

Title

Characterization and aerosol mass balance of PM_{2.5} and PM₁₀ collected in Conakry, Guinea during the 2004 Harmattan period

Authors

Jason P. Weinstein ^{a,*}, Scott R. Hedges ^b, Sue Kimbrough ^a

Affiliations

^a U.S. EPA, 109 Alexander Drive, Durham, NC 27711, USA

^b U.S. EPA, 1200 Pennsylvania Avenue, N.W., Washington, DC 20460, USA

Corresponding author information

Address: U.S. EPA MD-E205-03, 109 Alexander Drive, RTP, NC 27711, USA

Telephone: 1-919-541-2717

Fax: 1-919-541-0960

Email: weinstein.jason@epa.gov

Abstract

Background PM_{2.5} and PM₁₀ levels were determined during Harmattan (West African wind blown dust) at a background site in Conakry, Guinea. The study was conducted from January to February, 2004 when Harmattan dust appeared to be most pronounced. PM_{2.5} concentrations at the Nongo American housing compound ranged from 38 $\mu\text{g m}^{-3}$ to 177 $\mu\text{g m}^{-3}$, and PM₁₀ ranged from 80 $\mu\text{g m}^{-3}$ to 358 $\mu\text{g m}^{-3}$, exceeding standards set by EPA and European Commission Environment Directorate-General. PTFE filter samples were analyzed for insoluble and soluble inorganic constituents by XRF and IC,

26 respectively. Sulfur and associated SO_4^{2-} concentrations were notably consistent among
27 $\text{PM}_{2.5}$ and PM_{10} samples which marked a relatively stable S background signal from
28 anthropogenic sources. Enrichment factor (EF) analysis and aerosol mass reconstruction
29 (AMR) techniques were used to isolate potential PM source contributors. The EF's for
30 SiO_2 , TiO_2 , Al_2O_3 , Fe_2O_3 , and MnO were near unity which suggests a crustal origin for
31 these elements. EF's for Na_2O and K_2O were above unity and highly variable, these
32 elements were elevated due to widespread mangrove wood combustion as a fuel source in
33 Conakry. The EF's for Cr were notably high with a median of 7 and interquartile range
34 from 5 to 16, the elevated levels were attributed to unregulated point source and mobile
35 source emitters in and around Conakry.

36

37 **Keywords**

38 Conakry, Guinea, Harmattan, Particulate matter, Enrichment factor, Mass reconstruction

39

40 **1. Introduction**

41 The United States EPA conducted a six week air quality screening survey of the city
42 of Conakry, Guinea, West Africa in 2004 at the request of the U.S. Embassy in Conakry.
43 The study was conducted to assess the background levels of anthropogenic and natural
44 particulate matter (PM) and to investigate the local and regional sources of those
45 pollutants. This paper presents the first reported concentrations of airborne particulate
46 from one of the world's dirtiest cities (Luck, 2008).

47 The air quality survey was conducted from January 11 through February 22, 2004.
48 This period was selected because Conakry was in the middle of the dry season when
49 visible air pollution appears to be most pronounced. The survey period overlaps with the

50 Harmattan dust season where cool, dry trade winds blow from the Sahara Desert toward
51 the southwest from November to March every year (Breuning-Madsen and Awadzi,
52 2005).

53 Conakry has a wide range of environmental and public health problems including
54 respiratory illnesses due to elevated levels of air pollution (World Health Organization,
55 2006a). Local pollution sources include: unregulated combustion and processing
56 emissions from industrial point sources, unregulated emissions from leaded gasoline
57 vehicles, widespread open pit burning of household and vegetative waste, and residential
58 wood burning cooking ovens. The local industrial point source emitters include: an
59 asphalt manufacturing plant, cement manufacturing plant, diesel and fuel oil combustion
60 electric power plants, brick manufacturing operation, fish processing and smoking
61 facilities, brewery, soft drink bottling plant, soap manufacturing facility, plastic injection
62 molding facility, steel smelter, paint formulation plant, medical waste incinerator, and
63 major bauxite, alumina, and cement operations (Fig. 1; Bermudez-Lugo, 2006).

64 This paper presents concentrations of $PM_{2.5}$ integrated and real-time samples and
65 PM_{10} integrated samples. The integrated samples were chemically characterized by XRF
66 for inorganic constituents, ion chromatography (IC) for soluble species, and a limited
67 number of elemental carbon (EC) and organic carbon (OC) measurements using a
68 thermo-optical method. The paper explores the relative contributions of local pollution
69 sources, the influence of Harmattan dust influx, and the possible sea salt aerosol
70 contribution.

71

72 **2. Methods**

73 *2.1. Study Area*

74 Guinea is located on the Atlantic coast of West Africa and is bordered by Guinea-
75 Bissau, Senegal, Mali, Cote d'Ivoire, Liberia, and Sierra Leone. The country is divided
76 into four geographic regions: a narrow coastal belt (Lower Guinea), the pastoral Fouta
77 Djallon highlands (Middle Guinea), the northern savannah (Upper Guinea), and a
78 southeastern rain forest region (Forest Guinea). Lower Guinea has a tropical climate with
79 a rainy season lasting from April to November, relatively high and uniform temperatures,
80 and high humidity. The dry season spans November to March and features a cool, dry,
81 dust-laden trade wind originating from the Sahara Desert, termed Harmattan wind
82 (Adepetu et al., 1988).

83 The capital of Guinea, Conakry, is located on the west coast of the country on a
84 peninsula extending into the Atlantic Ocean. Conakry has a population of approximately
85 2 million people located on the peninsula and partially on the mainland toward the east
86 with a total area of approximately 135 km² (The World Bank Sub-Saharan Africa
87 Transport Policy Program, 2004). Conakry's year round average high temperature is 29
88 °C and the low is 23 °C with an average annual rainfall of 430 cm. During Harmattan,
89 Conakry is uniquely situated on the Inclined Meteorological Equator (IME) which forms
90 the west-east boundary between the northeast trade winds and the southwest monsoon in
91 the West African region (Giresse, 2008). The IME migrates seasonally which establishes
92 the wet and dry seasons in West Africa; the northerly migration establishes the rainy
93 season and southerly migration establishes the dry season (Dupont et al., 1996).

94

95 2.2. Sampling and analysis

96 The bulk of the air quality monitoring was conducted at a secure background site
97 located at the northeast corner of the Nongo American housing compound. The
98 background site was located north of the geographic center of Conakry and had no major

99 emission sources within 100 m, as such, it meteorologically and geographically
100 represented typical ambient PM in the Conakry area. The PM sampling devices were
101 located on scaffolding 4.3 m above the ground per the U.S. Code of Federal Regulations
102 40 CFR 58, Appendix E for ambient air quality monitoring (U.S. Code of Federal
103 Regulations, 2002).

104 Point source air quality monitoring was conducted at fifteen sites in addition to the
105 background PM sampling effort at Nongo. A variety of sampling technologies and
106 techniques were employed during the air quality survey. This paper presents the
107 quantitative results from the most robust sampling techniques, namely, the 24 h PM filter
108 samples. One 24 h filter sample was collected at a home in the Sangoyah district of
109 Conakry to measure PM from prolific residential outdoor cooking. Another 24 h filter
110 sample was collected at the Guinean government's Presidential Palace site which is in
111 strikingly close proximity to the alumina, bauxite, and cement ship loading operations
112 (Fig. 1).

