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## **Lead isotope composition and host phases in airborne particulate matter from Budapest, Hungary**

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## *Abstract*

Lead is a frequent potentially toxic pollutant of the urban environment. Its risk assessment in the airborne particulate matter requires data both on its speciation and potential sources. In this paper we present results on detailed mineralogical (XRD and TEM) and geochemical (selective chemical extractions and lead isotope ratio analyses) study of total suspended particulate (TSP) matter samples from Budapest, Hungary to fulfil this requirements.

Total lead concentrations showed significant enrichment in the studied TSP samples as compared to its geochemical background value. It could be associated to several host phases. The potentially mobile fraction of lead, which could be also harmful to human, can be as high as 16% of the total lead. This is represented by Pb sorbed on the surface of clay minerals and in form of carbonates (and sulphates). Contrarily, between 20 and 30% of total lead of TSP materials is hosted by magnetite, a highly resistant mineral. However, its fast oxidation during combustion processes to hematite and/or weathering in the acidifying urban environment to ferrihydrite may result in the enhanced mobilization of lead.

Lead isotope composition of the TSP samples suggests the mixing of several sources for this metal with slight variation among the sampling sites. Despite the phasing out of leaded gasoline, its contribution to the Pb content of the TSP was observed. Our data also supported that the presence of lead of gasoline origin decreases in the airborne TSP in the last decade in Budapest. Another important source for lead is found to be the coal combustion due to domestic and industrial heating. Lead isotope

ratio data suggest additional source(s) for this metal at least in certain localities, but further investigations are necessary to specify them.

### ***Introduction***

Studies on sources, compositions, and distribution of airborne particulate matter components are necessary for their risk assessment to atmospheric quality, ecology and human health. This is especially true for the urban environment, where population and traffic density are relatively high, and harmful effect of airborne particulate matter is expected to be significantly increased (Vardoulakis et al. 2003).

Lead is one of the potentially toxic metals showing significantly high enrichment in the urban particulate matter (Braun et al., 2007). The most important source of this metal was the traffic until the phase out of leaded gasoline, which resulted in decrease of lead concentration in urban aerosol as it was shown also in Budapest (Salma et al., 2000). However, vehicles still exhaust Pb-containing phases to the environment (Zajzon et al., 2013) as this metal can be found in lubricating oil and grease, and it is also the common component of bearings, tires and break linings. Lead may also originate from domestic and industrial combustion for heating purposes and it is the common component of construction materials and the built environment, too (Sutherland, 2000). Therefore, lead is widely distributed in the surface urban environment due to the long history of its emission from anthropogenic sources. Analysis of the composition of airborne particulate matter indicates that a portion is composed of soil that has been resuspended and it has the capability of entraining significant volumes of Pb into the air of urban areas (Laidlaw and Filippelli, 2008).

Owing to the fact that lead may be originated from several sources in the urban environment, its speciation in the different environmental matrices shows large variation. Although lead is often associated to magnetic particles in urban environment (Gautam et al., 2005), several studies showed that significant proportion of this metal can be dissolved by weak acids (Duong and Lee, 2009). Sequential chemical extraction of lead from urban dust samples showed that besides the residual phases oxidizable, reducible and easily extractable fractions may also contain high amounts of lead (Banerjee, 2003). These findings correspond to the observations of Barrett et al. (2010) who found that Pb occurs primarily in the form of Pb-sorbed goethite, as well as lead chloride, carbonate, oxide and phosphate in the urban dusts.

Knowing only the total concentrations and chemical forms of Pb is not sufficient for a precise evaluation of contamination sources. As each source of Pb can have distinct or sometimes overlapping isotope ratio ranges, lead isotope studies may provide a convenient approach for studying and tracing sources of Pb pollution in different environmental matrices (Komárek et al., 2008).

The risk assessment of lead in the airborne particulate matter requires data both on speciation and potential sources of this metal. Correspondingly, our goals were (1) to identify the host phases of lead in total suspended particulate matter by detailed mineralogical analyses and selective chemical extractions, and (2) to provide data on the potential sources of pseudo total (aqua regia soluble) lead by isotope ratio analyses.

### ***Materials and methods***

Total suspended particulate (TSP) matter samples were collected from the air filters placed in the respiration channels used for the air supply of methane-heated turbines in four thermal power stations in Budapest (Figure 1). The 60×60 cm large textile filters are in use until their transmission is high enough, generally for a few months or even up to a year. Such a filter may transmit more than one million m<sup>3</sup> of air monthly. They are generally placed at 5-15 m height so the contribution of local soil to TSP material is minimal. As compared to other urban environments, however, contribution of soot and carbonaceous particles may be overrepresented with this sampling method due to the by-products of methane combustion in the thermal power stations. Altogether the 9 samples were collected from the following filters from four sampling sites with the application times and periods in the parentheses. Four filters from the Kelenföld station: KF1 (used for 3 months in the summer of 2010), KF2 (used for 3 months in the summer of 2010), KF3 (used for 6 months between June and December of 2010), KF4 (used for 6 months between June and December of 2010); two filters from the Kőbánya station: KB1 (used for 13 months between July of 2009 and August of 2010), KB2 (used for 6 months between April and October of 2010); 2 filters from the Újpest station: UP1 (used for 11 months between January and December of 2010), UP2 (used for 6 months March and August of 2010); and 1 filter from the Csepel station (used for 15 months between April of 2010 and July of 2011). As the filters were in use in different date and time periods with varying overlap, the samples can not be used for comparison of spatial or temporal changes of TSP characteristics in Budapest. However, they supposed to give a good outline on the general characteristics of TSP for Budapest. Samples were removed from the filters mechanically. Large plant and animal

debris were removed by passing the TSP through a 2 mm sieve. Before the chemical analyses, samples were powdered in agate mortar to get particle size smaller than 10 $\mu$ m.

Loss on ignition (at 450°C and 1050°C) was studied by a MOM derivatograph (Institute for Geological and Geochemical Research). The bulk samples were characterized for their mineralogical composition by a Philips PW 1710 X-Ray diffractometer (XRD) (Institute for Geological and Geochemical Research). Phase composition of the bulk soil was estimated on random-powdered samples by semi-quantitative phase analysis after the method of Bárdossy et al. (1980). High resolution transmission electron microscopy (HR-TEM) and selected area electron diffraction (SAED) analyses were carried out to characterize the mineralogical and chemical composition of individual mineral particles in the samples with special emphasis on those containing lead. The samples were suspended in ethanol, and then they were dropped onto a holey carbon coated Cu grid for the analyses. The measurements were performed on a Philips CM 20 TEM with a LaB6 filament, equipped with a Noran energy dispersive spectrometer (EDS) (Institute of Technical Physics and Materials Science). For the chemical analyses a 20 nm spot size and counting times of 100 s were used. The relative standard deviations of the EDS analyses are below 2.5%, 10% and 50% for element concentrations >10 wt%, 1-10 wt%, and <1 wt%, respectively. We pretended to analyse only one discrete particle in each case, which could be confirmed from the corresponding diffraction pattern.

