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Abstract

The chemical composition of one smart phone and two mobile phones including their Li-batteries was analyzed by instrumental neutron activation analysis (INAA), infrared spectroscopy, fusion specific ion selective electrode, thermal conductivity, inductively coupled plasma optical emission spectroscopy (ICP-OES) and inductively coupled plasma mass spectrometry (ICP-MS).

Because the applied analytical methods require the introduction of dilute solutions, the mobile phones and batteries were crushed and partially powdered by electronic fragmentation carried out by the SELFRAG laboratories. However, the electronic fragmentation gave only partially satisfying results. The disadvantages were the loss of light components, in particular plastic and crystalline graphite and the large particle size of large single-material components such as the plastic body, screen and metal frame. Because of the weight loss, the provided concentrations of light elements, including C, S, P, Cl, F, B, and Li, have large errors.

The investigated mobile phones are rich in Ag (mean 915 ± 526 ppm), Au (mean 255 ± 120 ppm), Cu (mean 19.2 ± 5.6 wt.%), Sn (mean 1.2 ± 0.4 wt.%), In (mean 56 ± 48 ppm), Ta (mean 409 ± 203 ppm) and Ni (mean 1.6 ± 1.3 wt.%) compared to the average composition of the Earth's upper crust. The Li-batteries have high Co (mean 17.1 ± 11.0 wt.%), Cu (10.2 ± 4.4 wt.%), Au (mean 35.0 ± 15.8 ppm), Li (mean 2.0 ± 1.2 wt.%), Sn (mean 1610 ± 864 ppm), Ni (mean 1.9 ± 2.5 wt.%) and B (mean 583 ± 1010 ppm). However, due to the limited number of analyses and the errors caused by the mass loss during fragmentation, these numbers have large errors and represent only rough approximations.

According to the Strategy Analytics 1,575,000,000 mobile phones were shipped worldwide (not sold) in 2012. Applying the results of this study, the production of 1.6 billion mobile phones including their Li-batteries requires approximately 27,438 t Cu, 5,926 t Co, 2,657 t Ni, 1,520 t Sn, 1309 t Zn, 702 t Li, 330 t Nd, 114 t Ag, 61 t Ta, 32 t Au, 18 t Dy, and 7 t In. These are very valuable metals and, thus, recycling of mobile phones and batteries is of great ecological and economic interest. However, the technologies for the extraction and enrichment for most of these elements from recycled mobile phones have not yet been developed. The most valuable and currently recyclable elements determined in this study are Ag, Au and In and to minor extend Cu and Ni. However, Cu and Ni form large, relative easy minable deposits in nature and, thus, their recycling is not as profitable as the recycling of the precious metals.

Keywords: Technical report	Geochemistry	Mobile phones
Li-batteries		

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1. Introduction

In recent years an exhibition of ore minerals and their applications has been established at the Geologic Survey of Norway, mainly for educational purposes. The exhibition illustrates which natural minerals are needed and have to be mined for the production of objects in daily use such as mobile phones. Today mobile phones are one of the most common electronic devices used by the public and 1,575,000,000 mobile phones were shipped worldwide in 2012 (Strategy Analytics 2013). Mobile phones consist of many materials with complex chemical compositions. In general, they contain 40 % metals, 40 % plastics, and 20 % ceramics. Several sources provide information on the major and some trace element compositions of mobile phones. However, complete and precise chemical bulk analyses of individual mobile phones are not readily available, if at all.

The purpose of this study is to provide complete chemical bulk analyses of the mobile phones Nokia Nuron 5230 Smart phone (on market since 2009), Nokia 5130 XpressMusic (on market since 2009) and Sony Ericsson W595 (on market since 2008) and their batteries Nokia BL-5J, Nokia BL-5C and Sony Ericsson BST-33 (Figure 1). The Nokia batteries are Li-ion batteries providing 3.7 V and the Sony Ericsson battery is a Li-polymer battery providing 3.6 V.

The preparation of mobile phones (crushing and powdering) was carried by the SELFRAG electrical fragmentation laboratory in Kerzers, Switzerland, by using high-voltage, pulsepower fragmentation (SELRAG 2013). The chemical analyses were performed at Activation Laboratories Ltd. in Ancaster, Ontario, Canada (ACTLABS 2013) applying the following methods (with the specific company codes):

- Instrumental Neutron Activation Analysis (INAA) for Ag, Au, Br, Cl, Ir, Lu, Na, Sc, Cl (Code 4A and 4F)
- Infrared spectroscopy for C and S (Code 4F)
- Fusion specific ion selective electrode for F (Code 4F)
- Thermal conductivity for N (Code 4F)
- Sodium peroxide fusion Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) for remaining major and trace elements (Code Ultratrace (UT)-7)

The analytical results are discussed and compared with the average composition of the Upper Crust (of Earth) in order to understand the magnitude of the industrial enrichment of the detected elements.



Figure 1. Analyzed mobile phones and batteries. The photos are from different sources available from mobile phone providers.

2. Methods

2.1 Electronic fragmentation of mobile phones and batteries

The applied analytical methods require the introduction of dilute solutions with totally dissolved solids $<0.1\%$ and, therefore, the mobile phones and batteries had to be crushed and milled down to the smallest possible particle size, preferably $<200\ \mu\text{m}$. This was the biggest challenge of the project because mobile phones can only be crushed and milled by conventional methods with great difficulty. For that reason electrical fragmentation was chosen as the preferred method.