113 Two MiniVol (Airmetrics) portable, battery-powered samplers were used to collect
114 24 h PM_{2.5} and PM₁₀ (particle equivalent aerodynamic diameter less than or equal to
115 2.5µm and 10µm, respectively) on 47 mm polytetrafluoroethylene (PTFE) and quartz
116 filters at the Nongo background site (Hill et al., 1999). The MiniVol samplers were
117 subject to the following field QC procedures: leak and zero flow check, rotameter
118 adjustment to 5 L min⁻¹, and flow rate recording before and after each run. Field and
119 transportation blank filters were collected for contamination assessment. An EPAM-
120 5000 (Environmental Devices Corporation) real-time aerosol nephelometer provided 10 s
121 continuous PM_{2.5} measurement data in conjunction with a 47 mm backup PTFE filter at
122 three sampling sites. EPAM-5000 measurements were scaled to the corresponding
123 gravimetric mass results from the MiniVol filter samples. Gravimetric results from the

MiniVol filters were considered more representative of the actual PM levels than those measured by nephelometry. The field sampling matrix is described in Table 1.

PTFE filter (Whatman 2 μ m pore size) samples were pre- and post-weighed in a temperature and humidity controlled chamber using a Mettler ME22 balance with a BE22 control unit and BA25 electronic display. 47 mm quartz fiber filters were punched from 20 cm x 25.4 cm sheets of Pallflex Tissuquartz sheet, heated overnight at 500 °C, and sealed in Petri dishes for transport to the field.

The inorganic constituents of the PTFE filters were determined by energy-dispersive X-ray fluorescence (XRF) using a Kevex EDX-771 spectrometer. The instrument sample chamber maintained a positive flow of helium gas to minimize the loss of volatile species. The XRF procedures are listed in the EPA Compendium of Methods for the Determination of Inorganic Compounds in Ambient Air Method IO-3.3 (U.S. Environmental Protection Agency, 1999). NIST SRM 1833 and SRM 1832 standards were analyzed immediately before and after the unknown filter samples and the QC results were within the NIST certified value range. PTFE filter samples were subsequently extracted in deionized water using a heated ultrasonic bath for 15 min and analyzed for major ions using a Dionex DX-500 IC. The IC procedures are listed in Method A of the EPA Method 300.0 Determination of Inorganic Anions by Ion Chromatography (Pfaff, 1993).

Elemental carbon (EC) and organic carbon (OC) analyses were performed on five PM_{2.5} quartz filters collected with the MiniVol sampler at the Nongo background site. One quartz filter was analyzed in duplicate with two 1.45 cm² punch samples and the resulting analytical precision was 0.25%. The EC/OC analysis was performed with a custom made thermo-optical transmission instrument by Sunset Laboratory Inc. per the NIOSH Standard Method 5040 (Birch, 1999).

149 The sampling equipment and filter samples were transported from the U.S. to
150 Conakry and back to the U.S. via standard passenger airline transport methods. The filter
151 samples were individually labeled and sealed in sterilized 49mm molded polystyrene
152 petri dishes (Millipore Corp., product number: PD1004700).

153

154 **3. Results and discussion**

155 *3.1. Particulate mass concentration*

156 Table 1 gives a summary of the concentrations of PM_{2.5} and PM₁₀ collected with the
157 MiniVol and EPAM-5000 samplers. PM_{2.5} concentrations at the Nongo site ranged from
158 38 $\mu\text{g m}^{-3}$ to 177 $\mu\text{g m}^{-3}$, and PM₁₀ ranged from 80 $\mu\text{g m}^{-3}$ to 358 $\mu\text{g m}^{-3}$. Concentrations
159 of PM_{2.5} and PM₁₀ increased markedly on February 6 through February 13 which
160 coincided with field observations of unusually strong Harmattan winds during that
161 period. As shown in Fig. 2, real-time measurements of PM_{2.5} at the Nongo background
162 site indicate baseline levels of approximately 20 $\mu\text{g m}^{-3}$ to 40 $\mu\text{g m}^{-3}$ with pronounced
163 spikes into the mg m^{-3} range from 0200 to 0600 Coordinated Universal Time (UTC \pm 0).
164 On February 6, the baseline concentrations of PM_{2.5} began to rise at approximately 1400
165 UTC \pm 0 which corresponded with the onset of a strong Harmattan wind event that lasted
166 several days. The origin of the pronounced PM_{2.5} concentration spikes is unknown, one
167 plausible explanation is the initiation of a major industrial activity or set of activities from
168 the port of Conakry or land-based point source polluters (Fig. 1).

169 The PM_{2.5} filter sample collected at the Sangoyah residential cooking site had an
170 integrated concentration of 187 $\mu\text{g m}^{-3}$. The real-time analysis at that location marked a
171 PM_{2.5} baseline of approximately 200 $\mu\text{g m}^{-3}$ with substantial spikes during the majority of
172 the daylight hours (Fig. 2). The PM_{2.5} filter sample collected at the Presidential Palace
173 site had an integrated concentration of 76 $\mu\text{g m}^{-3}$. The real-time analysis showed a

jagged PM_{2.5} baseline centered on 30 $\mu\text{g m}^{-3}$ and there were pronounced PM_{2.5} concentration spikes at several times throughout the day and night with a sustained PM spike at approximately 1300 UTC \pm 0 (Fig. 2).

Overall, sustained PM_{2.5} and PM₁₀ levels were high and spike levels were extremely high in comparison to PM regulations promulgated by the U.S. EPA, the European Union Directorate-General (DG Environment), and guidelines adopted by the World Health Organization (WHO). The EPA National Ambient Air Quality Standards (NAAQS) established a 24 h average concentration of 35 $\mu\text{g m}^{-3}$ for PM_{2.5} and 150 $\mu\text{g m}^{-3}$ for PM₁₀ (U.S. Code of Federal Regulations, 2008). The European Commission and the WHO established a 24 h average concentration of 25 $\mu\text{g m}^{-3}$ for PM_{2.5} and 50 $\mu\text{g m}^{-3}$ for PM₁₀ (World Health Organization, 2006; European Parliament and the Council of the European Union, 2008). Further, the EPA and DG Environment set the annual arithmetic mean for PM_{2.5} at 15 $\mu\text{g m}^{-3}$ and 25 $\mu\text{g m}^{-3}$, respectively. DG Environment specifies a 40 $\mu\text{g m}^{-3}$ annual arithmetic mean for PM₁₀. Every PM_{2.5} filter sample collected during the study period exceeded the standards set by EPA and DG Environment; every PM₁₀ filter sample exceeded 24 h and annual mean standards set by DG Environment.

3.2. Elemental concentrations

The average concentrations of inorganic chemical species at three sampling sites are given in Table 2. Elemental concentrations at the Nongo background site were highly variable for most major elements (Cl⁻, NO₃⁻, Na, Mg, Al, Si, K, Ca, and Fe) in both the PM_{2.5} and PM₁₀ modes. The sulfur and associated sulfate concentrations are notably consistent among all sample modes and sampling locations. The source for ambient sulfur was likely the unregulated combustion of fossil fuels in motor vehicles and

198 industrial point sources. The Conakry area contained over 90% of the vehicles on the
199 road in the entire country and field observations during the sampling period indicated that
200 a vast majority of motor vehicles had visible smoke emanating from the tailpipe (The
201 World Bank Sub-Saharan Africa Transport Policy Program, 2004). Industrial point
202 sources including electric power generation, public works, and the mining industry
203 generated unregulated emissions from the combustion of diesel and fuel oil (International
204 Monetary Fund, 2008). Lead was detected in $PM_{2.5}$ and PM_{10} at the Nongo background
205 site and the Presidential Palace site which was likely due to the use of leaded gasoline in
206 motor vehicles. All filter samples had Pb levels below ambient exposure regulatory
207 standards set by the EPA (U.S. Code of Federal Regulations, 2008).

