



## Fertilizing the Amazon and equatorial Atlantic with West African dust

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[1] Atmospheric mineral dust plays a vital role in Earth's climate and biogeochemical cycles. The Bodélé Depression in Chad has been identified as the single biggest source of atmospheric mineral dust on Earth. Dust eroded from the Bodélé is blown across the Atlantic Ocean towards South America. The mineral dust contains micronutrients such as Fe and P that have the potential to act as a fertilizer, increasing primary productivity in the Amazon rain forest as well as the equatorial Atlantic Ocean, and thus leading to N<sub>2</sub> fixation and CO<sub>2</sub> drawdown. We present the results of chemical analysis of 28 dust samples collected from the source area, which indicate that up to 6.5 Tg of Fe and 0.12 Tg of P are exported from the Bodélé Depression every year. This suggests that the Bodélé may be a more significant micronutrient supplier than previously proposed.

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### 1. Introduction

[2] Atmospheric mineral dusts, also known as soil dust or desert dust, contributes significant amounts of micronutrients such as iron (Fe) and phosphorus (P) to marine [Fasham, 2003], and terrestrial ecosystems [Okin et al., 2004]. These micronutrients are required for the growth of oceanic phytoplankton and terrestrial ecosystems; processes that lead to N<sub>2</sub> fixation and CO<sub>2</sub> sequestration [Swap et al., 1992; Okin et al., 2004; Jickells et al., 2005; Mahowald et al., 2005]. The Bodélé Depression, which lies within the southern Sahara in Chad, has been identified as the world's largest single source of atmospheric mineral dust [Prospero et al., 2002; Washington et al., 2003], and has been proposed as a potential tipping element in the radiative budget of Earth's atmosphere and biogeochemical cycles [Washington et al., 2009].

[3] Dust production in the Bodélé Depression is due to a combination of an easily eroded, friable, low-density sediment and a strong, frequent, surface wind, that can erode the sediment [Washington and Todd, 2005]. The sediments of the Bodélé depression include lake bed deposits, shoreline sediments with beach ridges and a delta, as well as some fluvial and Aeolian sediments [Bristow et al., 2009]. The most outstanding feature is around 24,000 km<sup>2</sup> of diatomite rich sediments which have a high albedo and stand out on satellite images. These sediments, which accumulated on the

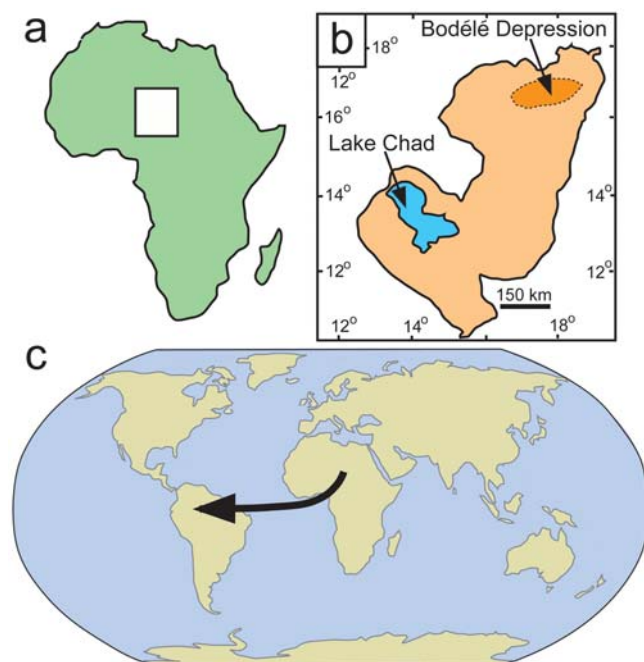
bed of palaeolake Megachad, are primarily authigenic, having been formed within the lake, and are not the product of previous cycles of weathering, erosion, transport and deposition as has been implied in some reports [Prospero et al., 2002; Mahowald et al., 2005]. The bulk of the sediments are diatom frustules which are essentially hollow tubes of biogenic silica, giving the sediments a very low bulk density (around 0.8 g cm<sup>-2</sup>). The diatom frustules are weakly cemented with authigenic calcite, Mg-calcite, aragonite and gypsum cements (Figure S1 of the auxiliary material).<sup>3</sup> The poorly cemented sediments are friable and readily eroded with at least 4 m of sediment eroded locally by the wind since the lake dried out around 1000 years ago. The authigenic minerals and detrital clay minerals including kaolinite contribute to the geochemistry.