Electrical fragmentation of the mobile phones and batteries was carried out at the SELFRAG laboratory in Kerzers, Switzerland (SELEFRAG, 2013). The SELEctive FRAGmentation technology of SELFRAG uses these effects to liberate material along the material boundaries, to weaken material along particle boundaries or to diminish the size of component parts without introducing contamination. Like natural lightning a SELFRAG plant creates repetitive electrical discharges. It applies the electrical energy to materials immersed in a process liquid. Dielectric liquids, like water, have a high dielectric strength when voltage rise time is kept below 500 ns. As a result, discharges are forced through the immersed material. The introduced electrical energy is then transformed into an acoustical shockwave resulting into a huge tensile stress regime within the material. Particles inside a composite material or defects in a crystalline material lead to discontinuity in the electrical and acoustical properties. The discontinuity in the dielectric permittivity enhances the electrical field at the grain boundaries and forces the discharge channels to the boundaries. The sudden expansion of the created plasma produces a shock wave with local pressures up to 10 kbar. The interaction of a shock wave and an acoustical discontinuity concentrate tensile stress at these interfaces.

The fragmentation setting consists of a HV power supply, HV pulse generator, portable process vessels and a lifting table. Samples are loaded into a portable water-loaded processing vessel which is subsequently placed onto the lifting table in the loading section. Thereafter, short pulses (pulse rise time less than 500 ns) of high-voltage electrical fields are applied. Once the predetermined voltage is reached, the energy of the pulse generator is discharged from the electrode through the solid sample to the bottom of the processing vessel. The sample is fragmented as a result of a spherical shock wave which propagates throughout the material. A sieve is inserted in the bottom of the process vessel to collect the fragmented particles.

Table 1. Parameters of electronic fragmentation of mobile phones and batteries and their weights.

	Nokia 5230 smart phone	Nokia BL-5J Li-ion battery	Nokia 5130 mobile phone	Nokia BL-5C Li-ion battery	Sony Ericsson W595 mobile phone	Sony Ericsson BST-33 Li-polymer battery
Parameters of electronic fragmentation						
Pulse (Hz)	1000	1000	1000	1000	1000	1000
EG (mm)	40	20	40	20	40	20
voltage (kV)	160	160	160	160	160	160
Sample weight						
weight before fragmentation [g]	86.0	27.3	65.8	21.0	85.0	19.1
weight after fragmentation [g]	73.5	19.6	59.2	15.4	84.0	5.2
weight loss [%]	14.5	28.2	10.0	26.7	1.2	72.3

The various components of the mobile phones and batteries reacted differently to the electronic fragmentation. The fragmentation resulted in a wide range of particle sizes ranging from powder (~20 μm) to nearly undestroyed parts up to 10 cm in size (Figures 2 to 7). Multiple composed components such as printed circuit boards and micro-processors were well fragmented and partially powdered. Large single-material components, such as plastic body, glass window and supporting metal frame were hardly damaged. This is due to the fact that electronic fragmentation weakens the object primarily along particle and component boundaries. Thus, single-material components without internal boundaries are hardly affected

by electronic fragmentation. Components >1 cm were therefore cut manually down to <1 cm (Figures 8 to 10).

The disadvantage of the method in respect to the aims of this study is the weight loss during fragmentation. The mobile phones exhibited a weight loss of 1.2 to 14.5 wt.% and the batteries of 26.7 to 72.3 wt.%. The weight loss is mainly due to poor recovery of the light components such as plastic parts and the graphite powder of the Li-batteries from the process water. A loss of 7-10% can be considered normal for this type of material, if the process water is not recovered and specially filtered (SELFRAG 2013, personal communication) The concentrations of the elements C, S, P, Cl, F, B, and Li of mobile phones and batteries presented in the following chapters have therefore large errors.