The chemical composition of the bulk samples was analysed by a Philips PW2404 X-Ray fluorescence spectrometer (Pannon University, Veszprém, Hungary). The powdered samples were homogenized with 20 wt% of boric acid as binding material under ethanol and they were pressed in aluminium rings at 10 t/cm<sup>2</sup>. The

standard deviations of the analyses were generally below 5% and 10% for major elements and lead, respectively. Selective chemical extractions were also carried out to study the mobilization conditions of lead on parallel samples in each case with standard deviations generally below 10%. Water soluble amounts of lead were determined from 2.5 g samples and 25 mL of distilled water at 21°C with continuous agitation. The solution was filtered and analysed by a Perkin-Elmer Elan 9000 ICP-MS instrument (AcmeLabs, Vancouver, Canada) for its Pb content. Aqua regia digestion was carried out on 0.5 g sample with 12 mL aqua regia in heating block of hot water bath at 95°C for 1 hour. Before evaporation the cooled sample was made up to 10mL with dilute hydrochloric acid. Concentrations of lead isotopes ( $^{204}\text{Pb}$ ,  $^{206}\text{Pb}$ ,  $^{207}\text{Pb}$  and  $^{208}\text{Pb}$ ) in the solutions were analysed by a Perkin-Elmer Elan 9000 ICP-MS instrument. The quality of the Pb isotopic analyses has been checked by the study of two standard reference materials (SRM). Analysed and expected concentrations for the NIST-981-1Y SRM are 0.29 and 0.29 mg/kg for  $^{204}\text{Pb}$ , 4.91 and 4.83 mg/kg for  $^{206}\text{Pb}$ , 4.45 and 4.42 mg/kg for  $^{207}\text{Pb}$ , and 10.68 and 10.47 mg/kg for  $^{208}\text{Pb}$ , respectively. Analysed and expected concentrations for the NIST-983-1Y SRM are <0.01 and 0.007 mg/kg for  $^{204}\text{Pb}$ , 18.72 and 18.43 mg/kg for  $^{206}\text{Pb}$ , 1.38 and 1.31 mg/kg for  $^{207}\text{Pb}$ , and 0.32 and 0.25 mg/kg for  $^{208}\text{Pb}$ , respectively.

Two more chemical extractions were also carried out to study the potential toxicity of lead for human. They are supposed to simulate the neutral lung (Niu et al., 2010) and the acidic stomach environment (Mercier et al., 2002), respectively. In the first one, 25 mL 0.01M ammonium-acetate was added to 2 g of samples and reacted for 2 hours at 37°C with occasional agitation. In the second one, 25 mL dilute acetic acid (6 mL glacial acetic acid in 8 L distilled water) was added to 2 g of samples and the pH of

the suspension was adjusted to pH 2 with addition of 12M hydrochloric acid. The extraction was carried out for 6 hours at 37°C with occasional agitation. In both cases, the solution was separated by centrifugation at 3500 rpm for 20 minutes. The concentration of lead in the solutions was analysed using a Perkin Elmer AAnalyst 300 AAS instrument (Institute for Geological and Geochemical Research).

## **Results**

### *Samples characterization*

The major element composition of the samples is shown in Table 1. As compared to the geochemical background values for Hungary (Ódor et al., 1997), the samples show significant enrichment in S, Na and K. The high amount of sulphur may originate from construction materials (gypsum) or from the reaction between sulphuric acid and sulphate-forming cations (e.g. K or Ca) in the urban air (Panigrahy et al., 2003), and it may also reflect the presence of organic material (plant and animal remains) in the samples. Sodium enrichment can be due to the extended use of halite as de-icing agent. The presence of both gypsum and halite was also proved by the mineralogical analyses: gypsum (around 5 wt%) was identified in each sample whereas halite only in the KF1 sample (nearly 10 wt%) by X-ray diffraction (XRD) analyses (Figure 2).

The relatively high loss on ignition (LOI) values (between 21 and 37 wt%) show the presence of large amount of volatile components in the samples (Table 1). The LOI values between 105 and 450°C provides a rough estimate for the organic matter content



of geological materials (Craft et al., 1991). These values for the studied samples suggest that their organic matter content is expected to be between 14 and 25 wt%. This corresponds to the results of XRD analyses, with which large amount of amorphous phases were identified. They can be due to the expected presence of organic material and soot. Transmission electron microscopic (TEM-EDS) analyses showed that soot aggregates consisting of nano-sized (few tens of nm) soot particles are common phases in the studied TSP samples (see Figure 3a). Soot is a common anthropogenic component of urban airborne particulate matter as a result of different combustion (vehicle, heating, industrial etc.) processes (Grobéty et al., 2010).

The bulk mineralogical composition of the samples is dominated by the presence of minerals characteristic of the geological environment of the sampling sites (Figure 2). The samples consist mostly of 15-20 wt% quartz, 5-20 wt% carbonates, 5-10 wt% clay minerals and 5-10 wt% (plagioclase) feldspar. Carbonate phases are represented by nearly similar amount of calcite and dolomite with probable Fe and Mn substitution in the latter. Among the clay minerals illite dominates, but chlorite and smectite also appear. Such phases are characteristic natural components of urban dust representing primarily the fraction depositing fast (Farkas and Weiszburg 2006; Grobéty et al., 2010).

Dominant typically anthropogenic phases in the samples were found to be the iron oxides. Our XRD analyses showed the presence of large amounts of magnetite (5-10 wt%) at most of the sampling sites except in the UP samples (Figure 2). This phase was also shown by our TEM-EDS analyses (Figure 3b), together with ferrihydrite and hematite (Figure 3c), but the frequency of the latter two phase was much lower than that of magnetite. They can be the oxidation/weathering products of magnetite. The

oxidation may proceed already in the anthropogenic combustion process, as suggested by the results of Zajzon et al. (2013) who found the close association of magnetite and hematite in vehicle exhaust samples. Besides gypsum and halite mentioned earlier, further metal oxides and carbonates were found sparingly by TEM-EDS (one single franklinite, a smithsonite and a ZnO particle were found in the UP1 sample).