208 Significant elemental concentration differences were observed between the Nongo
209 background site, the Sangoyah residential cooking site, and the Presidential Palace site.
210 The Sangoyah residential cooking site was an effective source marker for the combustion
211 of mangrove wood and charcoal in outdoor residential cooking. Field observations
212 indicated that residential cooking fires are routinely ignited with plastic. Mangrove wood
213 is an abundant and easily obtained fuel source in Conakry as it grows in the estuarine
214 environments surrounding the city. Mangrove wood combustion emissions are relatively
215 enriched in K, Na, Ca, Mg, Cl, and SO_4^{2-} (Loto and Fakankun, 1989). The ambient
216 concentrations of K, Na, and Cl at Sangoyah were 2 to 10 times higher than those at the
217 Nongo background site due to the combustion of mangrove wood. The Presidential
218 Palace site was an effective source marker for the aerosolization of alumina (Al_2O_3) and
219 Portland cement (65% CaO, 20% SiO_2) dust due to the short distance and geographic
220 proximity to major ship loading operations handling those materials (Ilyasov et al., 2008).
221 The Presidential Palace $PM_{2.5}$ Al concentration was 1.8 times higher than the median

PM_{2.5} background concentration measured at Nongo, Si was 1.63 times higher, and Ca was over 12 times higher. The relatively high Ca signal was due to the widespread cement dust fallout from the port operations. Ground observations noted that a white dust perpetually covered grass, plants, vehicles, roads, and buildings near the port and surrounding neighborhoods.

3.3. IC versus XRF

IC results were compared with XRF results as a QC check between the analytical methods and to assess the soluble components of PM. Sulfate, as measured by IC, was converted to sulfur ($S_{IC} = \frac{[SO_4^{2-}]_{IC}}{2.995}$) in order to compare with elemental S by XRF.

Good inter-method agreement was observed for S ($r = 0.91$), Na ($r = 0.95$), Cl ($r = 0.95$), and K ($r = 0.90$). The recovery rate, PM_r , for each soluble species was estimated using Eq. (1),

$$PM_r = \sum E_i \left(\frac{IC_{Ei}}{XRF_{Ei}} \right) \quad (1)$$

where E_i is the element of interest, IC_{Ei} is the individual elemental concentration as measured by IC, and XRF_{Ei} is the individual elemental concentration as measured by XRF. Eq. (1) includes both PM_{2.5} and PM₁₀ samples and PM_r showed a mean and standard deviation as follows: $S_{mean} 0.823 \pm 0.114$, $Na_{mean} 0.816 \pm 0.364$, $Cl_{mean} 0.667 \pm 0.324$, and $K_{mean} 0.785 \pm 0.201$. The high recovery rates suggest that these elements are largely unassociated with the local or regional deposition of insoluble Harmattan dust; rather, they are associated with anthropogenic emissions, aerosolized sea salt, or both. In this study, the sea salt component in measured PM could not be estimated due to the pervasive open vegetative burning for residential cooking and waste disposal in Conakry;

these burning activities contributed substantially to the overall soluble Na and Cl signature as seen in the Sangoyah residential cooking site PM_{2.5} sample (Table 2). In contrast to other well known air sheds characterized in the literature, it cannot be assumed that the soluble Na and Cl are solely due to sea salt (Cheng et al., 2005).

3.4. Enrichment factor analysis

The enrichment factor (EF) for each measured element was calculated to understand the relative contribution of Harmattan dust and anthropogenic emissions in the Conakry air shed. Typically, Al is used as a reference element because it has no significant anthropogenic source (Petaloti et al., 2006). However, Conakry had many potential sources of anthropogenic Al from the mining and refinement of bauxite ore. Further, Guinea featured the world's largest bauxite reserves which comprised the bulk of exposed soil in Lowland-Guinea (Boulange et al., 1996; Plunkert, 2002). Titanium was used a reference element for Saharan-blown desert sand comprising the Harmattan dust (Eltaieb et al., 2001). The EF for each elemental component in PM was calculated using Eq. (2),

$$EF = \frac{[E]_{PM} / [Ti]_{PM}}{[E]_{soil} / [Ti]_{soil}} \quad (2)$$

where $[E]_{PM}$ and $[Ti]_{PM}$ are normalized XRF concentrations, in $\mu\text{g g}^{-1}$, of the elemental component of interest and Ti in the PM sample; $[E]_{soil}$ and $[Ti]_{soil}$ are the average concentrations of the elemental component and Ti in Harmattan dust.

The PM airborne concentration data were converted to $\mu\text{g g}^{-1}$ according to Eq. (3),

$$[E]_{PM} = \sum \frac{Ei (1 \times 10^{-3} DF)}{M} \quad (3)$$

where Ei is the element of interest in ng m^{-3} , D is the sampling duration in min, F is the sampler flow rate in L min^{-1} , and M is the total measured PM mass on the filter in mg. Eq. (3) values were converted to their corresponding element oxide forms for the most abundant elements: SiO_2 , TiO_2 , Al_2O_3 , Fe_2O_3 , MnO , MgO , CaO , Na_2O , and K_2O . The trace elements Cr and Zn were left in their elemental form. The summation of the 11 elements of interest for each sample was normalized to 100% to facilitate the EF calculation for each element.

A composite Harmattan dust profile was created using instrumental neutron activation analysis (INAA) data from Adepetu et al. (1988), and XRF data from Eltayeb et al. (2001). The INAA method does not routinely include Si and Ca; the absolute concentrations of these elements were estimated from the $2.6 \mu\text{m}$ tick line in Figure 2 from Eltayeb et al. (2001). The major elements Si, Ti, Al, Fe, Mn, Mg, Ca, Na, and K were converted to their crustal oxide forms and the results added to the reported concentrations of the trace elements As, Au, Ba, Br, Ce, Co, Cr, Cs, Eu, Ga, Hf, La, Rb, Sb, Sc, Se, Sm, Th, U, V, and Zn. The resulting summation of absolute concentrations was normalized to 100%, and the results of the Harmattan dust profile are given in Table 3.

The $\text{PM}_{2.5}$ and PM_{10} elemental concentrations were first converted to μg per filter, then converted to weight percent (wt%) for major element oxides and $\mu\text{g g}^{-1}$ for trace elements, and finally converted to the crustal oxide forms for major elements. The EF analysis results are presented in Fig. 3. The TiO_2 EF median and interquartile range is close to unity which suggests the valid application of this element as a reference. EF's for SiO_2 , Al_2O_3 , Fe_2O_3 , and MnO are also close to unity which suggests a crustal origin for these elements. The EF's for Na_2O , and K_2O show a wide range which suggests variable sources for these elements. Calcium oxide is relatively depleted compared to the

Harmattan dust profile for $PM_{2.6}$ presented in Eltayeb et al. (2001), this relationship is likely the result of a poor estimate of the Ca concentration in the composite profile due to widely variable levels of Ca as a function of PM cut point in the original measurements. The relatively large range observed between the 5th and 95th percentile box plot whiskers for Zn suggests a widely variable source in Conakry (Fig. 3). The median Zn EF value is significantly below unity which indicates a weakness in the EF analysis for Zn. The original Harmattan dust profile data sources reported unusually high Zn concentrations which they attributed to possible anthropogenic contributions for Zn. The Harmattan PM concentration data obtained from the literature for Si, Al, Fe, Mn, Na, K, and Cr were reported as representative values for wind blown dust originating from the Saharan region of Nigeria and Sudan (Adepetu et al., 1988; Eltayeb et al., 2001).