[4] The wind responsible for the deflation is the Bodélé Low Level Jet, which is part of the northeasterly Harmattan flow [Washington and Todd, 2005]. Satellite data indicate that the dust-emission peaks during the winter months between December and March [Washington et al., 2006]. During this time of year, the northeasterly winds transport dust southwest from the Bodélé across the Sahel towards a more equatorial latitude where the dust plume turns west across the Atlantic towards the Amazon (Figure 1c) [Tegen et al., 2006; Ben-Ami et al., 2010]. The transport of dust from the Bodélé Depression across the Atlantic to the Amazon takes around 10 days [Ben-Ami et al., 2010] and dust emissions from the Bodélé are associated with an order of magnitude increase in atmospheric dust over the Amazon Basin [Ben-Ami et al., 2010] although not all dust episodes reach the Amazon [Ansmann et al., 2009]. During the summer months when there is less dust emission from the Bodélé, the transport path from the Bodélé is towards the west over West Africa in the core of the African Easterly Jet [Washington et al., 2009]. Sediment eroded from the Bodélé at this time of year augments the other summer dust sources from the western Sahara [Washington et al., 2009].

[5] The Bodélé Dust Experiment (BoDEX) in February and March 2005 resulted in the first-ever surface-based measurements of aerosol optical thickness, wind regime [Washington et al., 2006], collection of emitted dust samples [Chappell et al., 2008], as well as field studies of deflation and the source sediments [Bristow et al., 2009] within the Bodélé. The source sediments are diatomites, lacustrine and fluvio-deltaic sediments covering an area of *c.* 10,800 km<sup>2</sup>, which were deposited in palaeolake Megachad, a giant lake (10,000 × 6,000 km) that was filled with fresh water to a depth of around 150 m during the Holocene [Drake and Bristow, 2006] (Figure 1b). We present in this paper

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**Figure 1.** (a) Map of Africa with inset box (b) showing extent of palaeolake Megachad, Lake Chad, and the Bodélé Depression, (c) path of dust from Chad across the Atlantic to South America during the winter months modified from *Tegen et al.* [2006].

analyses of 28 Bodélé dust samples, describe their bulk major element geochemistry, and examine their implications for the geochemical cycling of iron (Fe) and phosphorus (P) in the Amazon and equatorial Atlantic.

## 2. Materials and Methods

[6] The samples were collected in modified Wilson and Cooke dust traps at elevations of 1.4 m (mid) and 2.4 m (top) above the surface during a dust storm on the 10th, 11th and 12th of March 2005 (Figure S2). The dust traps were arranged across three barchan dunes and the downwind interdune areas [*Chappell et al.*, 2008]. Samples from the lower traps were not sampled in order to avoid saltation load, but even so the material collected includes particles that are too coarse to be emitted as aerosols.

[7] Dust samples were digested with HF and HNO<sub>3</sub> according to US-EPA Method 3052. Digestions were performed in an Ethos Touch Control Microwave System. Excess HF was neutralized with 5% w/v boric acid, and samples were made up to 50 mL volume prior to analysis. Analysis was carried out by ICP-OES (JY-Optima 2C). Digestions of international reference materials (NCS DC73322 and 73323), duplicates and blanks were prepared according to the same procedure. Analytical errors and precisions are both estimated at <10%.