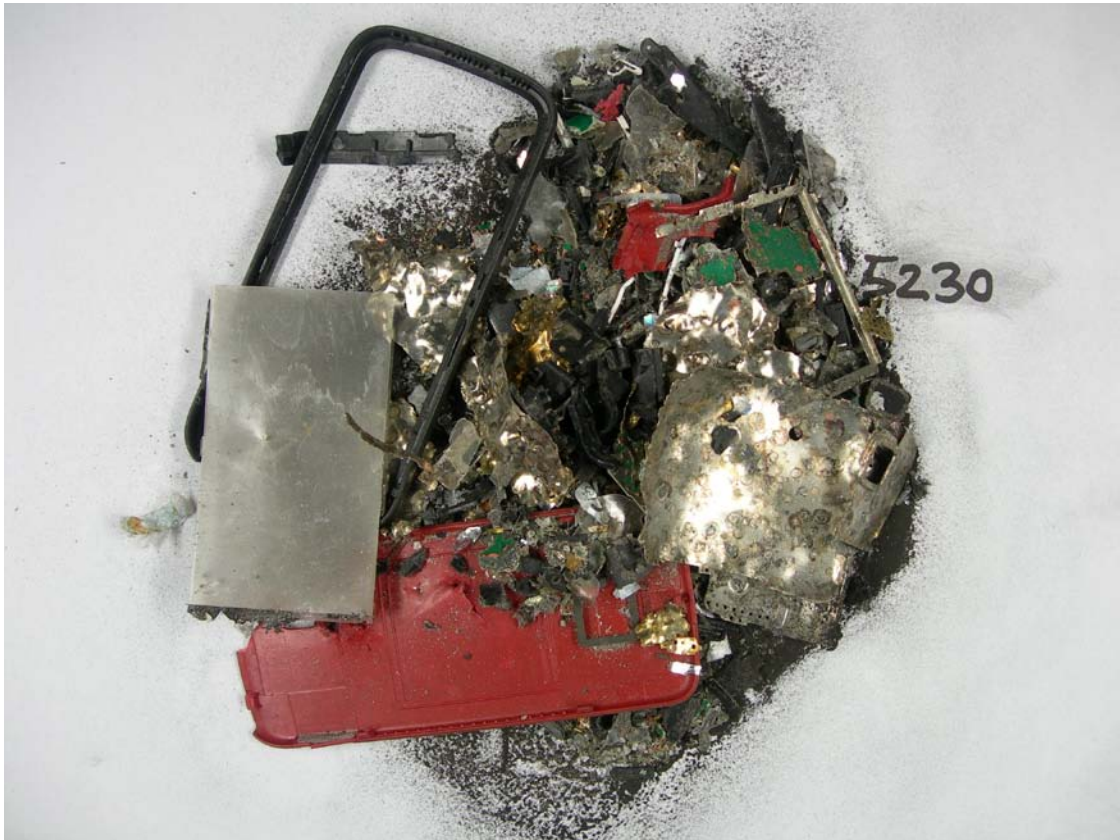


Figure 2. Electronically fragmented Nokia 5230 smart phone.



Figure 3. Electronically fragmented Nokia 5130 mobile phone.



Figure 4. Electronically fragmented Sony Ericsson W595 mobile phone.



Figure 5. Electronically fragmented Nokia BL-5J Li-ion battery.



Figure 6. Electronically fragmented Nokia BL-5C Li-ion battery.



Figure 7. Electronically fragmented Sony Ericsson BST-33 Li-polymer battery.



Figure 8. Electronically fragmented Nokia 5230 smart phone. Components >1 cm were cut manually.



Figure 9. Electronically fragmented Nokia 5130 mobile phone. Components >1 cm were cut manually.



Figure 10. Electronically fragmented Sony Ericsson W595 mobile phone. Components >1 cm were cut manually.

2.2 Instrumental neutron activation analysis (INAA)

A 1 g aliquot is encapsulated in a polyethylene vial and is irradiated with flux wires and an internal standard (1 for 11 samples) at a thermal neutron flux of $7 \times 10^{12} \text{ n cm}^{-2} \text{ s}^{-1}$ (ACTLABS 2013). After a 7-day decay to allow Na-24 to decay, the samples are counted on a high purity Ge detector with resolution of better than 1.7 keV for the 1332 keV Co-60 photopeak. Using the flux wires, the decay-corrected activities are compared to a calibration developed from multiple certified international reference materials. The standard present is only a check on accuracy and is not used for calibration purposes. 10-30% of the samples are checked by re-measurement.

2.3 Fusion Specific Ion Selective Electrode (ISE) for F determination

The ion-selective electrode represents the standard instrumental technique in which the simple pH meter has been adapted to the determination of the concentration of F ions. 0.2 g samples are fused with a combination of lithium metaborate and lithium tetraborate in an induction furnace to release the fluoride ions from the sample matrix (ACTLABS 2013). The fused sample is dissolved in dilute nitric acid, prior to analysis the solution is complexed and the ionic strength adjusted with an ammonium citrate buffer. The fluoride ion electrode is immersed in this solution to measure the fluoride-ion activity directly. An automated fluoride analyzer from Mandel Scientific is used for the analysis. The limit of detection for F is 0.01 wt.%.

2.4 Infrared spectrometry for C and S determination

The analysis of C and S is performed with an Eltra CS-2000 infrared spectrometer (ACTLABS 2013). Accelerator material is added to a 0.2 g sample. The inductive elements of the sample and accelerator couple with the high frequency field of the induction furnace. The CS-2000 is equipped with an induction furnace for sample oxidation and can provide temperatures up to 2500 °C. Sulfur is measured as sulfur dioxide in the first IR cell. Carbon is measured as carbon dioxide in the IR cell as gases flow through the IR cells. Carbon dioxide absorbs IR energy at a precise wavelength within the IR spectrum. Energy from the IR source is absorbed as the gas passes through the cell, preventing it from reaching the IR detector. All other IR energy is prevented from reaching the IR detector by a narrow bandpass filter. Because of the filter, the absorption of IR energy can be attributed only to carbon dioxide (CO₂). The concentration of CO₂ is detected as a reduction in the level of energy at the detector.

2.5 Thermal Conductivity for N determination

A 0.2 g sample is combusted in a resistance furnace at 1350°C using a LECO CNS-2000 (ACTLABS 2013). Combustion gases are collected in a 4.5-liter ballast tank and then flow to the detectors. Nitrogen, as N₂ is detected by thermal conductivity detection. The limit of detection for N is 0.01 wt.%.

2.6 Inductively Coupled Plasma Mass Spectrometry (ICP-MS)

The majority of elements are analyzed by ICP-MS using a Perkin Elmer Sciex ELAN 6000, 6100 or 9000 ICP-MS (ACTLABS 2013; Table 2). Samples were prepared by sodium peroxide fusion. Fused blank is run in triplicate for every 22 samples. Controls and standards fused with samples are run after the 22 samples. Fused duplicates are run every 10 samples. The instrument is recalibrated after every 44 samples.