The EF for Cr is notably high with a median greater than 7 and an interquartile range from 5 to 16. All $PM_{2.5}$ and PM_{10} samples have Cr EF values that are moderately to significantly higher than the Harmattan dust profile which suggests an anthropogenic source influence for Cr (Sutherland, 2000). Anthropogenic emissions of Cr are well documented in the combustion of fuel oil and coal for power generation, cement production, refractory brick production, and refuse incineration (Nriagu and Nieboer, 1988). All of these known Cr emitting point source types were present in the greater Conakry area. Additionally, the point source and mobile source emitters in and around Conakry had no emission control devices to reduce probable emissions of Cr and other toxic metals.

3.5. Mass reconstruction

An aerosol mass reconstruction (AMR) analysis was conducted to explore the relative contributions of the measured inorganic and organic chemical species and their

relationship to the total measured gravimetric mass. On five sampling days the two MiniVol samplers were collocated at the Nongo background site and PM_{2.5} was collected on both PTFE and quartz filters for inorganic and organic analysis, respectively (Table 1).

The AMR was performed using the method from Edgerton et al. (2005). The calculation differed slightly in that no nylon filters were collected during this study. The volatilized component of NO₃⁻ and NH₄⁺ on the PTFE filters was therefore not quantified. The mass reconstruction for the sample collected on February 7, 2004 was omitted from further discussion due to a malfunction detected on the MiniVol sampler with the PTFE filter, the AMR recovery rate was erroneously calculated at 152% of measured mass.

The total recovery rate, $R\%$, is calculated according to Eq. (4),

$$R\% = \left(\frac{\sum E_i}{M_{\text{grav}}} \right) \times 100 \quad (4)$$

where $\sum E_i$ is the sum of the mass concentrations of the individual species and M_{grav} is the measured gravimetric mass on the PTFE filter. Overall, the recover rates were very good with values of 92%, 71%, 92%, and 95% (Fig. 4).

The AMR analysis shows that the organic matter and metal oxide components comprise the vast majority of the sample, yet these components vary significantly among the samples. In contrast, the EC, sulfate, nitrate, and ammonium values represent a consistently small portion of each sample (Fig. 4). The relatively large organic matter values, low EC/Total carbon ratios, and low sulfate values strongly suggest a significant wood burning source contribution in the PM_{2.5} samples (Hays et al., 2002). Further, the relatively high EF's for K in the Nongo background site samples coupled with the high

concentrations of K, Cl, and Na measured at the Sangoyah residential cooking site and the results of the AMR analysis indicate wood burning was a significant source of air pollution in Conakry (Khalil et al., 2003). The significant wood burning contribution to the local pollution inventory is consistent with the 2×10^6 kg of mangrove wood that is burned in Conakry per year, based on conservative estimates (International Monetary Fund, 2008). The local meteorological conditions during the study period support the assertion that wood burning was partly responsible for elevated $PM_{2.5}$ concentrations in Conakry. The 24 h mean wind speed for all sampling days, as measured at Gbessia international airport, was relatively calm with a range from 7.96 km h^{-1} to 13.15 km h^{-1} (National Weather Service AWIPS NDW, 2009).

4. Conclusions

A unique air quality study was conducted during Harmattan in Conakry, Guinea in 2004. A combination of integrated and real-time PM sampling instruments collected samples over a one month period. Real-time $PM_{2.5}$ measurements indicated high baseline levels of PM coupled with markedly high PM spikes from 0200 to 0600 UTC \pm 0. The origin of the $PM_{2.5}$ spikes is uncertain; however, the source was likely a local or regional industrial point source emitter with substantial stack emissions. Every integrated $PM_{2.5}$ filter sample exceeded ambient air quality standards set by EPA and DG Environment and every PM_{10} filter sample exceeded 24 h and annual mean standards set by DG Environment.

A series of mass balance calculations were used to assess the relative contributions of unregulated industrial point source and mobile source emissions, widespread municipal and industrial burning emissions, and the Harmattan dust influx. Results suggest that the majority of the background $PM_{2.5}$ and PM_{10} originated from a

combination of pervasive open vegetative burning and Harmattan dust influx with a smaller contribution from fossil fuel combustion sources. The contribution from the wide variety of unregulated fossil fuel combustion sources was not insignificant. The majority of filter samples contained Pb in both the PM_{2.5} and PM₁₀ mode. Chromium in all filter samples substantially exceeded levels seen in wind blown dust from the Sahara desert region. Overall, this study highlighted the composite effects of an expansive, diverse, and largely unregulated emissions suite coupled with the seasonal Harmattan dust events and Conakry's geographic position on the IME.

Acknowledgements

The authors thank Sékouba Kaloga and Mahawa Sylla of the Ministerial Department for the Environment, Conakry, Guinea for their technical support and daily participation in the field monitoring effort. We wish to recognize the professional staff at the U.S. Embassy in Conakry, Guinea for their geospatial assistance. We wish to thank Richard Dulaney, CSC, for locating unique spatial road and polygon coverages. Kind recognition is given to Dr. David J. Williams, U.S. EPA, for satellite imagery analysis of unclassified geospatial information. The authors recognize Dr. Charles W. Lewis, U.S. EPA (deceased) for his help with the original enrichment factor analysis.

The United States Environmental Protection Agency through its Office of Research and Development funded and managed the research described here. It has been subjected to Agency's administrative review and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

388 **References**

- 389 Adepetu, J. A., Asubiojo, O. I., Iskander, F. Y., & Bauer, T. L., 1988. Elemental
390 composition of Nigerian harmattan dust. *J Radioan Nucl Ch Ar.* 121, 141-147.
391
- 392 Bermudez-Lugo, O., 2006. USGS minerals information: Africa and the Middle East.
393 USGS minerals yearbook 2004. The mineral industry of Guinea in 2004. Retrieved Aug.
394 8, 2009, from <http://minerals.usgs.gov/minerals/pubs/country/africa.html#gv>
395
- 396 Birch, M. E., 1999. NIOSH manual of analytical methods, NMAM. Retrieved Aug. 20,
397 2009, from <http://www.cdc.gov/NIOSH/nmam/method-6000.html>
398
- 399 Boulange, B., Bouzat, G., & Pouliquen, M., 1996. Mineralogical and geochemical
400 characteristics of two bauxitic profiles, Fria, Guinea. *Miner Deposita.* 31, 432-438.
401
- 402 Breuning-Madsen, H. & Awadzi, T. W., 2005. Harmattan dust deposition and particle
403 size in Ghana. *Catena.* 63, 23-38.
404
- 405 Cheng, M. T., Lin, Y. C., Chio, C. P., Wang, C. F., Kuo, C. Y., 2005. Characteristics of
406 aerosols collected in central Taiwan during an Asian dust event in spring 2000.
407 *Chemosphere.* 61, 1439-1450.
408
- 409 Dupont, L. M. & Weinelt, M., 1996. Vegetation history of the savanna corridor between
410 the Guinean and the Congolian rain forest during the last 150,000 years. *Veget Hist*
411 *Archaeobot.* 5, 273-292.
412

413 Edgerton, E. S., Hartsell, B. E., Saylor, R. D., & Jansen, J. J., Hansen, D. A., Hidy, G.
 414 M., 2005. The southeastern aerosol research and characterization study: Part II. Filter-
 415 based measurements of fine and coarse particulate matter mass and composition. *J Air*
 416 *Waste Manage.* 55, 1527-1542.

