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The application of magnetic measurements for the characterisation of atmospheric particulate pollution within the airport environment

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Highlights

- **Use of magnetic measurements to characterize airport derived PM.**
- **Three ‘aircraft’ sources of PM display distinctive magnetic ‘fingerprints’.**
- **Magnetic measurements of runway dusts suggest potential sources of PM.**
- **Magnetic ‘fingerprints’ are used for PM source attribution.**

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Abstract

The significant increase in global air travel which has occurred during the last fifty years has generated growing concern regarding the potential impacts associated with increasing emissions of atmospheric particulate matter (PM) on health and the environment. PM within the airport environment may be derived from a range of sources. To date, however, the identification of individual sources of airport derived PM has remained elusive but constitutes a research priority for the aviation industry.

The aim of this research was to identify distinctive and characteristic fingerprints of atmospheric PM derived from various sources in an airport environment through the use of environmental magnetic measurements. PM samples from aircraft engine emissions, brake wear and tyre wear residues have been obtained from a range of different aircraft and engine types. Samples have been analysed utilising a range of magnetic mineral properties indicative of magnetic mineralogy and grain size. Results indicate that the dusts from the three 'aircraft' sources, (i.e. engines, brakes and tyres) display distinctive magnetic mineral characteristics which may serve as 'magnetic fingerprints' for these sources. Magnetic measurements of runway dusts collected at different locations on the runway surface also show contrasting magnetic characteristics which, when compared with those of the aircraft-derived samples, suggest that they may relate to different sources characteristic of aircraft emissions at various stages of the take-off/landing cycle. The findings suggest that magnetic measurements could have wider applicability for the differentiation and identification of PM within the airport environment.

1. Introduction

During the last fifty years the global demand for air travel has increased exponentially. International air passenger numbers between 1960 and 2005 have, on average, increased by more than 8% year on year and, furthermore, this trend appears set to continue with a predicted rise in global air travel of between 4.5 and 6% per annum over the next twenty years (Stettler *et al*., 2011).

Alongside the increasing demand for air travel, concerns have been raised in relation to the anticipated environmental impacts associated with such growth, including aircraft noise, climate change and air quality issues (Mahashabde *et al.*, 2011). A major area of concern relating to air quality is the potential impact of emissions of atmospheric particulate matter (PM) on health (Press-Kristensen, 2012; Spassov *et al*., 2004; Saragnese *et al*., 2011; Stettler *et al*., 2011). The airport environment includes a wide range of sources of primary PM including aircraft (engines, brakes and tyres); service vehicles; ground support equipment, building emissions and adjacent road and rail networks. This paper focuses entirely on primary PM, although secondary PM, occurring as a result of chemical reactions associated with more volatile emissions, may also be present in the airport environment.

At present there is a limited amount of published data relating to the quantity and nature of airport derived PM. However, a recent study of PM emissions from various sources at Copenhagen Airport provided evidence to suggest that 90% of ultrafine PM (<0.1 μm diameter) on the apron originated from airport derived sources (Press-Kristensen, 2012). The Copenhagen study highlighted the urgent need for research into the nature of airport derived PM in order to assess the health implications for airport employees and, in particular, those working in close proximity to direct sources of ultrafine PM such as aircraft engines and diesel vehicle exhausts.

To assess the potential impact of airport derived PM emissions on airport employees, passengers and nearby communities, it is necessary to be able to attribute the measured ambient PM to individual emission sources. One approach to source attribution would be to identify particulate ‘fingerprints’ characteristic of each source to enable source differentiation of PM deposits. Previous studies of the airport environment have attempted to achieve this, predominantly through the use of geochemical analysis (Herndon *et al*., 2005; Amato *et al*., 2010). The identification of unambiguous ‘fingerprints’, however, has so far remained elusive and has been identified as a research priority for the aviation industry (Webb *et al*., 2008; Wood *et al*., 2008).