2.7 Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES)

The elements Al, Ca, Fe, K, Mg, P, Si, and Ti are analyzed by ICP-OES using a Varian 735 ES (ACTLABS 2013). The samples were prepared by sodium peroxide fusion and analyzed using a Varian 735ES ICP or a Thermo 6500 ICAP. The samples are analyzed with a minimum of 10 certified reference materials for the required analytes. Every 10th sample is prepared and analyzed in duplicate; a blank is inserted for every 30 samples and analyzed.

3. Results of the chemical analyses

3.1 Mobile phones

The analytical results are listed in Table 2. Table 3 shows 34 elements with the highest enrichment compared to the average composition of the Upper Crust of the Earth according to Rudnick and Gao (2005, with corrected value for Au of 0.0015 ppm). In general, the element distribution patterns are similar for the smart phone and the two mobile phones (Figures 11a-c). However, the smart phone has higher Br, Ag, Zn, Ni, and Sr and lower Dy, Gd, Nd, Pr, Sn and W compared to the mobile phones.

All three mobile phones have very high Ag (mean 915 ± 526 ppm), Au (mean 255 ± 120 ppm), Cu (mean 19.2 ± 5.6 wt.%), Sn (mean 1.2 ± 0.4 wt.%), In (mean 56 ± 48 ppm), Ta (mean 409 ± 203 ppm) and Ni (mean 1.6 ± 1.3 wt.%) compared to the average composition of the Upper Crust according to Rudnick and Gao (2005) (Table 3). Ag, Au, and Cu are the major metals in microelectronic components. Nickel is used in the microphone diaphragm, electrical connections and capacitors. Indium is part of the LCD display where it is used as Sn-doped In_2O_3 . Tantalum is the major component of micro capacitors.

In addition to the high concentrations of Au, Ag, Sn, Ni and In, the REEs Nd (2627 ± 1298 ppm), Pr (654 ± 299 ppm), Dy (146 ± 58 ppm) and Gd (83 ± 39 ppm) are considerably (at potentially economic levels) enriched (Figure 12). The average concentration of REE is 3540 ± 1687 ppm which is 24 times the average concentration of REE in the Upper Crust. However, some REE were not detected, including Ce, Eu, Tb, Tm, Yb, and Lu. The toxic metals As (64 ± 31 ppm) and Pb (106 ± 15 ppm) also have high concentrations.

Table 2. Chemical composition of mobile phones and Li-batteries. Note that due to significant weight loss during electronic fragmentations the concentrations of C, S, P, B, F, Cl and Li have large errors. LOD – limit of detection. ISE - ion selective electrode, IR – infrared spectroscopy, TC - thermal conductivity.