417

418 Eltayeb, M. A. H., Injuk, J., Maenhaut, W., Van Grieken, R. E., 2001. Elemental
 419 composition of mineral aerosol generated from Sudan Sahara sand. *J Atmos Chem.* 40,
 420 247-273.

421

422 European Parliament and the Council of the European Union., 2008. Air quality - existing
 423 legislation. Directive 2008/50/EC of the European parliament and of the council of 21
 424 May 2008 on ambient air quality and cleaner air for Europe. Retrieved Aug. 19, 2009,
 425 from [http://eur-](http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32008L0050:EN:NOT)
 426 [lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32008L0050:EN:NOT](http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32008L0050:EN:NOT)

427

428 Giresse, P., 2008. Tropical And Sub-Tropical West Africa. Marine And Continental
 429 Changes During The Late Quaternary. Elsevier Science, Burlington, Massachusetts.

430

431 Hays, M. D., Geron, C. D., Linna, K. J., & Smith, N. D., Schauer, J. J., 2002. Speciation
 432 of gas-phase and fine particle emissions from burning of foliar fuels. *Environ Sci*
 433 *Technol.* 36, 2281-2295.

434

435 Hill, J. S., Patel, P. D., & Turner, J. R., 1999. Performance characterization of the
 436 MiniVol PM_{2.5} sampler. 92nd Annual Meeting of the Air & Waste Management
 437 Association. 99, 1-18.

438

439 Ilyasov, A. G., Medvedeva, I. N., & Korneev, V. I., 2008. Accelerants for the setting and
 440 hardening of portland cement based on aluminum oxides and hydroxides. *Metallurgist*.
 441 52, 738-743.

442

443 International Monetary Fund., 2008. IMF publications. Guinea: Poverty reduction
 444 strategy paper. IMF country report No. 08/7. Retrieved Aug. 5, 2009, from
 445 <http://www.imf.org/external/pubs/cat/longres.cfm?sk=21579.0>

446

447 Khalil, M. K. & Rasmussen, R. A., 2003. Tracers of wood smoke. *Atmos Environ.* 37,
 448 1211-1222.

449

450 Loto, C. A. & Fakankun, O. A., 1989. Characterization of the ashes of Nigerian red and
 451 white mangrove woods. *Wood Sci Technol.* 23, 357-360.

452

453 Luck, T. M., 2008. Pollution: The World's Dirtiest Cities 2007. Retrieved Dec. 4, 2009,
 454 from [http://www.forbes.com/2008/02/26/pollution-baku-oil-biz-logistics-](http://www.forbes.com/2008/02/26/pollution-baku-oil-biz-logistics-cx_tl_0226dirtycities.html?feed=rss_popstories)
 455 [cx_tl_0226dirtycities.html?feed=rss_popstories](http://www.forbes.com/2008/02/26/pollution-baku-oil-biz-logistics-cx_tl_0226dirtycities.html?feed=rss_popstories)

456

457 National Weather Service AWIPS NDW., 2009. Retrieved Sep. 23, 2009, from
 458 <http://www.nws.noaa.gov/ndm/>

459

460 Nriagu, J. O., & Nieboer, E., 1988. Chromium In The Natural And Human Environments.
 461 John Wiley & Sons, Inc, New York, New York.

462

463 Petaloti, C., Triantafyllou, A., & Kouimtzis, T., 2006. Trace elements in atmospheric
 464 particulate matter over a coal burning power production area of western Macedonia,
 465 Greece. *Chemosphere*. 65, 2233-2243.
 466
 467 Pfaff, J. D., 1993. Clean Water Act Analytical, Approved General-Purpose Methods.
 468 Method 300.0 Determination of Inorganic Anions by Ion Chromatography Revision 2.1.
 469 Retrieved July 20, 2009, from <http://www.epa.gov/waterscience/methods/method>
 470
 471 Plunkert, P. A., 2002. USGS Minerals Yearbook 2000. Bauxite and alumina. Retrieved
 472 Aug. 20, 2009, from <http://minerals.usgs.gov/minerals/pubs/commodity/bauxite/>
 473
 474 Sutherland, R. A., 2000. Bed sediment-associated trace metals in an urban stream, Oahu,
 475 Hawaii. *Environ Geol*. 39, 611-627.
 476
 477 The World Bank Sub-Saharan Africa Transport Policy Program., 2004. Sub-Saharan
 478 Africa transport policy program- Guinea. Poverty and urban mobility in Conakry SSATP
 479 Report No. 09/04/CKR. Retrieved Aug. 5, 2009 from
 480 <http://go.worldbank.org/DAT5LR0A90>
 481
 482 U.S. Code of Federal Regulations., 2002. Title 40--Protection of Environment. Chapter I--
 483 -Environmental Protection Agency. Part 58- ambient air quality surveillance. Retrieved
 484 Aug. 20, 2009 from http://www.access.gpo.gov/nara/cfr/waisidx_02/40cfr58_02.html
 485
 486 U.S. Code of Federal Regulations., 2008. Title 40--Protection of Environment Chapter I--
 487 Environmental Protection Agency, continued Part 50--national primary and secondary

488 ambient air quality standards. Retrieved July 20, 2009 from
489 http://www.access.gpo.gov/nara/cfr/waisidx_08/40cfr50_08.html
490
491 U.S. Environmental Protection Agency., 1999. Air monitoring methods - inorganic, IO
492 compendium methods. Compendium method IO-3.3. Determination of metals in ambient
493 particulate matter using X-ray fluorescence, XRF spectroscopy. Retrieved July 31, 2009
494 from <http://www.epa.gov/ttnamti1/inorg.html>
495
496 World Health Organization., 2006a. World health organization. Country Health System
497 Fact Sheet 2006. Retrieved Dec. 4, 2009 from
498 http://www.afro.who.int/home/countries/fact_sheets/guinea.pdf
499
500 World Health Organization., 2006b. World health organization. Public health and
501 environment, PHE. Air quality guidelines - global update 2005. WHO Air quality
502 guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide.
503 WHO/SDE/PHE/OEH/06.02. Retrieved Aug. 3, 2009 from
504 http://www.who.int/phe/health_topics/outdoorair_aqg/en/
505

1 **Tables**2 **Table 1**3 **Description of sampling matrix and gravimetric analysis**