### *Lead in the samples*

Total concentration and the amount of lead mobilized by the different chemical extractions are shown in Table 2. The total lead concentrations of the samples are higher by 1-2 magnitude than the geochemical background concentration of lead in Hungary (21 mg/kg; Ódor et al., 1997). Samples from the KF site are characterized by the highest lead concentrations (between 1953 and 5942 mg/kg), while other samples contain by a magnitude lower amounts of this metal (between 368 and 942 mg/kg). Total lead concentrations do not show linear correlation with any major chemical component of the TSP material. Between 14 and 28% of total lead is insoluble in hot aqua regia, except in sample KF1, where only 38% of total lead could be extracted from the sample such a way (Figure 4). This difference is also shown by the fact that the total and aqua regia soluble lead shows perfect linear correlation ( $r = 1.00$ ;  $p < 0.05$ ) in most of the samples except in sample KF1 (if this latter sample is also included in the regression analysis the  $r$  value changes to 0.89). The weak acid extraction at pH 2 (stomach test) resulted in the mobilization of 1-16% of total lead content of the samples (Figure 4). The ratio of lead extracted by weak acid show large variation among the samples, its highest values are reached in two samples from Kelenföld (KF3 and KF4). In these

samples the weak acid extractable amount of lead is more than 600 mg/kg showing that even such a high Pb quantity is easily mobilized in urban or in stomach environment (Table 2). Several studies (e.g. Tokalioglu and Kartal, 2006; Sutherland et al., 2012) found that weak acid extractable lead show large variation among urban particulate matter samples (from a few % up to 20-30%). The metals extractability show significant increase with decreasing particles size (Sutherland et al., 2012) therefore the comparison of samples of different origin or those collected different methods is not possible. The extraction (by 0.01M ammonium-acetate at pH 7) used for simulating the lung environment resulted in lead concentrations below the detection limit for each sample (Table 2). Our data show that very similar extraction efficiency could be reached with this reagent to distilled water for lead. The data from latter extraction provides information that there is a very small ratio of total lead (between 0.1 and 1% corresponding to concentrations between 0.1 and 5.4 mg/kg) in the samples which is water soluble (Figure 4). Although the water soluble lead in the airborne particulate matter may show high variation, its ratio rarely exceeds 10% of the total lead (e.g. Fernandez Espinosa et al., 2002; Feng et al., 2009).

According to the TEM-EDS analyses, the spherular or xenomorphic magnetite particles may be the most important Pb bearing phases in the samples (Figure 3b). They sometimes contain 2-3 wt% of Pb (and also similar amount of Zn and occasionally less Mn). This is also observed by several authors (e.g. Gautam et al., 2005) who found significant linear relationship between magnetic susceptibility (primarily due to magnetite) and Pb content of urban particulate matter. The magnetite particles often form aggregates and are closely associated with soot and/or clay minerals. In samples with high magnetite content (primarily the KF samples), metal-free magnetite spherules

up to a few  $\mu\text{m}$  sizes also appeared. Clay minerals (primarily smectites) may also contain small amount of Pb (up to a few wt%) (Figure 3a). The Pb is probably sorbed on the surface of clay minerals in the soil of which re-suspension may contribute to the airborne particulate matter. This is a well-documented phenomenon in urban environment (Laidlaw and Filipelli, 2008). A single aggregate consisting of magnetite and calcite was also found by TEM analyses in which the latter contained significant amount of Pb (4.88 wt%) suggesting the presence of Pb in carbonates. Among other lead phases,  $\text{PbCO}_3$  was found as a common component of urban airborne particulate matter by others. Its presence can be due to the contribution of fly ashes from fossil fuel combustion, waste incineration (Wichmann et al., 2000) or industrial (smelter) dust (Spear et al., 1998) to the urban airborne material.

#### *Lead isotope composition of the samples*

The isotopic composition of lead shows very similar distribution in the samples. The most frequent isotope of this metal is  $^{208}\text{Pb}$  ( $52.08 \pm 0.51\%$ ), followed by nearly similar ratio for  $^{206}\text{Pb}$  ( $25.06 \pm 0.33\%$ ) and  $^{207}\text{Pb}$  ( $21.34 \pm 0.19\%$ ), and the less frequent is  $^{204}\text{Pb}$  ( $1.43 \pm 0.01\%$ ). This distribution show slight differences as compared to the average natural abundances of lead isotopes (DeLaeter et al., 2003). The ratio of  $^{204}\text{Pb}$  and  $^{206}\text{Pb}$  is generally higher in the studied samples than expected from their natural abundances (1.40 and 24.1%, respectively), whereas that of  $^{207}\text{Pb}$  is lower (its natural abundance is 22.1%). The ratio of  $^{208}\text{Pb}$  show slight variation among the studied samples: the sample UP is the only one showing higher ratio for this Pb isotope (53.02%) than its natural abundance, which is 52.4%. Most of the samples show similar

(KF1, KF2, KF3) or slightly lower ratios (CS1, KF4, KB1, KB2, UP2). These slight differences are due to the mixing of several lead sources (both natural and anthropogenic) in the samples. It is important to note that lead isotope analyses were carried out after the aqua regia dissolutions of the samples; hence they do not represent the magnetite-bound lead despite that it is supposed to be also of anthropogenic origin primarily. Moreover, DeVivo et al. (2001) found that the lead isotope ratios of the acid-leachable fraction of fluvial sediments showed slightly different Pb isotope ratios as compared to the residual fraction, which is due to the much stronger anthropogenic signal in the mobile fractions. Thus the shift of the lead isotope ratio values towards that of anthropogenic sources can be also expected in our case. The lead isotope composition of airborne particulate matter generally reflects the mixing of different sources, therefore source appointment can be quantified exactly in cases where all potential sources of Pb are characterized and have specific ratios (Komárek et al., 2008). Since the contribution of re-suspended soil or road dust to the TSP material may be as high as 74% (Young et al., 2002) significant presence of lead isotope characteristics of past emission sources are expected in our case. However, isotope composition of past sources can not be specified thus our evaluation is based on comparisons with literature data. According to their  $^{208}\text{Pb}/^{207}\text{Pb}$  and  $^{206}\text{Pb}/^{207}\text{Pb}$  ratios, most of the studied samples show that their lead comes from the mixing of two major sources: European leaded fuel and the natural lead (Figure 5a). This plot also shows that all the studied samples can be found between the field of urban aerosol samples collected in the 1990's in Budapest, Hungary and that of natural lead. However, the CS1 and UP1 samples present slightly different Pb isotopic composition from this mixing line suggesting the contribution of some more lead sources. These two samples can be characterized very similar