element	unit	LOD	method	Nokia	Nokia	Sony E.	Nokia	Nokia	Sony E.
				5230	5130	W595	BL-5J	BL-5C	BST-33
				smart phone	mobile phone	mobile phone	Li-battery	Li-battery	Li-battery
Ag	ppm	2	INAA	1490	457	799	< 2	< 2	< 2
Al	%	0.01	ICP-OES	1.85	1.66	1.95	15.3	8.19	23.6
As	ppm	5	ICP-MS	35	60	97	56	69	54
Au	ppm	2	INAA	373	133	260	19.3	34.8	50.8
B	ppm	10	ICP-MS	3840	4920	3850	420	180	340
Ba	ppm	3	ICP-MS	3210	3510	4380	1140	204	579
Be	ppm	3	ICP-MS	< 3	6	< 3	< 3	< 3	< 3
Bi	ppm	2	ICP-MS	< 2	6	6	14	< 2	7
Br	ppm	0.5	INAA	288	92.5	25.9	< 0.5	< 0.5	1750
C	%	0.01	IR	26.6	24	30.1	25.4	25.9	28
Ca	%	0.01	ICP-OES	1.74	1.78	2.08	0.24	0.36	0.21
Cd	ppm	2	ICP-MS	< 2	8	5	< 2	< 2	< 2
Ce	ppm	0.8	ICP-MS	< 0.8	< 0.8	< 0.8	< 0.8	< 0.8	< 0.8
Cl	%	0.01	INAA	0.02	0.02	0.04	0.02	0.05	0.21
Co	ppm	0.2	ICP-MS	948	1540	376	233000	236000	44000
Cr	ppm	30	ICP-MS	4440	7860	5280	480	390	260
Cs	ppm	0.1	ICP-MS	< 0.1	0.8	0.3	0.4	< 0.1	0.7
Cu	%	2	ICP-MS	24.90	19.0	13.7	7.01	8.42	15.3
Dy	ppm	0.3	ICP-MS	83.8	155	199	4.4	4.2	8.7
Er	ppm	0.1	ICP-MS	1.3	4	3.2	< 0.1	0.1	0.2
Eu	ppm	0.1	ICP-MS	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
F	%	0.01	ISE	0.07	0.04	0.05	0.4	0.71	0.41
Fe	%	0.05	ICP-OES	2.28	5.1	6.68	1.03	1.26	0.79
Ga	ppm	0.2	ICP-MS	29.2	41.4	44.1	19.5	11.7	31.9
Gd	ppm	0.1	ICP-MS	38.3	103	108	3.7	2.6	5.2
Ge	ppm	0.7	ICP-MS	28.3	135	74	< 0.7	1.3	2.2
Hf	ppm	10	ICP-MS	< 10	< 10	< 10	< 10	< 10	< 10
Ho	ppm	0.2	ICP-MS	5.8	17.8	14.4	0.4	< 0.2	0.4
In	ppm	0.2	ICP-MS	42.2	16	109	25.1	1.5	0.6
Ir	ppb	2	INAA	< 2	< 2	< 2	< 2	< 2	< 2
K	%	0.1	ICP-OES	< 0.1	< 0.1	< 0.1	0.7	0.8	0.2
La	ppm	0.4	ICP-MS	13.2	9.6	18.5	39.6	14	16.4
Li	ppm	3	ICP-MS	123	150	41	27400	26900	5370
Lu	ppm	0.01	INAA	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Mg	%	0.01	ICP-OES	0.22	0.17	0.15	1.5	1.75	0.46
Mn	ppm	3	ICP-MS	629	624	775	1640	531	6670
Mo	ppm	1	ICP-MS	82	72	72	6	8	4
N	%	0.01	TC	0.16	0.06	0.06	0.08	0.1	1.37
Na	%	0.001	INAA	0.049	0.031	0.051	0.029	0.177	0.061
Nb	ppm	2.4	ICP-MS	7.3	7.4	14.1	12.7	8.2	7.9
Nd	ppm	0.4	ICP-MS	1180	3690	3010	69.3	109	126
Ni	ppm	10	ICP-MS	31000	9990	7460	4560	3970	47600
P	%	0.005	ICP-OES	0.133	0.209	0.148	0.13	0.199	0.127
Pb	ppm	0.8	ICP-MS	110	90.4	119	29.3	33.7	373
Pr	ppm	0.1	ICP-MS	316	884	763	20	16.8	32.5
Rb	ppm	0.4	ICP-MS	1.2	1.2	0.9	< 0.4	3.3	2.9
S	%	0.01	IR	0.13	0.13	0.12	< 0.01	0.11	0.01
Sb	ppm	2	ICP-MS	14	36	26	6	5	19
Sc	ppm	0.01	INAA	15	10.5	10.2	< 0.01	< 0.01	2.83
Si	%	0.01	ICP-OES	4.74	6	5.32	0.64	1.27	0.75
Se	ppm	0.8	ICP-MS	14.3	17.6	21.6	21.5	19.3	6.8
Sm	ppm	0.1	ICP-MS	1.2	0.4	1	7.9	0.8	< 0.1
Sn	ppm	0.5	ICP-MS	7410	14900	13000	1890	641	2300
Sr	ppm	3	ICP-MS	3420	831	738	59	29	32
Ta	ppm	0.2	ICP-MS	300	284	644	7.2	2.6	3.1
Tb	ppm	0.1	ICP-MS	0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Te	ppm	6	ICP-MS	< 6	< 6	< 6	< 6	< 6	< 6
Th	ppm	0.1	ICP-MS	< 0.1	0.9	< 0.1	< 0.1	< 0.1	< 0.1
Ti	%	0.01	ICP-OES	0.13	0.28	0.17	0.18	0.25	0.04
Tl	ppm	0.1	ICP-MS	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Tm	ppm	0.1	ICP-MS	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
U	ppm	0.1	ICP-MS	< 0.1	< 0.1	< 0.1	< 0.1	0.2	< 0.1
V	ppm	5	ICP-MS	26	46	35	38	26	32
W	ppm	0.7	ICP-MS	63.3	317	191	8.2	10	64.1
Y	ppm	0.1	ICP-MS	16.6	11.7	24.1	2.4	3.2	3.2
Yb	ppm	0.1	ICP-MS	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Zn	ppm	30	ICP-MS	27400	3000	1160	280	100	110
ΣREE	ppm			1639.7	4863.8	4117.1	145.3	147.5	189.4

Table 3. Average concentrations of elements in mobile phones and Li-batteries and their enrichment (norm) compared to the average composition of the Upper Crust of Earth according to Rudnick and Gao (2005, with corrected value for Au of 0.0015 ppm). SD – standard deviation.