Sampling date	Sample type	Filter type	Instrument	Location	Sampler flow rate (L m ⁻¹)	PM concentration (µg m ⁻³)
2004-01-19	PM _{2.5}	PTFE	MiniVol	Nongo	5.15	73
2004-01-19	PM ₁₀	PTFE	MiniVol	Nongo	5.10	84
2004-01-19	PM _{2.5}	PTFE	EPAM-5000	Nongo	4.00	62
2004-01-21	PM _{2.5}	PTFE	MiniVol	Nongo	5.25	57
2004-01-21	PM ₁₀	PTFE	MiniVol	Nongo	5.25	85
2004-01-21	PM _{2.5}	PTFE	EPAM-5000	Nongo	4.00	52
2004-01-23	PM _{2.5}	PTFE	MiniVol	Nongo	5.25	45
2004-01-23	PM ₁₀	PTFE	MiniVol	Nongo	5.20	92
2004-01-24	PM _{2.5}	PTFE	MiniVol	Nongo	5.20	55
2004-01-24	PM ₁₀	PTFE	MiniVol	Nongo	5.10	80
2004-01-26	PM _{2.5}	PTFE	MiniVol	Nongo	5.15	77
2004-01-26	PM _{2.5}	Quartz	MiniVol	Nongo	5.20	-
2004-01-28	PM _{2.5}	PTFE	MiniVol	Nongo	5.30	44
2004-01-28	PM ₁₀	PTFE	MiniVol	Nongo	5.05	100
2004-01-30	PM _{2.5}	PTFE	MiniVol	Nongo	5.30	53
2004-01-30	PM ₁₀	PTFE	MiniVol	Nongo	5.20	94
2004-01-31	PM _{2.5}	PTFE	MiniVol	Nongo	5.30	38
2004-01-31	PM ₁₀	PTFE	MiniVol	Nongo	5.15	90
2004-02-02	PM _{2.5}	PTFE	MiniVol	Nongo	5.30	50
2004-02-02	PM _{2.5}	Quartz	MiniVol	Nongo	5.30	-
2004-02-02	PM _{2.5}	PTFE	EPAM-5000	Nongo	4.00	46
2004-02-04	PM _{2.5}	PTFE	MiniVol	Nongo	5.30	48
2004-02-04	PM ₁₀	PTFE	MiniVol	Nongo	5.20	126
2004-02-06	PM _{2.5}	PTFE	MiniVol	Nongo	5.30	177
2004-02-06	PM _{2.5}	Quartz	MiniVol	Nongo	5.30	-
2004-02-07	PM _{2.5}	PTFE	MiniVol	Nongo	4.80	79
2004-02-07	PM _{2.5}	Quartz	MiniVol	Nongo	5.25	-
2004-02-09	PM _{2.5}	PTFE	MiniVol	Nongo	5.20	126
2004-02-09	PM ₁₀	PTFE	MiniVol	Nongo	5.10	344
2004-02-11	PM _{2.5}	PTFE	MiniVol	Nongo	5.20	116
2004-02-11	PM ₁₀	PTFE	MiniVol	Nongo	5.08	358
2004-02-11	PM _{2.5}	PTFE	EPAM-5000	Sangoyah cooking	4.00	187
2004-02-13	PM _{2.5}	PTFE	MiniVol	Nongo	5.20	67
2004-02-13	PM _{2.5}	Quartz	MiniVol	Nongo	5.20	-
2004-02-15	PM _{2.5}	PTFE	EPAM-5000	Presidential palace	4.00	76

Table 2
Concentrations^{a,b,c} of PM and associated elemental compositions at three sampling sites
in Conakry

Species	Nongo (N=18)	Nongo (N=10)	Sangoyah (N=1)	Palace (N=1)
Type	PM _{2.5}	PM ₁₀	PM _{2.5}	PM _{2.5}
Mass	70309 ± 35792	145256 ± 109194	186717	76198
F ⁻	16 ± 17	100 ± 118	81	
Cl ⁻	545 ± 536	1455 ± 996	5198	462
Br ⁻	27 ± 21	10 ± 2	12	
NO ₃ ⁻	955 ± 710	3412 ± 1605	1425	616
PO ₄ ³⁻		351 ± 342		
SO ₄ ²⁻	1470 ± 459	2209 ± 421	1599	2140
Na ⁺	258 ± 182	780 ± 377	2503	291
NH ₄ ⁺	527 ± 193	658 ± 214	243	291
K ⁺	931 ± 527	1406 ± 661	2155	890
Na	343 ± 158	936 ± 362	2399	445
Mg	405 ± 350	1252 ± 1046	659	302
Al	3062 ± 3102	12613 ± 12355	4870	4197
Si	6537 ± 6980	24971 ± 27848	10847	7172
P	131 ± 1	187 ± 82	109	118
S	633 ± 162	831 ± 163	547	764
Cl	941 ± 850	1753 ± 1123	6672	496
K	1200 ± 676	2231 ± 1530	2490	745
Ca	537 ± 487	2542 ± 1979	1489	4445
Ti	184 ± 173	821 ± 781	289	197
V	14 ± 6	22 ± 15		11
Cr	24 ± 13	144 ± 52	60	13
Mn	35 ± 27	113 ± 115	46	21
Fe	1868 ± 1558	9248 ± 5767	3364	1531
Ni	8 ± 2	18 ± 6		
Cu	179 ± 264	10 ± 3		19
Zn	69 ± 132	37 ± 16	28	22
Br	23 ± 10	27 ± 10	60	33
Mo	36 ± 12	35 ± 8	30	45
Te	70 ± 18	172 ± 115		204
Pb	36 ± 9	42 ± 13		64

^a Concentrations in ng m⁻³.

^b Mean ± standard deviation.

^c Data were filtered to include individual elemental concentrations > 2σ uncertainty to minimize type I errors.

14 Table 3
 15 Average concentration of
 16 chemical species in the
 17 composite Harmattan dust
 18 profile (Adepetu et al., 1988;
 19 Eltayeb et al., 2001)

Species	Concentration ^a
Na ₂ O	1.3
MgO	2.2
Al ₂ O ₃	17.3
SiO ₂	57.8
K ₂ O	2.8
CaO	7.4
TiO ₂	1.2
MnO	0.1
Fe ₂ O ₃	9.3
Sc	15
V	123
Cr	179
Co	31
Zn	3304
Ga	33
As	10
Se	10
Br	293
Rb	124
Sb	49
Cs	4
Ba	1044
La	81
Ce	183
Sm	10
Eu	2
Hf	12
Au	0.2
Th	21
U	9

20 ^a Concentrations of element
 21 oxides in wt% and trace
 22 elements in $\mu\text{g g}^{-1}$.

Figure

[Click here to download high resolution image](#)