## 3. Results

[8] Major element data (not corrected for grain size) for Al, Fe, Mn, Mg, Ca, Na, K, P and Ti are given in Table 1 and plotted against average upper crustal concentrations

(UCC) [*Wedepohl*, 1995], in Figure 2. Median values of Fe, Mn, P, and Ti lie close to the UCC averages, while median values for Al, Mg, Ca, K and especially Na are depleted and fall beneath the average UCC values (Figure 2). The higher end of the concentration ranges (Table 1) are similar to chemical data for two samples of Chad Basin dust analysed by *Moreno et al.* [2006].

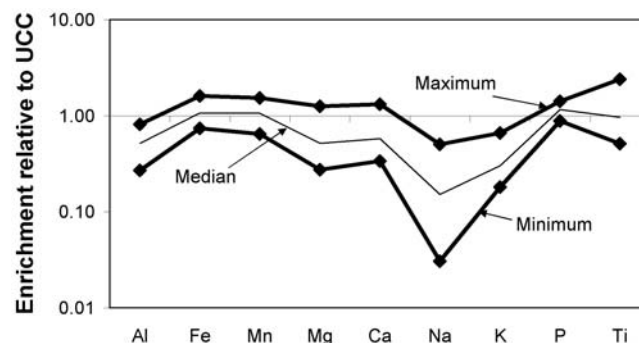
## 4. Discussion and Conclusions

### 4.1. Bulk Major Element Geochemistry

[9] The major element chemistry of the Bodélé dusts reflects their mineralogy and the weathering, depositional, and diagenetic processes that produced their source materials. This includes authigenic opaline silica in diatom frustules as well as detrital quartz sand grains which are not described here. The presence of kaolinite, and lack of mobile elements (Na, K, and to a lesser extent, Mg and Ca) suggest an origin that has been intensely weathered. This was also suggested by *Moreno et al.* [2006] for kaolinitic dusts from sub-Saharan Africa, including two from the Chad Basin. The low concentrations of Na in our samples reflect the freshwater character of palaeolake Megachad as evidenced by the diatom flora [*Servant and Servant-Vildary*, 1980; *Gasse*, 2002] relatively high Mg and Ca in our samples reflect the presence of calcite, Mg-calcite and aragonite cements in the diatomite, and possibly, calcite and dolomite as detected in other samples of Bodélé dusts by *Millham et al.* [2008]. *Millham et al.* [2008] also detected Ti-bearing minerals, which might explain the elevated Ti concentrations in some of our samples. The moderate amounts of Al, Fe, Mg, Mn and K in some samples likely reflect the presence of ferromagnesian and Al silicate minerals [*Millham et al.*, 2008]. The Fe in the samples may also reflect the presence of Fe oxides such as goethite and hematite, or Fe sulphate salts that are detected in Saharan dusts [*Schroth et al.*, 2009]. The P may be held in detrital phases such as apatite or P-sorbed Fe oxides, or in biogenic or organic P as found in dusts elsewhere [*Monbet et al.*, 2007]. Further work is required to confirm these Fe and P hypotheses.

### 4.2. Fe and P Nutrient Supply

[10] The median Fe and P concentrations of Bodélé dust (33,000 and 780 ppm, respectively) are close to upper crustal Fe and P concentrations proposed by *Taylor and*



**Figure 2.** Maximum, median and minimum major element concentrations of 28 Bodélé dusts normalized to average upper crustal concentrations (UCC) [*Wedepohl*, 1995].