Environmental magnetism involves a number of non-destructive, inexpensive and relatively rapid measurements involving the application of artificially induced magnetic fields to natural materials. The measurements provide information about the type, grain size and concentration of magnetic minerals in the material. Environmental magnetism has been used as an effective technique for the identification of characteristic particulate ‘fingerprints’ allowing for the discrimination of different emission types and PM sources in the urban environment (Hunt *et al*., 1984) and to distinguish between PM arising from fossil fuel combustion/industrial processes and those derived from natural sources such as soil erosion (Oldfield *et al.,* 1985; Hunt, 1986). Hunt *et al*. (1984) found that vehicle-derived particulates were dominated by ferrimagnetic (i.e. magnetite/maghemite-like) minerals, while fly-ash samples from solid fuel (coal) combustion showed different magnetic behaviour consistent with a significant antiferromagnetic (i.e. haematite-like) content. Different combustion processes and fossil fuels give rise to particulate emissions of contrasting magnetic mineralogy and grain size. More recently, magnetic measurements have been applied to sinks of atmospheric PM such as tree leaves and surface vegetation (Matzka and Maher, 1999; Maher *et al*., 2008), and road surface dusts (Robertson *et al.,* 2003; Bucko *et al*., 2010; Wang *et al*., 2012; Crosby *et al*., 2014) to obtain qualitative attribution of atmospheric PM sources in the urban environment.

This paper investigates the use of environmental magnetic measurements as a technique for discriminating between atmospheric PM from different emission sources in the airport environment, thereby establishing distinctive 'magnetic fingerprints' to assist in source apportionment.

2. Methodology

2.1 Engine, Brake and Tyre Dust Sampling

Engine, brake and tyre dust samples were collected from a range of jet aircraft at the British Airways (BA) engineering facility at London Heathrow Airport (LHR), UK between August 2010 and October 2013. The aircraft sampled comprised Boeing 747-436; 767-336; 777-236 and Airbus A319-131 and A320-232. Engine dust samples (n = 13; sample mass: 0.6 – 1.4 g) from several engine types were collected from the mixer shroud surrounding the turbine blades, onto which some PM in the exhaust emissions impacts directly during routine engine function, leading to a slight accumulation over time (BA Engineering, pers. comm.). Brake dust samples (*n* = 16; sample mass: 0.75 – 3.5 g) were collected from the wheel hubs of these aircraft. Brake lining wear occurs most commonly during landing and less significantly during taxiing operations as a result of frictional heat generation (Curran, 2006) which results in the production of brake dust. Bennett *et al*. (2011) suggest that samples collected from the undercarriage and wheel hubs would contain PM from a range of sources including tyres, brakes, runways and taxiways. However, following the advice of BA engineers (pers. comm.) it was decided that brake dust sampling would focus on the wheel hub area as it was their view that this would largely restrict the sample to brake derived material. Samples of tyre dust (*n* = 4; sample mass: 1.9 – 5.0 g) were collected from the nose landing gear (NLG) wheel well of a Boeing 747-436 and a Boeing 767-336 aircraft. Tyre abrasion occurs at the point of nose wheel retraction due to the action of the spin brake function associated with these aircraft types. The resultant tyre debris accumulates on ledges and gullies in the nose landing gear. All dust samples were collected using a clean wooden spatula and/or small paint brush before being transferred to clean, self-sealed polythene bags to avoid contamination.

2.2 Runway Dust Sampling

Runway dust sampling was conducted at Manchester International Airport (MIA) (Figure 1). MIA is located 17km south west of Manchester in the north west of England and is the third largest airport in the UK, serving a total of 19.7 million passengers in 2012 (CAA, 2013). A minimum of five days dry weather preceded each sampling visit to diminish the wash-out effect as described in Kim *et al.* (2007). MIA has two runways 23R/05L (Runway 1) and 23L/05R (Runway 2). Dual runway manoeuvres occur throughout the week for a maximum period of up to eight hours per day. The nature of the operations are dependent on the prevailing wind direction. When westerly wind directions prevail departures take place on runway 23L and landings on 23R. There are no landings on 23L, apart from in exceptional circumstances, due to the absence of an Instrument Landing System (ILS) on this runway. When the wind is from an easterly direction 05R is used for arrivals, and 05L for departures. Outside these periods single runway operations are maintained with 23R/05L operating as the main runway.

Samples of runway dust (n = 13; sample mass: 0.6 – 0.8 g) were collected at 100m intervals along runway 23L/05R using a clean plastic dustpan and brush before being transferred to clean self-sealed polythene bags. Sampling commenced from the start of the runway pre-threshold area of runway 23L and continued along the entire length of the runway.