$^{206}\text{Pb}/^{207}\text{Pb}$  ratios but significantly lower (CS1) and higher (UP1)  $^{208}\text{Pb}/^{207}\text{Pb}$  ratios than the other samples. Sample CS1 can be characterized by the lowest, whereas sample UP1 by the highest  $^{208}\text{Pb}$  ratio among the studied samples. When other potential lead sources, such as Central European coals and ores are taken into account, the plot of  $^{208}\text{Pb}/^{206}\text{Pb}$  vs.  $^{206}\text{Pb}/^{207}\text{Pb}$  ratios (Figure 5b) shows that the majority of samples can be characterized by very similar lead isotope ratios to the Central European lead ores and coals, except again the samples CS1 and UP1. If other more Pb ore and coal sources are involved in the comparison, the plot of  $^{208}\text{Pb}/^{206}\text{Pb}$  vs.  $^{207}\text{Pb}/^{206}\text{Pb}$  ratios (Figure 5c) suggests the presence of at least three anthropogenic sources for lead: coals, fuels and (Italian) lead ores. Sample UP1, one of the former outsider samples, shows the same Pb isotope ratios as Sardinian Pb ore do. However, sample CS1 still show slight difference in its Pb isotope ratios, e.g. the presence of other Pb source(s). Until now we did not found any literature data which could explain these unique Pb isotope characteristics for this sample.

### ***Discussion***

The most significant lead bearing phase, which was also directly identified, is magnetite. Iron impurities are often found in combustibles and can convert to iron oxides, such as magnetite or hematite, depending of the burning conditions (Muxworthy et al., 2003) but they can be also related to the presence of ferrocene as fuel additive (Braun et al., 2006). That is why several studies have revealed large concentrations of iron in anthropogenic particulate matter (generally between 5 and 15%) and magnetite was identified as the dominant magnetic phase of Fe-rich particles (e.g., Chen et al.,

2006). As this phase is a well-known mineral which do not dissolve in aqua regia (e.g. Cohen et al., 2012), we can suppose that the aqua regia insoluble lead in the samples can be primarily associated to magnetite. This finding can be also prevalent for the sample with relatively low ratio of aqua regia soluble lead (KF1), as it can be characterized twice as much magnetite than other samples. The lack of strong linear relationship between total iron and aqua regia insoluble lead ( $r = 0.48$ ;  $p < 0.05$ ) does not contradict the close association of lead and magnetite, as iron may be present not only in magnetite, but probably also in carbonates, and Pb-free magnetite particles were also found. On the contrary, oxidation/weathering products of magnetite, like hematite and ferrihydrite are soluble in hot aqua regia (Silva et al., 2007). Our data do not allow estimating the contribution of latter phases to the aqua regia soluble lead. However, these results call the attention that advanced oxidation of iron in anthropogenic combustion processes and/or intensified weathering of magnetite in the urban environment facilitate the release of potentially toxic components, like Pb enclosed in iron oxides. Aqua regia soluble lead show strong positive linear relationship with total Ca and S content of the samples ( $r = 0.79$  for both at  $p < 0.05$ ), whereas a negative one with the estimated organic matter content ( $r = - 0.80$ ;  $p < 0.05$ ). This finding suggests the close association of Pb to Ca and S containing phases. Based on this, however, exact phases can not be specified as hosts for lead due to the fact the aqua regia is a strong and effective solvent for numerous particulate matter components.

Despite that the weak acid extraction was used to model the acidic pH of stomach environment through a very simplified way, it is also useful to study the potential acidification of urban environment. X-Ray spectroscopy analyses by Barret et al. (2010) showed several lead phases in urban dust, such as surface-sorbed lead, lead-

chloride, lead-carbonate, lead-oxide and lead-phosphate, which are potentially soluble in weak mineral acids in varying degree. These are mostly the same phases controlling aqueous-solid partitioning of lead in natural systems. At pH 2 lead is not expected to be sorbed at natural mineral surfaces, and carbonate (cerussite), hydroxide, oxide and sulphate (anglesite) of lead is readily soluble while its phosphate (pyromorphite) is sparingly soluble (Rickard and Nriagu, 1978). Among major TSP components carbonates demonstrate complete while clay minerals partial dissolution at this pH (Köhler et al., 2003). As our TEM-EDS analyses also showed the association of lead to both clay minerals and carbonates the mobilization of lead can be expected from these phases by this extraction. The strong positive linear correlation of weak acid soluble lead and total Ca ( $r = 0.83$ ;  $p < 0.05$ ) and S ( $r = 0.85$ ;  $p < 0.05$ ) content of the samples suggest that Pb may be hosted also by the form of Ca or even Pb sulphates. However, our mineralogical investigations did not support this supposition probably due to their relatively low concentration in the samples and/or their instability in the electron beam. The Ca and other (e.g. K) sulphate phases detected after all by TEM-EDS did not contain detectable amounts of Pb by EDS, but this finding does not exclude its presence in sulphates completely as the detection limit of EDS is around 0.1% for given particle. Water soluble lead is a relatively low proportion of total lead in the samples but it is readily available for any organism. Other studies (e.g. Fernandez Espinosa et al., 2002) attributed the water soluble lead to the presence of this metal in form of nitrates and/or chlorides in the airborne particulate matter samples.

Metal-oxide and metal-carbonate particles in the TSP may be primarily originated from anthropogenic emissions, whereas clay particles derived rather from the re-suspension of roadside dust and urban soils. Magnetite particles are resistant to



weathering releasing its toxic components slowly to the environment (Graham et al., 1989). However, layer silicates and carbonates are much less resistant than magnetite (Vogelein et al., 2005) thus besides water soluble lead they may be the potential source of mobile Pb in the TSP samples. The occasionally very high amount (up to 631 mg/kg) of weak acid extractable lead is supposed to be mobilized in the stomach environment resulting in serious risk to the environment and human health potentially.

