± 0.015	1.840 ± 0.016	2.143 ± 0.018	1.280 ± 0.011	1.928 ± 0.016	3.415 ± 0.029
Cl ⁻	1.624 ± 0.009	0.588 ± 0.004	1.460 ± 0.008	1.216 ± 0.007	23.054 ± 0.123	1.034 ± 0.006	3.267 ± 0.018
NO ₃ ⁻	1.045 ± 0.038	0.418 ± 0.015	0.943 ± 0.034	0.396 ± 0.015	0.007 ± 0.003	0.004 ± 0.003	0.009 ± 0.003
SO ₄ ²⁻	3.241 ± 0.028	1.425 ± 0.012	1.591 ± 0.014	2.047 ± 0.018	2.778 ± 0.024	1.743 ± 0.015	3.042 ± 0.027
Total (ions)	10.410	4.930	7.324	6.831	42.187	5.980	12.496
Total (oxides + ions)	58.085	53.134	48.658	74.941	63.238	61.527	66.802
Note: CaO* and K ₂ O* are water insoluble, P ₂ O ₅ ⁻ calculated from total P							



Appendix A

Sample	DT2_Oct 2015	DT3_Oct 2015	DT1_Nov 2015	DT2_Nov 2015	DT3_Nov 2015	DT1_Dec 2015	DT2_Dec 2015	DT3_Dec 2015
Major and minor elements as oxides (%)								
SiO ₂	14.274 ± 0.028	38.421 ± 0.068	42.440 ± 0.076	23.596 ± 0.044	38.454 ± 0.070	33.248 ± 0.059	28.716 ± 0.053	28.860 ± 0.052
TiO ₂	0.206 ± 0.001	0.587 ± 0.001	0.687 ± 0.002	0.481 ± 0.001	0.651 ± 0.002	0.653 ± 0.001	0.486 ± 0.001	0.507 ± 0.001
Al ₂ O ₃	3.483 ± 0.048	4.611 ± 0.045	5.114 ± 0.052	3.202 ± 0.046	5.353 ± 0.069	4.657 ± 0.040	3.472 ± 0.055	3.603 ± 0.038
Fe ₂ O ₃	2.118 ± 0.005	5.577 ± 0.008	6.509 ± 0.010	4.736 ± 0.008	7.170 ± 0.012	6.180 ± 0.009	4.276 ± 0.008	4.597 ± 0.007
MnO	0.041 ± 0.002	0.103 ± 0.001	0.125 ± 0.002	0.119 ± 0.002	0.121 ± 0.003	0.121 ± 0.001	0.085 ± 0.002	0.079 ± 0.001
CaO*	5.742 ± 0.008	3.357 ± 0.015	0.731 ± 0.021	1.586 ± 0.010	2.370 ± 0.008	2.321 ± 0.011	1.965 ± 0.015	2.502 ± 0.014
K ₂ O*	0.090 ± 0.010	0.774 ± 0.002	0.822 ± 0.002	0.552 ± 0.003	0.954 ± 0.002	0.751 ± 0.002	0.590 ± 0.003	0.592 ± 0.003
P ₂ O ₅	0.000 ± 0.001	0.106 ± 0.001	0.000 ± 0.001	0.145 ± 0.001	0.181 ± 0.002	0.133 ± 0.001	0.155 ± 0.002	0.102 ± 0.001
Total (oxides)	25.953	53.537	56.429	34.418	55.254	48.064	39.745	40.840
Trace elements (ppm)								
V	67 ± 1	125 ± 1	130 ± 1	149 ± 2	180 ± 2	144 ± 1	97 ± 2	65 ± 1
Cr	26 ± 5	110 ± 4	119 ± 5	300 ± 6	135 ± 8	218 ± 4	103 ± 7	71 ± 4
Ni	33 ± 3	84 ± 2	68 ± 2	971 ± 3	121 ± 4	211 ± 2	134 ± 3	64 ± 2
Cu	28 ± 5	111 ± 4	59 ± 4	102 ± 5	74 ± 7	78 ± 3	89 ± 6	55 ± 3
Zn	82 ± 8	250 ± 7	205 ± 8	507 ± 9	358 ± 12	534 ± 6	328 ± 10	231 ± 6
As	0 ± 5	0 ± 4	0 ± 5	0 ± 5	0 ± 8	0 ± 3	0 ± 7	3 ± 4
Br	457 ± 5	27 ± 4	56 ± 4	66 ± 5	61 ± 7	59 ± 3	112 ± 6	95 ± 4
Rb	11 ± 1	40 ± 1	35 ± 1	26 ± 1	34 ± 2	27 ± 1	22 ± 2	22 ± 1
Sr	227 ± 5	422 ± 4	683 ± 5	253 ± 5	210 ± 7	329 ± 3	266 ± 6	310 ± 4
Y	14 ± 5	13 ± 4	14 ± 4	15 ± 5	39 ± 7	23 ± 3	13 ± 6	19 ± 3
Zr	38 ± 6	134 ± 5	143 ± 6	103 ± 6	192 ± 10	139 ± 4	113 ± 8	95 ± 5
Mo	0 ± 7	1 ± 6	0 ± 7	3 ± 7	0 ± 10	1 ± 5	3 ± 9	0 ± 5
Pb	8 ± 8	36 ± 6	17 ± 7	20 ± 8	24 ± 11	22 ± 5	30 ± 10	40 ± 6
Water soluble ions (%)								
NH ₄ ⁺	0.047 ± 0.005	0.043 ± 0.005	0.028 ± 0.003	0.024 ± 0.003	0.025 ± 0.003	0.032 ± 0.004	0.011 ± 0.001	0.025 ± 0.003
Na ⁺	10.668 ± 0.073	0.577 ± 0.006	0.675 ± 0.007	0.890 ± 0.008	0.684 ± 0.007	0.699 ± 0.007	1.279 ± 0.010	1.540 ± 0.012
K ⁺	0.447 ± 0.017	0.086 ± 0.003	0.106 ± 0.004	0.125 ± 0.005	0.072 ± 0.003	0.081 ± 0.003	0.136 ± 0.005	0.135 ± 0.005
Mg ²⁺	1.315 ± 0.018	0.164 ± 0.002	0.143 ± 0.002	0.185 ± 0.003	0.066 ± 0.001	0.095 ± 0.001	0.232 ± 0.003	0.225 ± 0.003
Ca ²⁺	2.543 ± 0.022	2.506 ± 0.021	1.851 ± 0.016	2.059 ± 0.018	0.573 ± 0.005	1.949 ± 0.017	3.422 ± 0.029	2.815 ± 0.024
Cl ⁻	18.796 ± 0.101	0.910 ± 0.005	1.181 ± 0.006	1.246 ± 0.007	1.071 ± 0.006	1.120 ± 0.006	2.083 ± 0.011	2.494 ± 0.013
NO ₃ ⁻	0.009 ± 0.003	0.007 ± 0.003	0.029 ± 0.003	0.004 ± 0.003	0.007 ± 0.003	0.033 ± 0.003	0.205 ± 0.008	0.026 ± 0.003
SO ₄ ²⁻	3.581 ± 0.031	1.411 ± 0.012	1.133 ± 0.010	2.297 ± 0.020	0.697 ± 0.006	1.734 ± 0.015	2.188 ± 0.019	1.964 ± 0.017
Total (ions)	37.407	5.704	5.146	6.831	3.196	5.745	9.558	9.224
Total (oxides + ions)	63.360	59.240	61.574	41.249	58.450	53.810	49.303	50.065

Note: CaO* and K₂O* are water insoluble, P₂O₅ calculated from total P