2.3 Magnetic Measurements

Samples were packed into 10ml plastic containers (Azlon, SciLabware Ltd, Staffs., ST4 4RJ, UK) prior to analysis. Low-field magnetic susceptibility (χ) was measured using a Bartington Instruments (Witney, Oxon., OX28 4GE, UK) MS2B sensor and meter. The values used here are low frequency mass-specific magnetic susceptibility (χ). An Anhysteretic Remanent Magnetisation (ARM) was induced in the samples using a peak alternating field (AF) of 100 mT and a direct current (DC) biasing field of 0.04 mT, provided by a Molspin shielded alternating field demagnetiser (Bartington Instruments, Witney, Oxon., OX28 4GE, UK). The resulting magnetisation retained by the sample (i.e. remanence) was measured using a Molspin magnetometer and recorded as the ARM. The ARM is presented as susceptibility of ARM (χARM) by normalising the ARM for the DC biasing field used. Isothermal remanent magnetisation (IRM) measurements were carried out using a Molspin pulse magnetiser and magnetometer. The IRM acquired in the initial forward field of 1 T is assumed to be equivalent to a Saturation Isothermal Remanent Magnetisation (SIRM). Reverse field ratios were determined by placing a previously saturated sample successively in reverse fields of increasing strength (-20 mT; -40 mT; -100 mT; -300 mT) and measuring the isothermal remanence at each stage. The data are expressed as a ratio IRM_{-xmT}/SIRM.

Some of these magnetic parameters can usefully be combined into ratios to provide further insight into variations in ferrimagnetic mineral grain size. These are referred to as interparametric ratios. The ratios used in this study are χARM/χ and χARM/SIRM. Relatively higher values of these ratios are indicative of finer ferrimagnetic mineral grain sizes, while lower ratios suggest the presence of coarser ferrimagnetic mineral grain sizes. The definition and relevance of the various magnetic parameters are listed in Table 1.

3. Results

Table 2 summarises the results of the magnetic analyses of the engine, brake and tyre dust samples. The variables presented in this paper provide information on the magnetic mineralogy and grain size of the magnetic assemblages within each sample set rather than concentration related variables.

The engine dusts are characterised by higher χARM/χ and χARM/SIRM ratios than those for the brake dusts. The tyre dusts display similar χARM/χ ratios to those of the brake dusts, whilst the χARM/SIRM ratios are intermediate between the other two sources. Statistical analysis using the Kruskal-Wallis Test demonstrate that the ratios display a significant difference between the three sample sets at a significance level of $p = 0.05$. The higher χARM/χ and χARM/SIRM ratios of the engine dusts are indicative of finer ferrimagnetic mineral grain sizes whilst the lower values exhibited by the brake and tyre dust samples suggest that these samples are dominated by coarser ferrimagnetic mineral grain sizes (Walden *et al*., 1999).

The contrast in the magnetic mineral characteristics of the engine, brake and tyre-derived particulates is further illustrated in Figure 2, which plots IRM_{-20mT}/SIRM against IRM_{-300mT}/SIRM for all samples. While there is only a slight variation in the range of the lower reverse field ratios (IRM_{-20mT}/SIRM), the higher reverse field ratio (IRM_{-300mT}/SIRM) discriminates between the three sample sets more effectively. The engine dust samples have significantly less negative IRM_{-300mT}/SIRM ratios, suggestive of a much higher antiferromagnetic component, than the brake dusts with more negative higher reverse field ratios (Walden *et al*., 1999). The tyre dust samples are situated midway between the engine dusts and brake dusts for the IRM_{-300mT}/SIRM ratio.

Cluster analysis was used to classify all the samples into groups using the four magnetic parameters presented here. An agglomerative method was applied to all the data and normalised to eliminate differences in magnitude between the variables. The analysis split the samples into three major groups, one group containing all the engine dust samples, a second including all the brake dust samples and a third group comprising the tyre dust samples.

Interparametric ratios (χARM/χ; χARM/SIRM) are not available for the runway dust samples due to low sample mass and low magnetic mineral concentrations precluding the accurate measurement of magnetic susceptibility and ARM. Figure 2 presents the runway dust samples plotted on the scatter plot of IRM_{-20mT}/SIRM versus IRM_{-300mT}/SIRM that also includes the aircraft engine, brake and tyre dust samples. The results for the samples collected from Zone A of the runway (Figure 1) show a close correspondence to those of the engine dusts, while dust samples collected from Zone B (Figure 1) display similar magnetic characteristics to those of the brake and tyre dusts. The most significant discriminator of the two variables used in the scatter plot is the higher reverse field ratio (IRM_{-300mT}/SIRM). Less negative values for this ratio are associated with the aircraft engine dusts and runway dust samples from Zone A. The ratio indicates a significant antiferromagnetic component in these samples, this being smaller and less evident in the brake and tyre dusts and Zone B runway dusts.