**Table 1.** Major Element Concentrations of Bodélé Dusts

Sample		Easting (m)	Northing (m)	Al (ppm)	Fe (ppm)	Mn (ppm)	Mg (ppm)	Ca (ppm)	Na (ppm)	K (ppm)	P (ppm)	Ti (ppm)
21-mid	Dune 1	228069	1874309	33,000	28,000	380	13,000	33,000	5,200	19,000	600	7,500
24-mid	Dune 1	227809	1874096	63,000	38,000	540	9,000	16,000	8,100	9,500	780	2,900
25-mid	Dune 1	227745	1874053	41,000	44,000	680	17,000	12,000	5,800	18,000	790	3,900
26-mid	Dune 1	227885	1874147	24,000	41,000	580	13,000	39,000	2,500	11,000	890	2,900
27-mid	Dune 1	227327	1874058	40,000	50,000	740	16,000	11,000	6,200	14,000	930	3,100
32-mid	Dune 2	230048	1871785	50,000	35,000	570	7,800	17,000	9,000	9,200	780	2,900
35-mid	Dune 2	230358	1872181	42,000	32,000	810	5,300	18,000	3,900	5,200	870	4,700
36-mid	Dune 2	230274	1872117	32,000	37,000	490	10,000	35,000	3,500	12,000	880	5,900
40-mid	Interdune	231204	1869290	21,000	25,000	370	7,600	17,000	1,500	7,300	660	6,500
44-mid	Interdune	231530	1869060	41,000	33,000	660	9,300	24,000	2,400	8,300	620	2,300
45-mid	Dune 3	231944	1869402	42,000	30,000	480	3,700	12,000	1,400	8,300	830	1,600
46-mid	Dune 3	231594	1869343	44,000	28,000	500	4,000	15,000	790	7,200	940	1,800
50-mid	Dune 3	231798	1869345	62,000	33,000	640	5,300	10,000	4,900	6,000	690	3,000
52-mid	Interdune	227362	1873544	25,000	38,000	600	8,900	17,000	5,900	8,900	720	3,000
57-mid	Interdune	227044	1873845	25,000	27,000	440	4,200	15,000	3,000	6,200	900	5,300
58-mid	Interdune	226883	1873725	39,000	29,000	430	6,600	26,000	1,500	12,000	870	3,300
59-mid	Interdune	226519	1873451	59,000	36,000	570	8,600	15,000	5,100	9,600	690	3,000
59-top	Interdune	226519	1873451	44,000	33,000	560	6,100	14,000	10,000	8,700	670	3,500
60-mid	Interdune	226236	1873239	38,000	32,000	550	6,000	14,000	5,900	7,100	680	2,700
66-mid	Interdune	229345	1871686	23,000	23,000	340	5,000	17,000	3,000	6,700	600	4,200
67-mid	Interdune	229134	1871530	34,000	33,000	560	5,500	17,000	9,600	6,700	630	2,700
69-mid	Interdune	229410	1870828	51,000	40,000	600	8,900	22,000	1,400	10,000	820	3,000
71-mid	Interdune	231033	1869175	39,000	26,000	410	3,800	13,000	1,600	7,500	760	2,100
73-mid	Interdune	230700	1868903	24,000	24,000	370	7,000	20,000	3,500	8,000	590	4,300
74-mid	Interdune	230476	1868631	42,000	33,000	610	5,400	18,000	13,000	7,100	710	2,700
76-mid	Interdune	231002	1868827	54,000	38,000	660	13,000	23,000	5,700	14,000	900	4,800
77-mid	Interdune	230800	1868735	59,000	38,000	650	9,700	19,000	9,700	9,600	770	3,100
80-mid	Interdune	228130	1870885	29,000	29,000	420	6,500	25,000	3,600	9,200	800	6,900
Median				40,000	33,000	560	7,300	17,000	4,400	8,800	780	3,100
Minimum				21,000	23,000	340	3,700	10,000	790	5,200	590	1,600
Maximum				63,000	50,000	810	17,000	39,000	13,000	19,000	940	7,500

McLennan [1995] (35,000 and 700 ppm, respectively) and Wedepohl [1995] (30,890 and 665 ppm, respectively), concentrations used in global P models (720 ppm) [Mahowald *et al.*, 2008], and Mediterranean Sea-deposited Saharan dust ( $4,500 \pm 4,900$  and  $820 \pm 110$  ppm, respectively) [Guieu *et al.*, 2002], the latter of which are regarded to be sufficient to act as sources of nutrients for the Mediterranean [Guieu *et al.*, 2002].