Lead isotope analyses were carried out to study the potential sources of lead in the total suspended particulate matter samples. The most important source of this metal in airborne materials was the traffic until the phase out of leaded gasoline, although traffic related activities still emit lead to the environment by several ways. Thus the lead isotope ratios of large majority of urban airborne particulate matter samples can be placed between that of leaded gasoline and natural lead (Bollhöfer and Rossman, 2001). Due to the gradual phasing out of leaded gasoline in several countries, a “cleaning” trend could be observed for the last decade, e.g. the lead isotope ratios of recent TSP materials has been moved towards that of natural lead. According to Tomašević et al. (2013), however, this “clearing” trend can be affected by the appearance of lead of Chinese origin in the European markets. Additionally, the lead isotope ratio of Chinese lead ores can be also placed between that of natural lead and European leaded gasoline. This phenomenon was also observed in our case, e.g. the studied samples contain much higher ratio of natural lead and/or much higher ratio of lead of Chinese origin than the airborne particulate matter collected in the 1990’s in Budapest. It is important to note, however, that as the contribution of road dust and urban soil to the suspended material may be very high (up to 74%; Young et al., 2002), and the urban soils also store the lead coming from the past anthropogenic in their surface horizons (Hjortekans et al., 2008),

the lead from leaded gasoline must be still present in the recent airborne particulate matter. Our data, however, suggest the presence of some more lead sources besides the two mentioned above. The majority of the samples, which mostly fit the line between the isotopic composition of natural and gasoline lead well, also show significant overlap with the Pb isotope characteristics of Central and Eastern European lead ores and coals as based on data by Komárek et al. (2008). The former is expected to be the presence of past emission sources as lead mining is minimal in this region, whereas the latter suggests the contribution of domestic and industrial coal combustion activity to the TSP of Budapest. As the Pb isotopic composition of these potential sources is also placed between that of leaded gasoline and natural lead, the contribution of these sources can not be verified unambiguously. However, the wide use of these raw materials is evident and they can not be excluded as potential lead sources. Two samples out of the 9 studied generally showed unique lead isotopic composition as compared to the others. One of these samples show high similarity to Sardinian (Italy) lead ores (Tarzia et al., 2002), but the highest contribution of natural soil materials (as suggested by its highest SiO<sub>2</sub> content) among the studied samples may also result in this unique behaviour. For the other outsider sample, we did not find any literature data which could explain its unique Pb isotope characteristics. These data suggest the presence of additional source(s) for this metal at least in certain localities, but further investigations are necessary to specify them. There may be numerous potential pollution sources, such as paints, mineral oils etc., for which data are not available but can not be excluded as potential sources of lead.

### ***Conclusions***

Total suspended particulate (TSP) matter samples from Budapest can be characterized by 1-2 order of magnitude higher lead concentrations than expected from its geochemical background value for Hungary.

Lead was found to be associated to several host phases with very different stability. Generally, between 20 and 30% of total lead content of the TSP materials is hosted by magnetite which may be the result of numerous combustion-linked anthropogenic processes. Although it is a highly resistant phase to weathering, its fast oxidation during combustion processes to hematite and/or weathering in the acidifying urban environment to ferrihydrite may result the more easy mobilization of lead (and its other potentially toxic components). Up to 16% of lead was found to be weak acid soluble in the TSP materials, primarily representing Pb sorbed on the surface of clay minerals and in from of carbonates (and probably sulphates). This is the potentially mobile fraction of lead which could be harmful to human, as well. It was shown that the water soluble amounts of lead in the TSP samples are negligible.

The lead isotope composition of the TSP samples suggests the mixing of several potential sources for this metal. These sources showed slight variation among the sampling sites. Despite the phasing out of leaded gasoline in Hungary in 1999, its contribution to the Pb content of the TSP can be still observed. However, our data show much similar isotope ratios to that of natural lead than aerosols collected in the 1990's in Budapest, supporting the observation that the presence of lead of gasoline origin decreases in the airborne particulate matter in urban environment gradually. Another important source for lead is found to be the coal combustion probably due to domestic

and industrial heating. Our data suggest additional source(s) for this metal at least in certain localities, but further investigations are necessary to specify them.

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## Figure captions

Figure 1. Sketch map showing the localities of the thermal power plants, namely Csepel (CS), Kőbánya (KB), Kelenföld (KF), Újpest (UP).

Figure 2. Characteristic X-Ray diffractograms showing the major components of some bulk particulate matter samples (KF1 – Kelenföld, KB2 – Kőbánya, UP2 – Újpest).

Figure 3. Dominant Pb-bearing phases in the particulate matter samples. Transmission electron microscopy micrographs, diffraction patterns and EDS spectra of (a) a Zn and Pb-bearing smectite particle associated with soot aggregates composed of nano-spheres; of (b) a Pb and Zn-bearing magnetite spheres; and of (c) Zn, Pb and Mn-bearing dense aggregates of magnetite, hematite ( $3.7\text{\AA}$ ) and poorly crystalline ferrihydrite.

Figure 4. Extracted lead ratios (%) in the different chemical extractions used. Lung test was carried out with weak ammonium-acetate solution at pH 7, whereas stomach test with mixture of weak acetic acid and hydrochloric acid at pH 2. Note that in the lung test the extracted amount of lead was below the detection limit (5 mg/kg) for each sample thus the corresponding columns show the respective ratio for this value.

Figure 5. Aqua regia soluble lead isotope ratios of the studied total suspended particulate matter samples (Csepel - CS, Kőbánya - KB, Kelenföld - KF, Újpest - UP). Comparison our data to (a) the lead isotope ratio data for European leaded gasoline and

natural lead (Grobéty et al., 2005), urban aerosol samples from the 1990's (Bollhöfer and Rosman, 2001) and Hungarian soils (Reimann et al., 2012) (The “clearing” trend indicated by the gray arrow is given by Tomašević et al. (2013)); to (b) the lead isotope ratio data for Central and East European lead ores and Central European coals (Komárek et al., 2008); and to (c) the lead isotope ratio data for lead ores of different origin and Appalachian coals (Tarzia et al., 2002).