mobile phones					Li-batteries				
element	unit	average conc	SD	norm	element	unit	average conc	SD	norm
Ag	ppm	915	526	172704	Au	ppm	35	16	23311
Au	ppm	255	120	170222	Co	ppm	171000	109995	9884
Cu	ppm	192000	56027	6857	Cu	ppm	102433	44356	3658
Sn	ppm	11770	3894	5605	Li	ppm	19890	12577	829
In	ppm	56	48	995	Sn	ppm	1610	864	767
Ta	ppm	409	203	455	Ni	ppm	18710	25021	398
Ni	ppm	16150	12923	344	Br	ppm	583	1010	365
B	ppm	4203	621	247	Se	ppm	16	8	176
Se	ppm	18	4	198	In	ppm	9	14	162
Zn	ppm	10520	14647	157	N	%	0.52	0.74	62
W	ppm	190	127	100	Bi	ppm	7	7	44
Nd	ppm	2627	1298	97	Sb	ppm	10	8	25
Pr	ppm	654	299	92	B	ppm	313	122	18
Br	ppm	135	136	85	W	ppm	27	32	14
Mo	ppm	75	6	68	As	ppm	60	8	12
Cr	ppm	5860	1782	64	F	%	0.51	0.18	9
Sb	ppm	25	11	63	Pb	ppm	145	197	9
Ge	ppm	79	54	57	S	%	0.04	0.06	6
Co	ppm	955	582	55	Mo	ppm	6	2	5
Cd	ppm	4	4	48	Ta	ppm	4	3	5
Dy	ppm	146	58	37	Cr	ppm	377	111	4
Bi	ppm	4	3	25	Nd	ppm	101	29	4
Gd	ppm	83	39	21	Pr	ppm	23	8	3
S	%	0.13	0.01	20	Cl	%	0.09	0.10	3
Ho	ppm	13	6	15	Zn	ppm	163	101	2
As	ppm	64	31	13	P	%	0.15	0.04	2
N	%	0.09	0.06	11	Al	%	15.70	7.71	2
Pb	ppm	106	15	6	Dy	ppm	6	3	1
Ba	ppm	3700	608	6	Ga	ppm	21	10	1
Sr	ppm	1663	1522	5	Ba	ppm	641	471	1
Li	ppm	105	57	4	Gd	ppm	4	1	1
P	%	0.16	0.04	2	Ge	ppm	1	1	1
Ga	ppm	38	8	2	Mg	%	1.24	0.68	1

3.2 Li-batteries

The analytical results are listed in Table 2. Table 3 shows 34 elements with the highest enrichment compared to the average composition of the Upper Crust according to Rudnick and Gao (2005, with corrected value for Au of 0.0015 ppm). In general, the element distribution pattern is similar for the two Li-ion batteries (BL-5J, BL-5C) and the Li-polymer battery (Figures 11a-c). However, the Li-polymer battery has higher Br, Mn, Ni, Pb, and W and lower Co and Li compared to the Li-ion batteries (Table 2). Surprisingly, the distribution pattern of Li-batteries is also similar to the pattern of the mobile phones, in particular the REE distribution (Figures 11a-c, 12). The Li-batteries have higher Co, Li and Mn and lower REE, Au, Ag, B, Ba, Ge, Ta, In, Sn, and W than mobile phones.

All three Li-batteries have high Co (mean 17.1 ± 11.0 wt.%), Cu (10.2 ± 4.4 wt.%), Au (mean 35.0 ± 15.8 ppm), Li (mean 2.0 ± 1.2 wt.%), Sn (mean 1610 ± 864 ppm), Ni (mean 1.9 ± 2.5 wt.%) and B (mean 583 ± 1010 ppm) compared to the average composition of the Upper Crust according to Rudnick and Gao (2005) (Table 3). The high Li, Co, C, Ni, Cu and Mn concentrations are due to the use of 3-element cathodes composed of LiCoO_2 , Ni, and Mn and of anodes composed of crystalline C coated on Cu foil. The valuable elements with high concentrations are Au, Co, and Ni. The toxic metals As (60 ± 8 ppm) and Pb (145 ± 197 ppm) also have high concentrations.

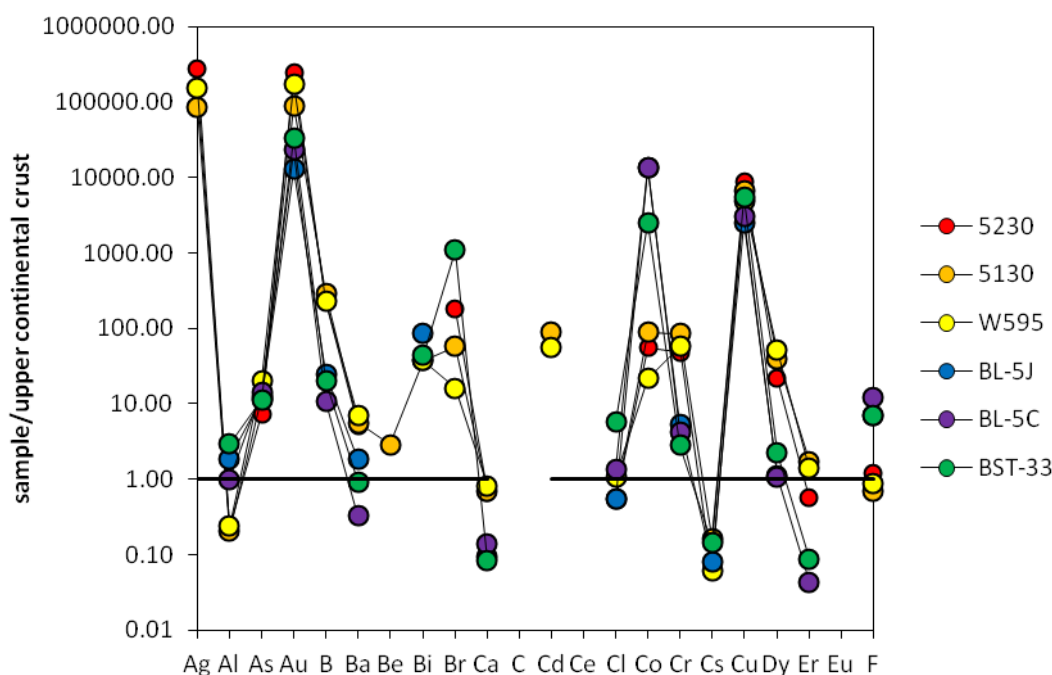


Figure 11a. Element concentrations in mobile phones (5230, 5130, W595) and Li-batteries (BL-5J, BL-5C, BST-33) normalized to the average composition of the Upper Crust according to Rudnick and Gao (2005, with corrected value for Au of 0.0015 ppm).