[11] The Amazon basin is, like tropical rain forests throughout the world, rich in animal and plant diversity and as a result, is an important source and sink of atmospheric  $\text{CO}_2$ ,  $\text{N}_2\text{O}$ ,  $\text{CH}_4$  and volatile organic C compounds [Keller *et al.*, 1997]. Terrestrial productivity in the Amazon is phosphorus-limited [Sanchez *et al.*, 1982; Okin *et al.*, 2004], but is balanced in part by inputs from P-bearing atmospheric dust [Swap *et al.*, 1992]. Koren *et al.* [2006] estimated that emissions from the Bodélé contributed 56% (i.e.,  $22.4 \pm 8$  Tg, where  $1 \text{ Tg} = 10^{12} \text{ g} = \text{one million tons}$ ) of the total annual burden of dust ( $40 \pm 13$  Tg) transported annually from the Sahara to the Amazon basin between  $20^\circ\text{S}$  and  $10^\circ\text{N}$ . For this range (14.4 to 30.4 Tg dust), our results suggest that  $0.0085\text{--}0.029$  Tg of P (and  $0.33$  to  $1.52$  Tg of Fe) reach the Amazon annually from the Bodélé. Swap *et al.* [1992] estimated that only 13 Tg of dust reached the Amazon from the Sahara annually, and using geochemical data of Talbot *et al.* [1986], suggested that this dust would contribute  $0.011\text{--}0.047$  P  $\text{kg ha}^{-1}\text{yr}^{-1}$  (equivalent to  $0.00075\text{--}0.0032$  Tg of P for their  $6.8 \times 10^7$  ha study area). Our estimates are up to 38 times greater than this, suggesting that Bodélé dust may be a much more significant nutrient supplier to the Amazon

that previously thought. Our data do, however, support the findings of Okin *et al.* [2004], who used the upper continental crustal P concentration (700 ppm), which is similar to our Bodélé P median concentration, in their models. Okin *et al.* [2004] suggested that the Amazon soil P reservoir is continually replenished by dust-borne P inputs, and that these would lead to a long-term increase in productivity, and our results confirm this.

[12] In the tropical North Atlantic, nitrogen fixation is co-limited by Fe and P, but is stimulated by the addition of Saharan dusts that supply these elements [Mills *et al.*, 2004]. Kaufman *et al.* [2005] estimate that  $140 \pm 40$  Tg of dust is transported annually from Africa to the Atlantic between  $20^\circ\text{S}$  and  $30^\circ\text{N}$ . If the Bodélé contributions 56% of this total, as it is proposed to do for the Sahara [Koren *et al.*, 2006], then this represents  $78.4 \pm 22$  Tg of dust and, using our range of Fe and P Bodélé dust concentrations, 2.3 to 5 Tg of Fe and 0.033 to 0.094 Tg of P deposited in the equatorial Atlantic annually. For Fe, this represents 30 to 83% of the 6.0 to 7.7 Tg of Fe calculated to be deposited in the North Atlantic annually [Duce and Tindale, 1991; Jickells and Spokes, 2001]. Of this, however, only *c.* 2% (0.046 to 0.1 Tg Fe) is likely to be soluble in ocean water and thus bioavailable [Jickells and Spokes, 2001] although solubility of iron varies considerably from 0.1 to 80% [Mahowald *et al.*, 2005].