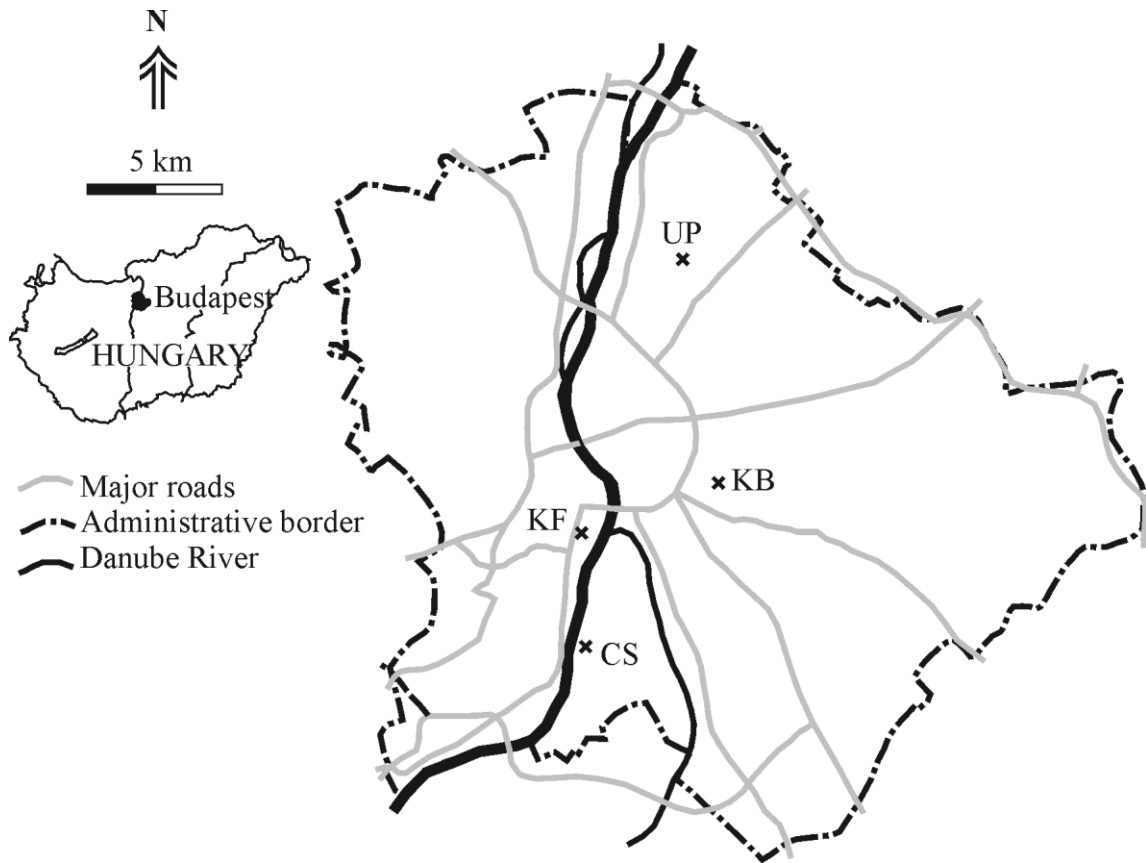


Figure 1.

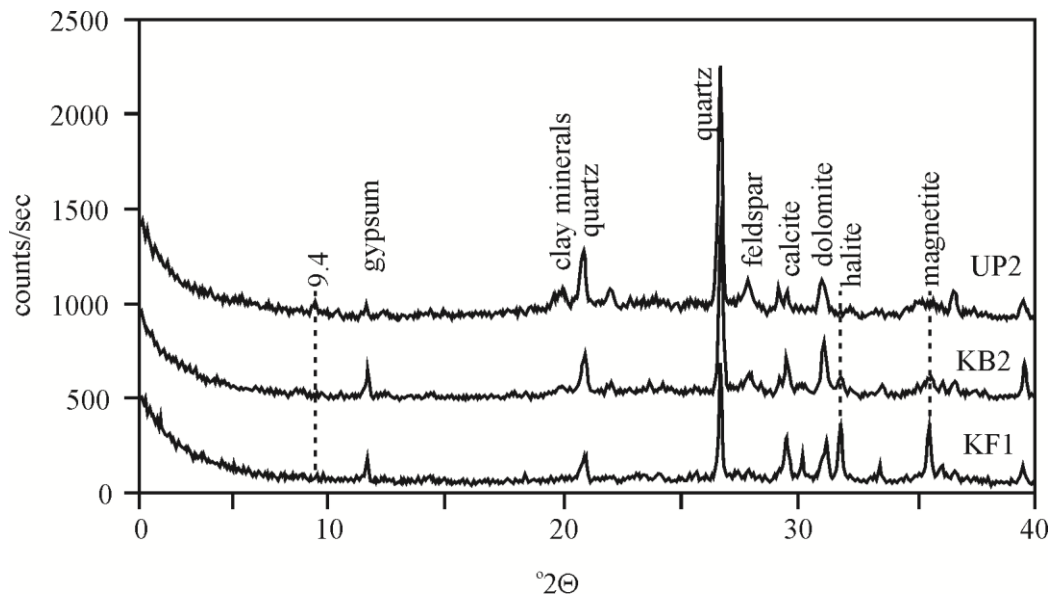


Figure 2.