The runway dusts may also contain PM and associated magnetic minerals from other, more regional sources associated with urban and industrial processes, particularly at locations in close proximity to urban areas. The IRM_{-100mT}/SIRM ratio (often referred to as the S-ratio) has been used as a quick index of magnetic mineral grain size and the relative amount of ferrimagnetic and anitiferromagnetic minerals in a sample. Ratios between -1.00 and -0.70 are characteristic of coarser-grained ferrimagnetic material (e.g. magnetite), whereas values above -0.40 are indicative of a significant antiferromagnetic (e.g. haematite) content. The IRM_{-100mT}/SIRM ratio of magnetic particles derived from fossil fuel combustion during industrial processes, and in urban road dusts, where the main source is motor vehicles, are typically between -1.00 and -0.72 (Petrovsky and Ellwood, 1999; Robertson *et al.*, 2003; Crosby *et al*., 2014). Ombrotrophic peat bogs receive all inputs directly from the atmosphere, and contain a record of atmospheric particulate pollution in layers of recent accumulation. Magnetic measurements of the uppermost layers of peat from locations close to urban and industrial areas have been shown to have IRM_{-100mT}/SIRM ratios of -0.80 – 0.65, which is indicative of the magnetic characteristics of the regional PM pollution input from a range of urban and industrial sources (Richardson, 1986; Thompson and Oldfield, 1986). The aircraft-derived PM has IRM_{-100mT}/SIRM ratios ranging from -0.71 to -0.37 (Table 2), and the runway dusts range from -0.54 - -0.30 (Table 3) suggesting that the magnetic characteristics of PM in the airport environment is quite different from more regional sources.

4. Discussion

Significant differences have been observed between the magnetic properties of the engine, brake and tyre dust samples. The magnetic minerals in the engine dusts are characterised by finer ferrimagnetic grain sizes and contain a significant antiferromagnetic component. Conversely, the magnetic assemblages in the brake and tyre-derived dust are predominantly coarser grained ferrimagnetic minerals. An explanation for such variation must relate to differences in the nature of the iron content in the aviation fuel Jet A-1, Carbon-Carbon (C/C) brakes and aircraft tyres, and the combustion processes and conditions at the point of conversion of non-magnetic or weakly magnetic forms of iron into magnetic iron oxides. Ultrafine particulates are a component of aircraft exhaust emissions and generally form from the incomplete combustion of jet fuel in the combustion section of the jet engine (Starik, 2008; Webb et al., 2008). The primary particulates are predominantly carbonaceous material (or soot) and are composed of organic compounds and elemental or black carbon (Petzold et al., 2005). Ultrafine primary particulate matter emitted directly from aircraft engines may also include metal particles (Starik, 2008). These may be derived from engine erosion or from iron impurities in the Jet A-1 fuel (Penner *et al*., 1999; Jones, 2008). During high temperature combustion, the iron impurities are converted into magnetic oxides which then contribute to the primary, non-volatile particulate matter. The significant antiferromagnetic mineral (haematite-like) content of these particulates may relate to the specific nature of the iron impurities in the fuel and/or the chemical processes which take place during the fuel combustion stage.

Brake dust or wear debris largely arises from mechanical and/or chemical reactions on sliding surfaces during brake operation when aircraft are taxiing, on landing or during undercarriage retraction on take-off (Hutton *et al*., 1999; Rietsch *et al*., 2009). Modern aircraft brakes consist of C/C combinations due to their stable behaviour characteristics at high temperatures. These brakes often contain additives to modify the friction properties, temperature characteristics and mechanical properties of the brakes or to act as antioxidants during brake operation (Blau, 2001). Such additives may include iron oxides such as magnetite (Blau, 2001). Frictional heat generation which occurs during braking operations, primarily upon landing and less significantly during taxiing operations, results in the wear of brake lining particles which form a friction film of abraded wear debris that often adheres to the wear surfaces of the C/C composite brakes. Some of this wear debris is ultimately released as airborne particulate matter (Curran, 2006, Hutton *et al*., 1999). Chemical reactions and elevated temperatures on the sliding/rubbing interface of the brakes during operation may lead to the conversion of any iron additives or impurities within the matrix of the C/C brake into coarse grained ferrimagnetic forms of magnetic minerals. This may be expected due to the operating temperatures generally between 300 - 400°C (BA Engineering, pers. comm.), and the oxidising environment within the area of the braking mechanism. It is presumed that such ferrimagnetic minerals (magnetite/maghemite-like) are a component of the PM which forms the wear debris ejected during braking.