[13] Our results from the analysis of African dusts collected from the Bodélé Depression improve estimates of the amount of Fe exported from Africa to the Atlantic Ocean and Amazon Basin, but not all of this will be bio-available

due to the limited solubility of Fe in seawater [Jickells and Spokes, 2001]. The solubility of iron in dust is influenced by a variety of factors [Mahowald et al., 2005], the mineralogy of the dust [Journet et al., 2008] and subsequent processing within the atmosphere [Mahowald et al., 2005]. Atmospheric processing appears to increase the solubility of iron [Hand et al., 2004]. Fine mode aerosols show larger iron solubilities than coarse mode aerosols [Siefert et al., 1999; Baker and Jickells, 2006], and physical concentration of fine modes during long distance transport will occur as coarse particles are preferentially removed by gravitational settling. In addition, solubility may also be increased by chemical reactions within the atmosphere [Mahowald et al., 2005]. Furthermore, the increased surface area to volume ratio of fine particles relative to coarser particles may increase chemical processing and further enhance iron solubility [Baker and Jickells, 2006]. All of the above factors will also likely affect phosphorus bioavailability. Additional analysis of the composition, size and solubility of iron and phosphorus minerals is required in order to determine the efficacy of the African dust as a fertilizer.

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## References

- Ansmann, A., H. Baars, M. Tesche, D. Müller, D. Althausen, R. Engelmann, T. Pauliquevis, and P. Artaxo (2009), Dust and smoke transport from Africa to South America: Lidar profiling over Cape Verde and the Amazon rainforest, *Geophys. Res. Lett.*, *36*, L11802, doi:10.1029/2009GL037923.
- Baker, A. R., and T. D. Jickells (2006), Mineral particle size as a control on aerosol iron solubility, *Geophys. Res. Lett.*, *33*, L17608, doi:10.1029/2006GL026557.
- Ben-Ami, Y., I. Koren, Y. Rudich, P. Artaxo, S. T. Martin, and M. O. Andreae (2010), Transport of Saharan dust from the Bodélé Depression to the Amazon Basin: A case study, *Atmos. Chem. Phys. Discuss.*, *10*, 4345–4372, doi:10.5194/acpd-10-4345-2010.
- Bristow, C. S., N. Drake, and S. Armitage (2009), Deflation in the dustiest place on Earth: The Bodélé Depression, Chad, *Geomorphology*, *105*, 50–58, doi:10.1016/j.geomorph.2007.12.014.
- Chappell, A., A. Warren, A. O'Donoghue, A. Robinson, A. Thomas, and C. S. Bristow (2008), The implications for dust emission modeling of spatial and vertical variations in the horizontal dust flux and particle size in the Bodélé Depression, northern Chad, *J. Geophys. Res.*, *113*, D04214, doi:10.1029/2007JD009032.
- Drake, N., and C. S. Bristow (2006), Shorelines in the Sahara: Geomorphological evidence for an enhanced monsoon from palaeolake Megachad, *Holocene*, *16*, 901–911, doi:10.1191/0959683606hol981rr.
- Duce, R. A., and N. W. Tindale (1991), Atmospheric transport of iron and its deposition in the ocean, *Limnol. Oceanogr.*, *36*, 1715–1726, doi:10.4319/lo.1991.36.8.1715.
- Fasham, M. J. R. (2003), *Ocean Biogeochemistry*, Springer, Heidelberg, Germany.
- Gasse, F. (2002), Diatom-inferred salinity and carbonate oxygen isotopes in Holocene waterbodies of the western Sahara and Sahel (Africa), *Quat. Sci. Rev.*, *21*, 737–767, doi:10.1016/S0277-3791(01)00125-1.