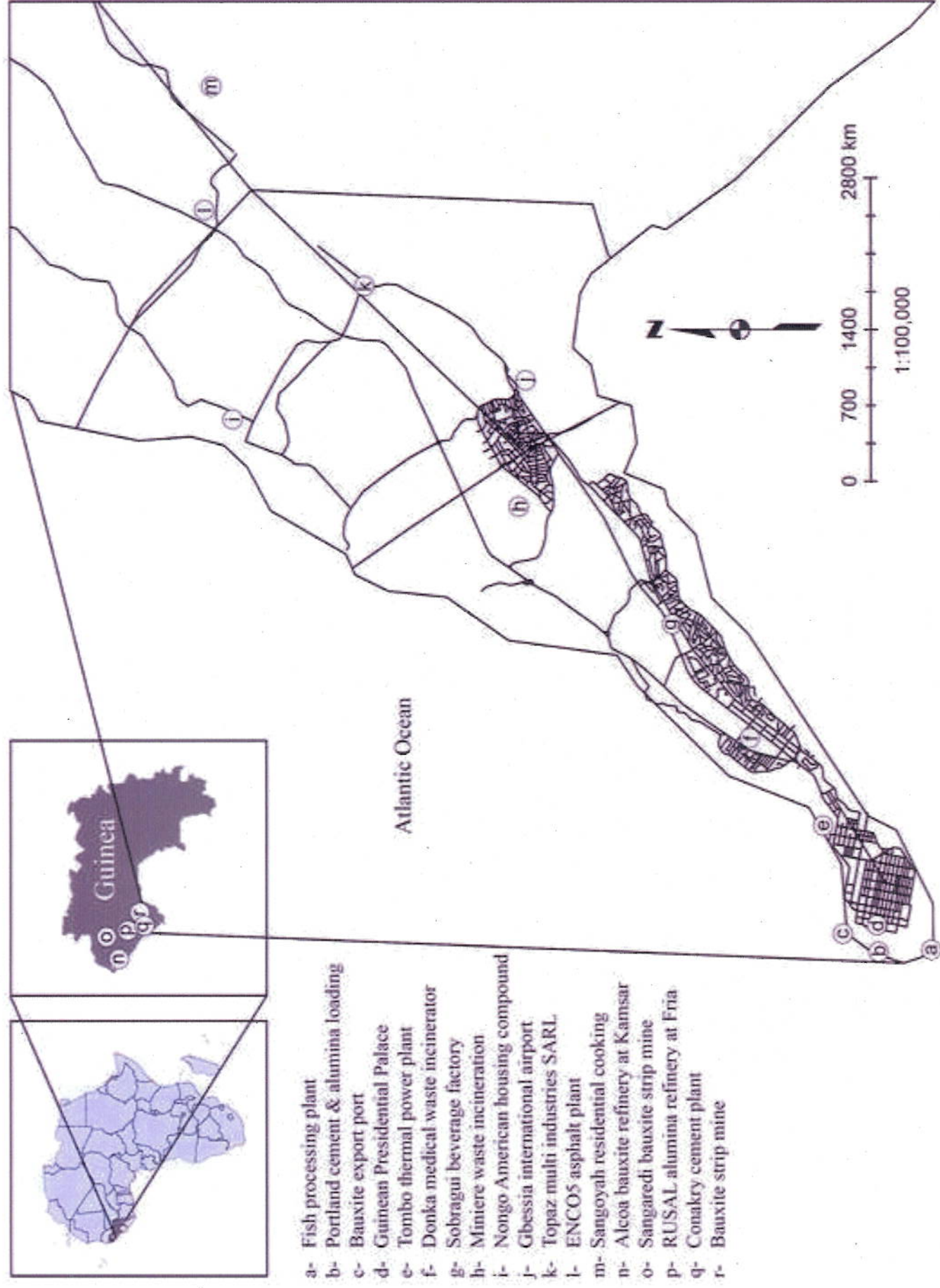


Figure
[Click here to download high resolution image](#)

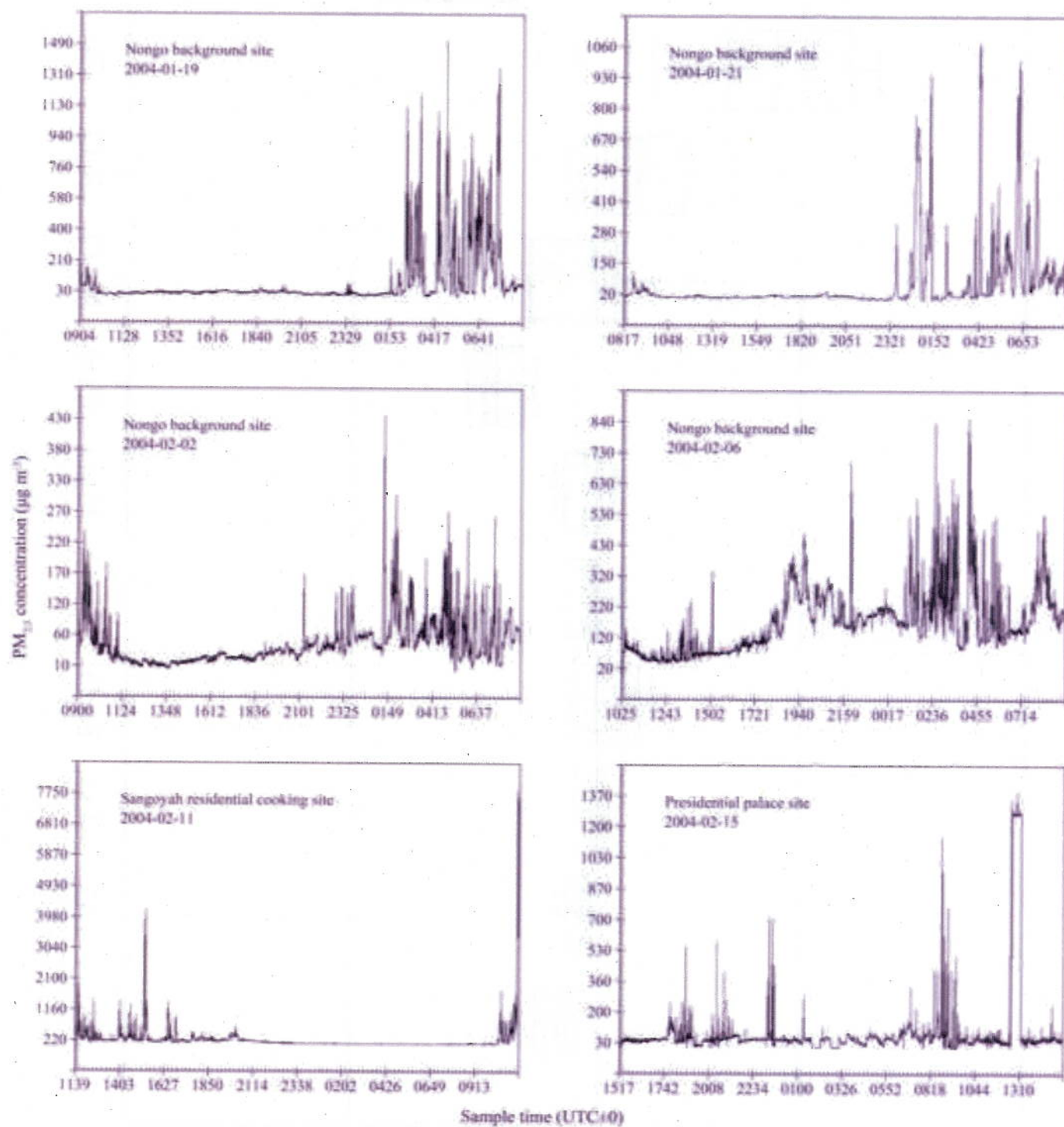
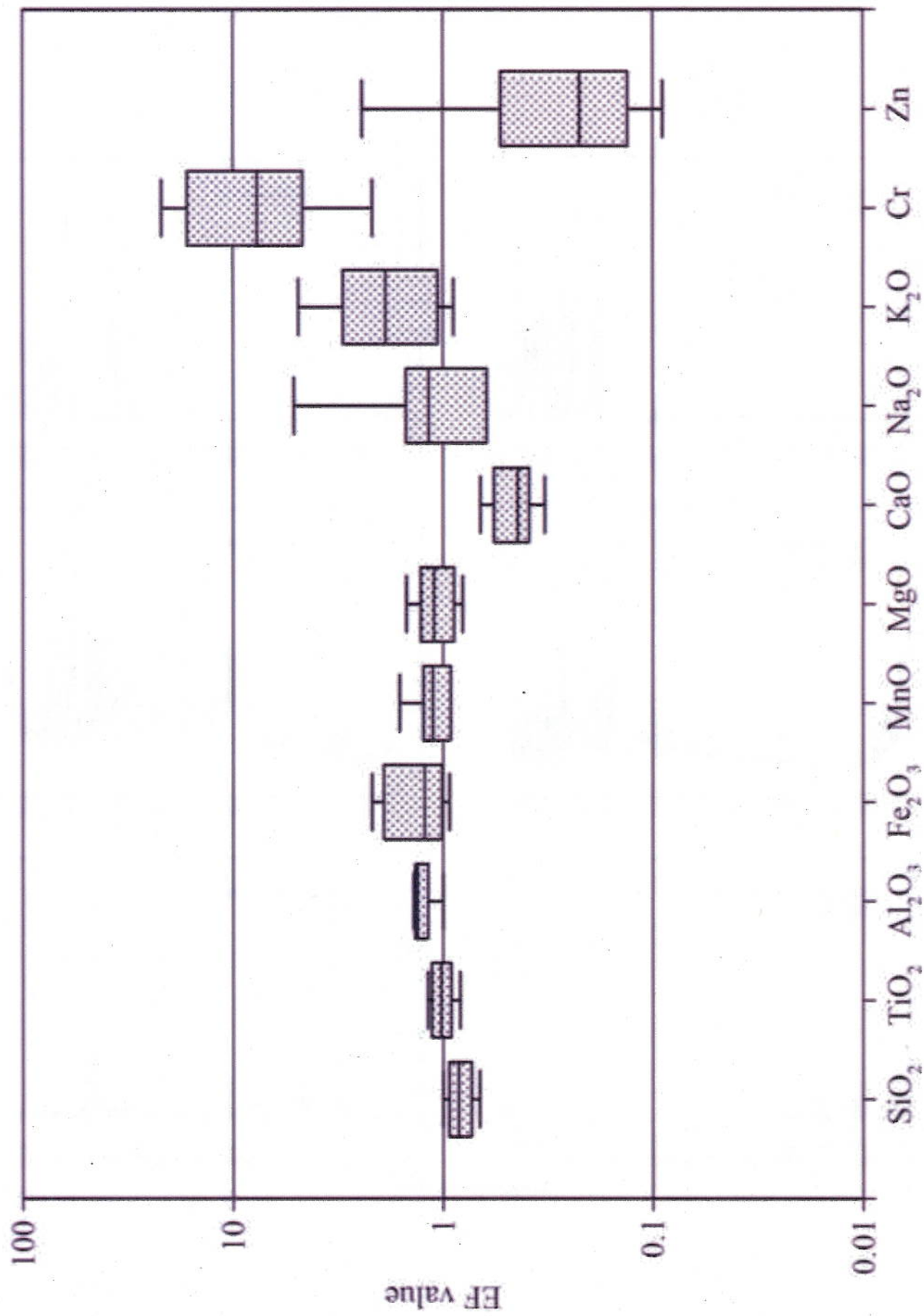