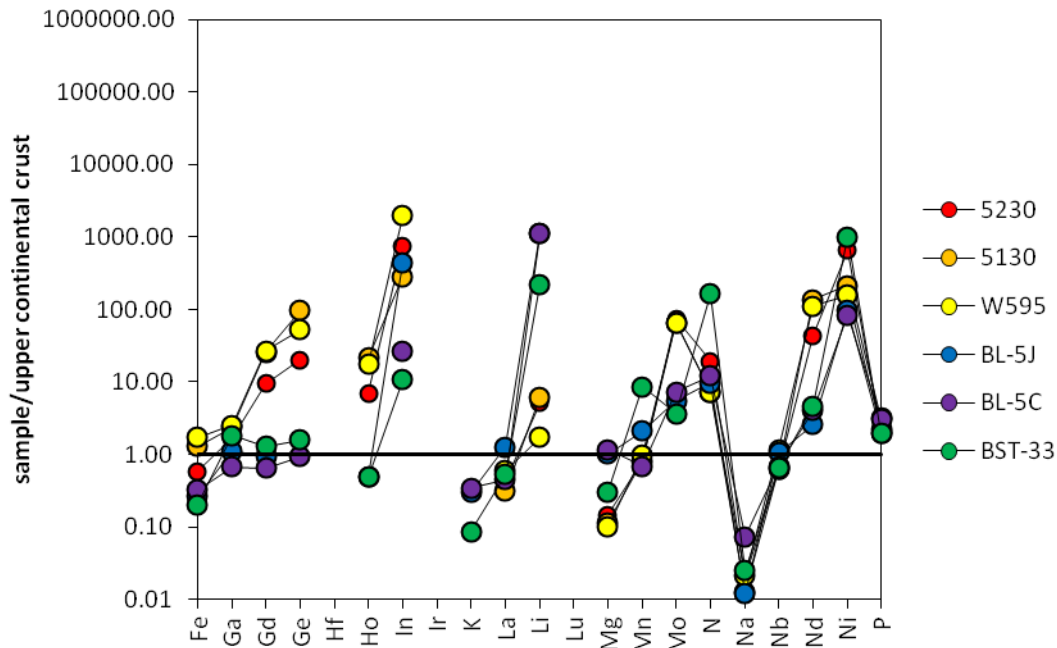


Figure 11b. Element concentrations in mobile phones (5230, 5130, W595) and Li-batteries (BL-5J, BL-5C, BST-33) normalized to the average composition of the Upper Crust according to Rudnick and Gao (2005).

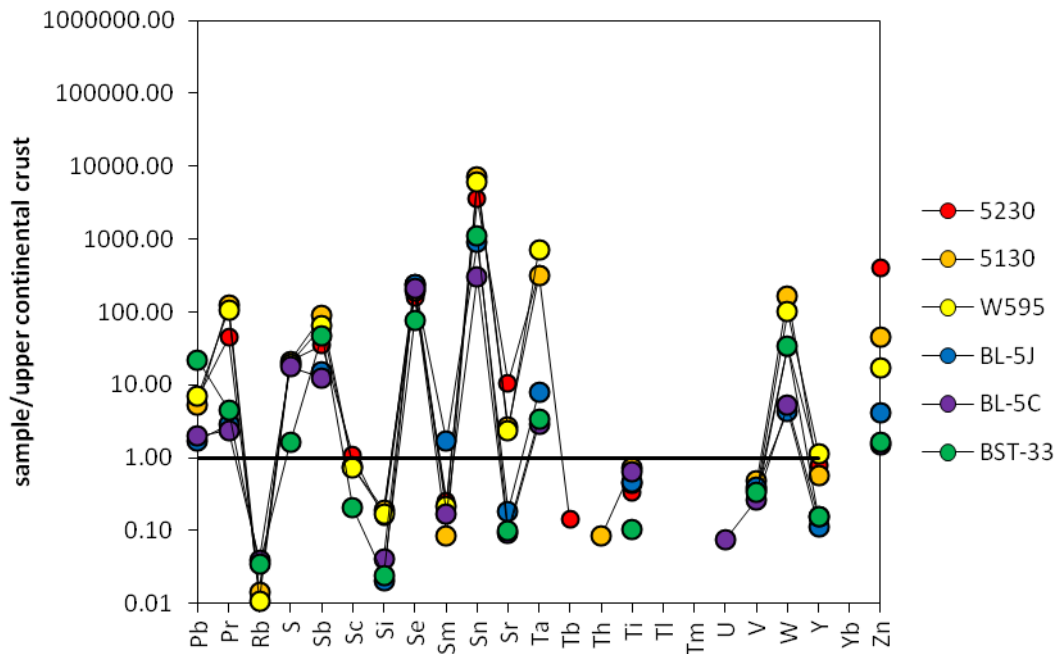


Figure 11c. Element concentrations in mobile phones (5230, 5130, W595) and Li-batteries (BL-5J, BL-5C, BST-33) normalized to the average composition of the Upper Crust according to Rudnick and Gao (2005).