- Guieu, C., M.-D. Loÿe-Pilot, C. Ridame, and C. Thomas (2002), Chemical characterization of the Saharan dust end-member: Some biological implications for the western Mediterranean, *J. Geophys. Res.*, *107*(D15), 4258, doi:10.1029/2001JD000582.
- Hand, J. L., N. M. Mahowald, Y. Chen, R. L. Siefert, C. Luo, A. Subramaniam, and I. Fung (2004), Estimates of atmospheric processed soluble iron from observations and a global mineral aerosol model: Biogeochemical implications, *J. Geophys. Res.*, *109*, D17205, doi:10.1029/2004JD004574.
- Jickells, T. D., and L. J. Spokes (2001), Atmospheric iron inputs to the ocean, in *Biogeochemistry of Iron in Seawater*, edited by D. Turner and K. A. Hunter, pp. 85–121, John Wiley, Hoboken, N. J.
- Jickells, T. D., et al. (2005), Global iron connections between dust, ocean biochemistry and climate, *Science*, *308*, 67–71, doi:10.1126/science.1105959.
- Journet, E., K. V. Desboefs, S. Caquineau, and J.-L. Colin (2008), Mineralogy as a critical factor of dust iron solubility, *Geophys. Res. Lett.*, *35*, L07805, doi:10.1029/2007GL031589.
- Kaufman, Y. J., et al. (2005), Dust transport and deposition observed from the Terra-MODIS space observations, *J. Geophys. Res.*, *110*, D10S12, doi:10.1029/2003JD004436.
- Keller, M., J. Melillo, and W. Z. de Mello (1997), Trace gas emissions from ecosystems of the Amazon basin, *Cienc. Cult.*, *49*, 87–97.
- Koren, I., Y. J. Kaufman, R. Washington, M. C. Todd, Y. Rudich, J. V. Martins, and D. Rosenfeld (2006), The Bodélé depression: A single spot in the Sahara that provides most of the mineral dust to the Amazon forest, *Environ. Res. Lett.*, *1*, 014005, doi:10.1088/1748-9326/1/1/014005.
- Mahowald, N. M., A. R. Baker, G. Berametti, N. Brooks, R. A. Duce, T. D. Jickells, N. Kubilay, J. M. Propero, and I. Tegen (2005), Atmospheric global dust cycle and iron inputs to the ocean, *Global Biogeochem. Cycles*, *19*, GB4025, doi:10.1029/2004GB002402.
- Mahowald, N., et al. (2008), Global distribution of atmospheric phosphorus sources, concentrations and deposition rates, and anthropogenic impacts, *Global Biogeochem. Cycles*, *22*, GB4026, doi:10.1029/2008GB003240.
- Millham, R. A., V. Martins, and M. C. Todd (2008), Mineral identification of dust emissions at the Bodele Depression, *Eos Trans. AGU*, *89*(53), Fall Meet. Suppl., Abstract A43A-0277.
- Mills, M. M., C. Ridame, M. Davey, J. La Roche, and R. J. Geider (2004), Iron and phosphorus co-limit nitrogen fixation in the eastern tropical North Atlantic, *Nature*, *429*, 292–294, doi:10.1038/nature02550.
- Monbet, P., G. J. Brunskill, I. Zagorskis, and J. Pfitzner (2007), Phosphorus speciation in the sediment and mass balance for the central region of the Great Barrier Reef continental shelf (Australia), *Geochim. Cosmochim. Acta*, *71*, 2762–2779, doi:10.1016/j.gca.2007.03.025.
- Moreno, T., X. Querol, S. Castillo, A. Alastuey, E. Cuevas, L. Herrman, M. Mounkaila, J. Elvira, and W. Gibbons (2006), Geochemical variations in Aeolian mineral particles from the Sahara-Sahel Dust Corridor, *Chemosphere*, *65*, 261–270, doi:10.1016/j.chemosphere.2006.02.052.