Coarse grained ferrimagnetic minerals in the tyre dust samples are a component of the PM formed as the nose wheel tyre rubs against the ‘snubber pads’ as part of the spin brake function following retraction of the undercarriage. The frictional temperatures generated during this short term phase must be sufficient to convert any iron impurities in the tyre to magnetic forms of iron oxides. Although composition data specific to aircraft tyres is not freely available in the literature as it is commercially sensitive, tyres are known to contain a wide range of materials including metals (Lobo *et al*. 2013)*.* Bennett *et al*. (2011) found irregularly shaped iron particulates of 10 μm diameter or less in undercarriage dust, which also contained PM chemically ascribed to tyre smoke.

The results of magnetic measurements of the runway dust samples from Zone A (Figure 1) show a predominance of fine-grained ferrimagnetic forms together with a significant antiferromagnetic component, both of which are consistent with the magnetic characteristics of the engine dusts. Zone A incorporates the initial stages of the take-off roll for aircraft departing on runway 23L. These results suggest an accumulation of magnetic particulates on the runway surface, released from aircraft engines during the initiation of take-off and when the aircraft is still moving slowly. Such findings are consistent with those of Zhu *et al*. (2011) who measured very high concentrations of ultrafine particulates immediately downwind of aircraft take-off at Los Angeles International Airport.

The runway dust samples from Zone B (Figure 1) are dominated by coarse-grained ferrimagnetic minerals, similar to the brake and tyre-derived dust samples. Zone B represents the main landing zone for aircraft arriving on runway 05R. Such findings point to the release of brake dust and tyre smoke PM followed by deposition on the runway surface during landing and braking operations. Lobo *et al*. (2013) and Bennett *et al*. (2011) suggest that the number density of brake dust and tyre smoke PM emissions from landing aircraft is rather low and difficult to detect by particle counters. The data presented here highlights the sensitivity of magnetic measurements for the identification and differentiation of different sources or types of atmospheric PM compared with other analytical techniques. It should be noted that some of the runway dust samples from Zone B contained visible tyre material. Rubber deposits build up on runway surfaces due to the friction of the aircraft tyres on the runway surface during landing, causing the rubber to polymerise and harden to the runway surface. This tyre material had similar physical characteristics to the tyre dusts sampled from the nose landing gear wheel well. It is possible that this coarse material dominates the 'tyre' magnetic characteristics of both the nose landing gear wheel well deposit and the runway dust rather than any fine PM from tyre smoke.

5. Conclusion

Dust samples collected from commercial aircraft engines, brakes and tyres have been shown to differ significantly in terms of the nature and grain size of the magnetic minerals they contain. A 'harder' magnetic mineral component related to the presence of antiferromagnetic minerals and finer ferrimagnetic mineral grain sizes is characteristic of engine dusts, distinguishing them from aircraft brake and tyre PM and deposits which display mainly coarser grained ferrimagnetic mineral assemblages. These contrasting magnetic characteristics are thought to be due to the different chemical compositions of aviation fuel (Jet A-1), C/C brakes and tyres used on commercial aircraft, and the combustion processes and temperatures under which the magnetic particulates are formed. The results demonstrate that magnetic measurements have the potential to identify and differentiate particles from three different aviation sources within an airport environment.

The magnetic measurement data for the runway dusts suggests wide variations in magnetic mineralogy and grain size. Samples collected in Zone A (close to the runway threshold) show a close correspondence in their magnetic characteristics to those of the engine dusts, whilst dust samples collected within Zone B (distal from the runway threshold) have similar magnetic characteristics to those of the brake and tyre dusts. When compared with the magnetic properties of other potential sources of a more regional nature, it would appear that the main sources of runway PM are aircraft derived. Therefore, these results suggest that magnetic measurements could be applied successfully for the identification of PM sources in the airport environment and, thus, contribute to studies of source apportionment and the potential impact on airport employees, passengers and the surrounding community.