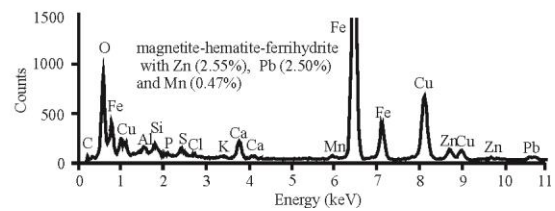
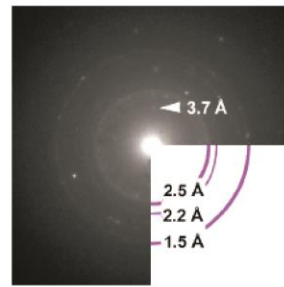
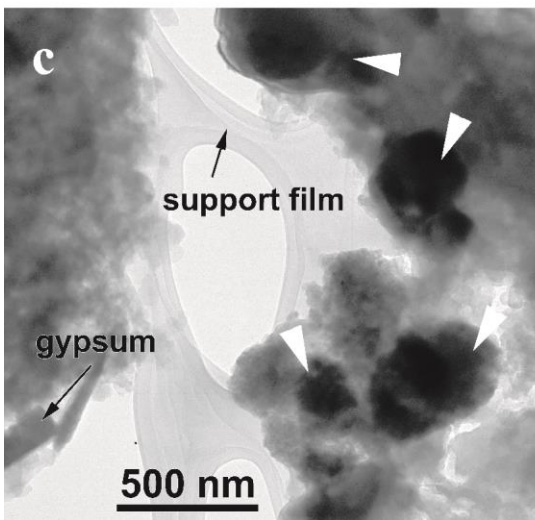
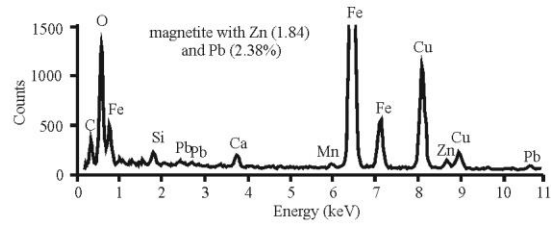
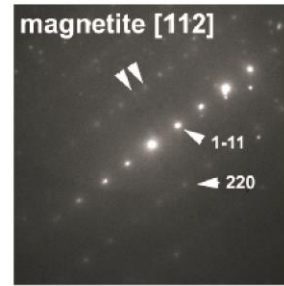
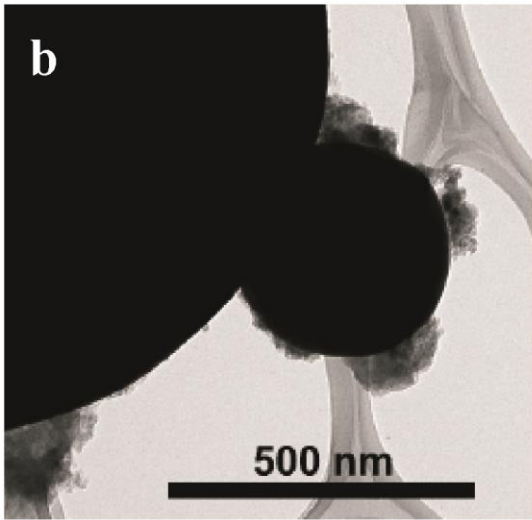
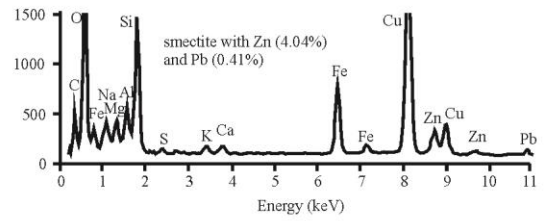
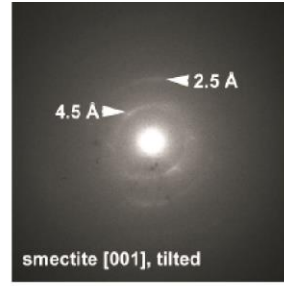
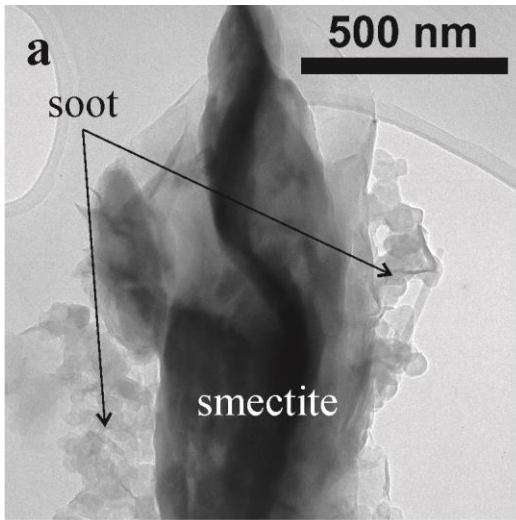


Figure 3.

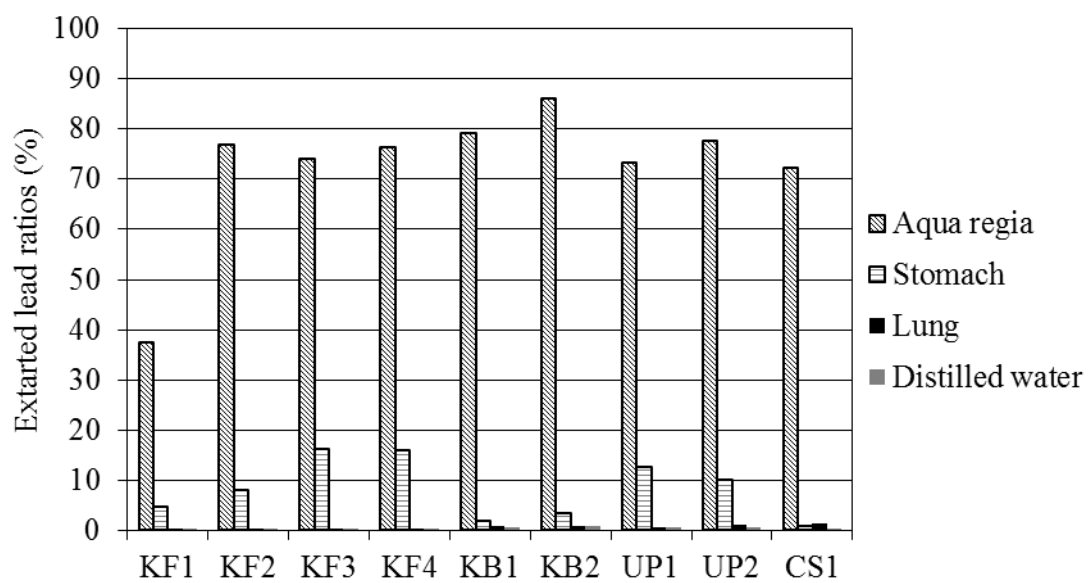


Figure 4.