- Okin, G. S., N. Mahowald, O. A. Chadwick, and P. Artaxo (2004), Impact of desert dust on the biogeochemistry of phosphorus in terrestrial ecosystems, *Global Biogeochem. Cycles*, *18*, GB2005, doi:10.1029/2003GB002145.
- Prospero, J. M., P. Ginoux, O. Torres, S. E. Nicholson, and T. E. Gill (2002), Environmental characterization of global sources of atmospheric soil dust identified with the NIMBUS 7 TOMS absorbing aerosol product, *Rev. Geophys.*, *40*(1), 1002, doi:10.1029/2000RG000095.
- Sanchez, P., D. Bandy, J. Villachica, and J. Nicholaides (1982), Amazon Basin soils: Management for continuous crop production, *Science*, *216*, 821–827, doi:10.1126/science.216.4548.821.
- Schroth, A. W., J. Crusius, E. R. Sholkovitz, and B. C. Bostick (2009), Iron solubility driven by speciation in dust sources to the ocean, *Nat. Geosci.*, *2*, 337–340, doi:10.1038/ngeo501.
- Servant, M., and S. Servant-Vildary (1980), L'environnement quaternaire du bassin du Tchad, in *The Sahara and the Nile*, edited by M. A. J. Williams and H. Faure, pp. 133–162, Balkema, Rotterdam, Netherlands.
- Siefert, R. L., A. M. Johansen, and M. R. Hoffmann (1999), Chemical characterization of ambient aerosol collected during the southwest monsoon and intermonsoon seasons over the Arabian Sea: Labile-Fe(II) and other trace metals, *J. Geophys. Res.*, *104*(D3), 3511–3526, doi:10.1029/1998JD100067.
- Swap, R., M. Garstang, S. Greco, R. Talbot, and P. Kallberg (1992), Saharan dust in the Amazon Basin, *Tellus, Ser. B*, *44*, 133–149, doi:10.1034/j.1600-0889.1992.t01-1-00005.x.
- Talbot, R. W., R. C. Harriss, E. V. Browell, G. L. Gergory, D. I. Sebacher, and S. M. Beck (1986), Distribution and geochemistry of aerosols in the tropical North Atlantic troposphere: Relationship to Saharan dust, *J. Geophys. Res.*, *91*(D4), 5173–5182, doi:10.1029/JD091iD04p05173.
- Taylor, S. R., and S. M. McLennan (1995), The geochemical evolution of the continental crust, *Rev. Geophys.*, *33*, 241–265, doi:10.1029/95RG00262.
- Tegen, I., B. Heinold, M. Todd, J. Helmert, R. Washington, and O. Dubovik (2006), Modeling soil dust aerosol in the Bodélé Depression during the BoDEX campaign, *Atmos. Chem. Phys.*, *6*, 4345–4359, doi:10.5194/acp-6-4345-2006.
- Washington, R., and M. C. Todd (2005), Atmospheric controls on mineral dust emission from the Bodele Depression, Chad: The role of the low level jet, *Geophys. Res. Lett.*, *32*, L17701, doi:10.1029/2005GL023597.
- Washington, R., M. C. Todd, N. Middleton, and A. S. Goudie (2003), Dust-storm source areas determined by the total ozone monitoring spectrometer and surface observations, *Ann. Assoc. Am. Geogr.*, *93*, 297–313, doi:10.1111/1467-8306.9302003.
- Washington, R., M. C. Todd, S. Engelstaedter, S. Mbainayel, and F. Mitchell (2006), Dust and the low-level circulation over the Bodélé Depression,

- Chad: Observations from BoDEx 2005, *J. Geophys. Res.*, *111*, D03201, doi:10.1029/2005JD006502.
- Washington, R., C. Bouet, G. Cautenet, E. Mackenzie, I. Ashpole, S. Engelstaedter, G. Lizcano, G. M. Henderson, K. Schepanski, and I. Tegen (2009), Dust as a tipping element: The Bodélé Depression, Chad, *Proc. Natl. Acad. Sci. U. S. A.*, *106*, 20,564–20,571, doi:10.1073/pnas.0711850106.
- Wedepohl, K. H. (1995), The composition of continental crust, *Geochim. Cosmochim. Acta*, *59*, 1217–1232, doi:10.1016/0016-7037(95)00038-2.
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