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Tables 1, 2 & 3

Table 1: Summary of magnetic parameters.

Magnetic parameter	Interpretation
χ	*Magnetic susceptibility* (χ) the ratio between the magnetisation induced in a sample and the strength of the magnetising field. It is indicative of the concentration of ferrimagnetic minerals such as magnetite (Units: $m^3\,kg^{-1}$).
ARM	*Anhysteretic Remanent Magnetisation* (ARM) is induced by subjecting a sample to a smoothly increasing then decreasing AC field (100mT) in a constant DC field (0.04mT). The data are expressed as the suscptibility of ARM (χARM) by dividing the ARM by the DC biasing field strength. χARM is sensitive to the concentration of ferrimagnetic grains mainly of finer, stable single domain grain sizes (Units: $m^3\,kg^{-1}$).
SIRM	*Saturation Isothermal Remanent Magnetisation* is the highest magnetic remanence that can be produced in sample by the application of a very high magnetic field (in this study 1.0T; 1000mT). SIRM relates to both magnetic mineral type and concentration (Units: $A\,m^2\,kg^{-1}$).
χARM/χ	Where there is little variation in magnetic mineral type, the ratio of these two parameters can be diagnostic of relative magnetic mineral grain size variations.
χARM /SIRM	The ratio of these two parameters is diagnostic of relative variations in magnetic mineral grain size in samples where the magnetic mineral type remains relatively constant (Units: $A\,m^{-1}$).
IRM_{-xmT} /SIRM	*Reverse field ratios* obtained by applying one or more reverse magnetic fields to a previously magnetically saturated sample. The loss of magnetisation at the selected reverse fields is expressed as a ratio of the SIRM and can be used to discriminate between ferrimagnetic and antiferromagnetic mineral types and/or magnetic mineral grain size.

Table 2: Summary of magnetic parameters of engine, brake and tyre dusts.

Magnetic parameters		Brake (*n* = 16)	Engine (*n* = 13)	Tyre (*n* = 4)
χARM/χ	Range	9.90 – 29.73	36.02 – 68.77	15.76 -27.9
	Mean ± SD	19.72 ± 5.2	53.42 ± 9.53	21.55 ± 6.09
χARM /SIRM	Range	87.92 – 152.16	166.7 – 331.8	150.5 – 176.06
	Mean ± SD	122.57 ± 17.44	260.8 ± 50.1	164.23 ± 12.89
IRM_{-20mT} /SIRM	Range	0.48 – 0.65	0.60 – 0.80	0.69 – 0.72
	Mean ± SD	0.58 ± 0.05	0.70 ± 0.06	0.71 ± 0.01
IRM_{-100mT} /SIRM	Range	-0.71 - -0.59	-0.65 - -0.37	-0.56 - -0.54
	Mean ±SD	-0.64 ± 0.04	-0.51 ± 0.09	-0.55 ± -0.01
IRM_{-300mT} /SIRM	Range	-0.98 - -0.95	-0.93 - -0.88	-0.95 - -0.94
	Mean ± SD	-0.97 ± 0.01	-0.90 ± 0.02	-0.94 ± 0.00

Table 3: Summary of magnetic parameters of runway dusts (Zone A and Zone B).

Magnetic parameters		Zone A (Take-off) (*n* = 6)	Zone B (Landing) (*n* = 7)
IRM_{-20mT} /SIRM	Range	0.62 – 0.79	0.66 – 0.73
	Mean ± SD	0.71 ± 0.06	0.70 ± 0.03
IRM_{-100mT} /SIRM	Range	-0.42 - -0.30	-0.54 - -0.50
	Mean ±SD	-0.36 ± 0.05	-0.52 ± 0.02
IRM_{-300mT} /SIRM	Range	-0.90 - -0.83	-0.97 - -0.94
	Mean ± SD	-0.87 ± 0.03	-0.96 ± 0.01