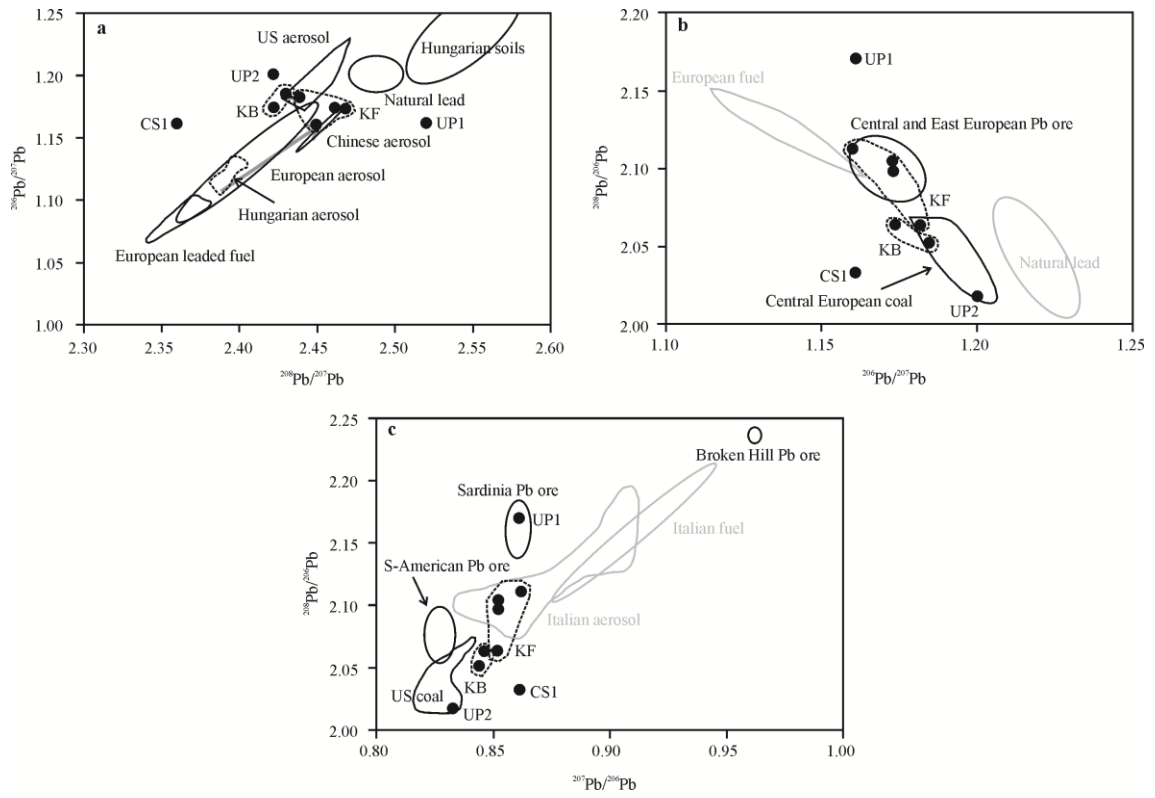


Figure 5.



Table 1. Major element concentrations and loss on ignition (LOI) (wt%) in the studied total suspended particulate (TSP) matter samples. LOI was determined at 1050°C, while LOI<sub>org</sub> concern to ignition loss between 105 and 450°C to estimate the organic matter content of TSP samples. \*Sum is the total sum of the major element concentrations as oxides and LOI.

|     | Na <sub>2</sub> O | MgO  | Al <sub>2</sub> O <sub>3</sub> | SiO <sub>2</sub> | K <sub>2</sub> O | CaO   | TiO <sub>2</sub> | Fe <sub>2</sub> O <sub>3</sub> | P <sub>2</sub> O <sub>5</sub> | SO <sub>4</sub> | MnO  | LOI   | Sum*   | LOI <sub>org</sub> |
|-----|-------------------|------|--------------------------------|------------------|------------------|-------|------------------|--------------------------------|-------------------------------|-----------------|------|-------|--------|--------------------|
| KF1 | 9.84              | 2.37 | 9.28                           | 25.52            | 0.96             | 9.82  | 0.41             | 13.50                          | 0.28                          | 7.92            | 0.23 | 22.41 | 102.55 | 16.79              |
| KF2 | 1.44              | 2.05 | 7.81                           | 23.38            | 1.75             | 15.24 | 0.50             | 10.73                          | 0.61                          | 6.67            | 0.15 | 27.07 | 97.40  | 18.10              |
| KF3 | 1.56              | 1.90 | 7.59                           | 21.30            | 1.36             | 20.89 | 0.51             | 10.63                          | 0.38                          | 12.89           | 0.14 | 20.84 | 99.99  | 14.11              |
| KF4 | 1.55              | 1.87 | 7.56                           | 21.43            | 1.38             | 20.74 | 0.50             | 10.51                          | 0.38                          | 13.29           | 0.14 | 21.33 | 100.68 | 14.24              |
| KB1 | 1.76              | 2.07 | 8.73                           | 28.21            | 1.74             | 10.70 | 0.53             | 13.67                          | 0.61                          | 8.64            | 0.16 | 25.45 | 102.28 | 19.27              |
| KB2 | 2.92              | 2.02 | 8.23                           | 25.68            | 1.60             | 13.48 | 0.47             | 12.29                          | 0.67                          | 8.48            | 0.18 | 23.37 | 99.39  | 16.36              |
| UP1 | 2.33              | 1.92 | 8.49                           | 28.43            | 1.56             | 8.72  | 0.71             | 7.79                           | 0.70                          | 4.93            | 0.13 | 32.25 | 97.95  | 21.41              |
| UP2 | 2.29              | 1.77 | 8.03                           | 24.56            | 1.92             | 8.03  | 0.67             | 7.11                           | 1.04                          | 5.70            | 0.13 | 37.25 | 98.49  | 22.32              |
| CS1 | 1.97              | 1.86 | 7.21                           | 19.86            | 2.77             | 10.55 | 0.48             | 7.93                           | 2.50                          | 6.34            | 0.13 | 35.53 | 97.12  | 25.20              |

Table 2. Total lead concentration and the amount of lead mobilized by different extractions used (mg/kg). Lung test was carried out with weak ammonium-acetate solution at pH 7, while stomach test with the mixture of weak acetic acid and hydrochloric acid at pH 2. Pb\* = lead concentrations were calculated as a sum of the concentrations of each lead isotopes in aqua regia dissolution.

|     | Total |      | Aqua regia        |                   |                   |                   | Stomach<br>at pH 2 | Lung<br>at pH 7 | Distilled<br>water |
|-----|-------|------|-------------------|-------------------|-------------------|-------------------|--------------------|-----------------|--------------------|
|     | Pb    | Pb*  | <sup>204</sup> Pb | <sup>206</sup> Pb | <sup>207</sup> Pb | <sup>208</sup> Pb | Pb                 | Pb              | Pb                 |
| KF1 | 5942  | 2231 | 32                | 553               | 477               | 1169              | 285                | <5              | 3.3                |
| KF2 | 1923  | 1478 | 21                | 369               | 314               | 773               | 154                | <5              | 4.2                |
| KF3 | 3878  | 2874 | 41                | 716               | 610               | 1506              | 630                | <5              | 2.6                |
| KF4 | 3916  | 2990 | 43                | 754               | 638               | 1555              | 631                | <5              | 2.6                |
| KB1 | 547   | 434  | 6.2               | 109               | 93                | 225               | 11                 | <5              | 3.7                |
| KB2 | 538   | 463  | 6.6               | 117               | 99                | 240               | 18                 | <5              | 5.1                |
| UP1 | 942   | 692  | 10                | 169               | 146               | 367               | 118                | <5              | 4.9                |
| UP2 | 427   | 331  | 4.8               | 85                | 71                | 171               | 43                 | <5              | 2.8                |
| CS1 | 368   | 267  | 3.8               | 67                | 58                | 137               | 2.8                | <5              | 0.4                |