Figure
[Click here to download high resolution image](#)



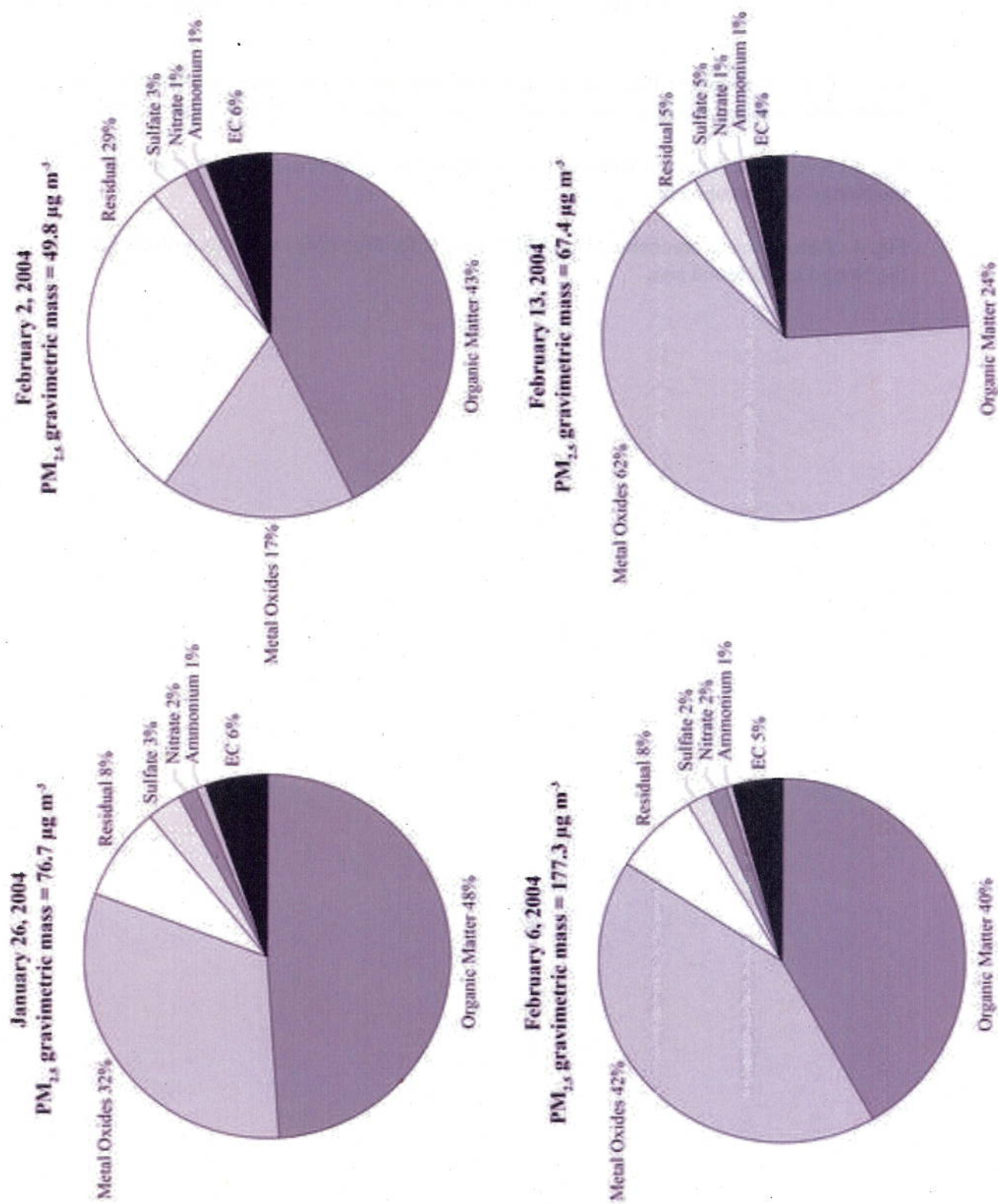


Figure captions

Fig. 1. Map of Conakry, Guinea, West Africa with monitoring sites and local points of interest.

Fig. 2. Concentrations of $PM_{2.5}$ at the Nongo background site measured with the EPAM-5000 nephelometer. Sample times are presented in coordinated universal time UST \pm 0.

Fig. 3. Average enrichment factor (EF) results for $PM_{2.5}$ and PM_{10} samples collected at the Nongo background site.

Fig. 4. Aerosol mass reconstruction (AMR) results for four $PM_{2.5}$ samples collected at the Nongo background site.