Figure 1 and figure caption

Figure 1

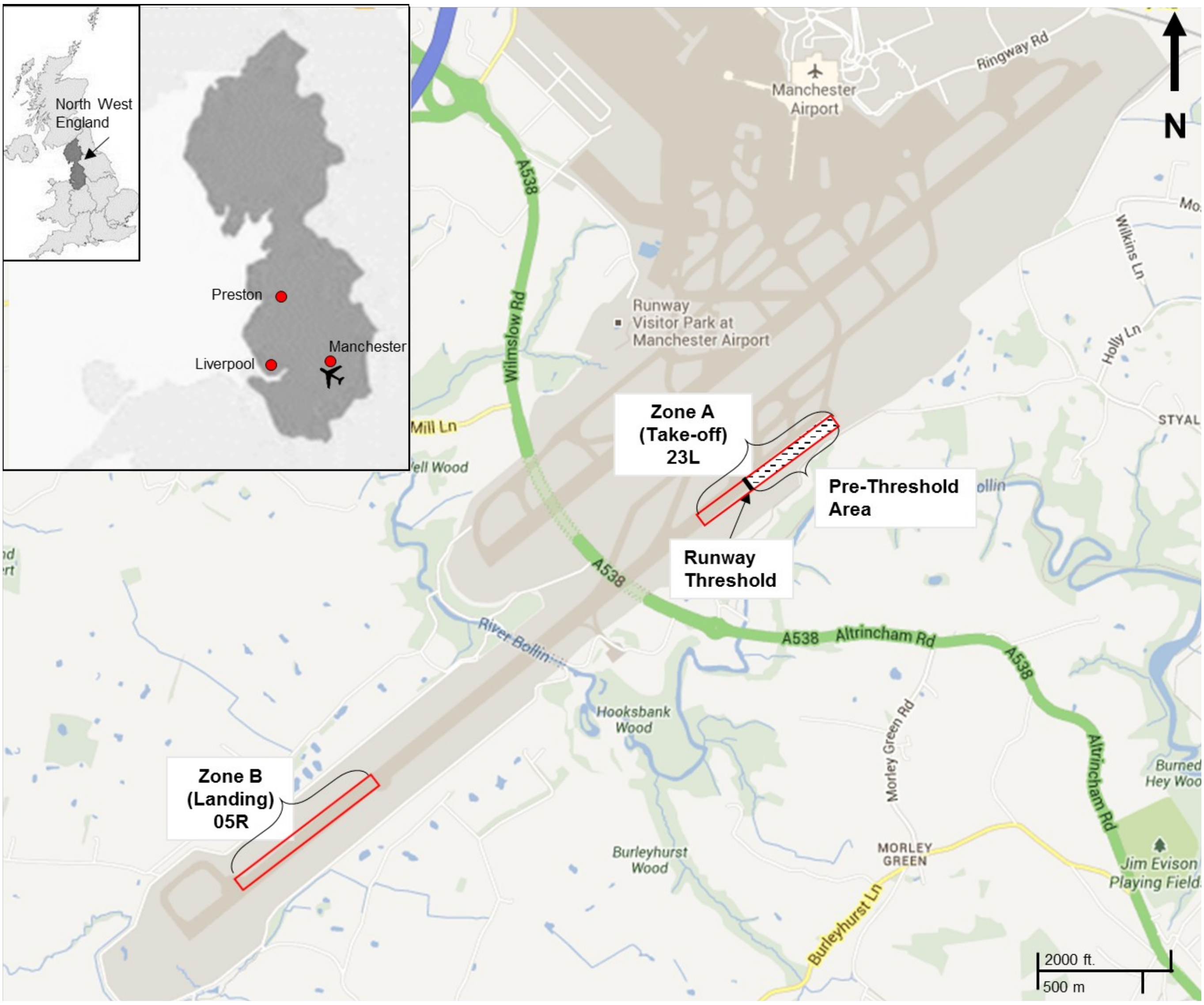

Figure 1 caption:

Location of runway dust sampling sites, runways 23L and 05R, Manchester International Airport (MIA), UK. Inset map shows the location of MIA within the north west of England, UK and its proximity to major cities. Zone A (0-700m) represents a section of the runway which would include the initial stages of the take-off cycle on runway 23L. Zone B (2300-

3000m) represents the main landing zone on runway 05R (Map adapted from Google Maps).

Figure 2 and figure caption

Figure 2

Figure 2 caption:

$IRM_{-20mT}/SIRM$ versus $IRM_{-300mT}/SIRM$ for aircraft engine, brake, tyre and runway dust samples (Zone A = Take-off zone; Zone B = Landing zone).

[Document ends]