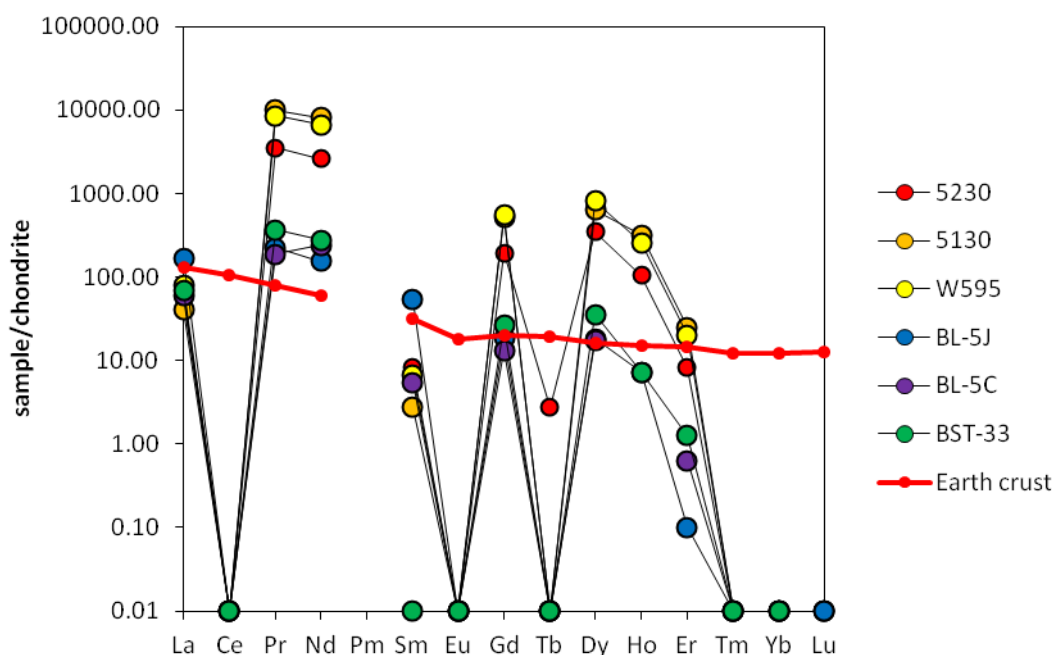


Figure 12. Chondrite normalized REE concentrations of mobile phones (5230, 5130, W595) and Li-batteries (BL-5J, BL-5C, BST-33). The values of the Upper Crust (red line) are from Rudnick and Gao (2005).

4. Conclusions

The chemical compositions of one smart phone and two mobile phones including their Li-batteries were determined by INAA, Infrared spectroscopy, fusion specific ion selective electrode, thermal conductivity, ICP-OES and ICP-MS. Because the analytical methods applied require the introduction of dilute solutions, the mobile phones and batteries were crushed and partially powdered by electronic fragmentation carried out by the SELFRAG laboratories. However, the electronic fragmentation give only partially satisfying results. The disadvantages were the loss of light components, in particular plastic and crystalline graphite and the large particle size of large single-material components such as the plastic body, screen and metal frame. Because of the weight loss, the concentrations of light elements provided, including C, S, P, Cl, F, B, and Li, have large errors.

The investigated mobile phones are rich in Ag (mean 915 ± 526 ppm), Au (mean 255 ± 120 ppm), Cu (mean 19.2 ± 5.6 wt.%), Sn (mean 1.2 ± 0.4 wt.%), In (mean 56 ± 48 ppm), Ta (mean 409 ± 203 ppm) and Ni (mean 1.6 ± 1.3 wt.%) compared to the average composition of the Upper Crust (Rudnick and Gao 2005). The Li-batteries have high Co (mean 17.1 ± 11.0 wt.%), Cu (10.2 ± 4.4 wt.%), Au (mean 35.0 ± 15.8 ppm), Li (mean 2.0 ± 1.2 wt.%), Sn (mean 1610 ± 864 ppm), Ni (mean 1.9 ± 2.5 wt.%) and B (mean 583 ± 1010 ppm). Due to the limited number of analyses and the errors caused by the mass loss during fragmentation, these values have large errors and represent only rough approximations.

According to the Strategy Analytics 1,575,000,000 mobile phones were shipped worldwide (not sold) in 2012 (Strategy Analytics 2013). An even higher number is provided by the Gartner Group which postulates that 1,746,176, 000 mobile phones were shipped in 2012 (Gartner Group 2013). Applying the results of this study, the production of 1.6 billion mobile phones including their Li-batteries requires approximately 27,438 t Cu, 5,926 t Co, 2,657 t Ni, 1,520 t Sn, 1309 t Zn, 702 t Li, 330 t Nd, 114 t Ag, 61 t Ta, 32 t Au, 18 t Dy, and 7 t In (Table 4). These are very valuable metals and, thus, the recycling of mobile phones and

batteries is of eminent ecological and economic interest. Unfortunately, only about 5 % of mobile phones produced worldwide are recycled (Weihe 2012).

The high concentrations of a number valuable elements such as Ag, Au, Cu, Co, Ni, Nd, Ta, In, and Li make the recycling of mobile phones economically attractive. For example the mining grade of Au in natural rock is about 4 g/t (4 ppm). Gold in the investigated mobile phones has an approximate grade of 255 g/t which corresponds to a high-grade gold deposit. Additional examples of mining grades of natural rocks are given in Table 5. Copper and Co have similar high “element-content-in-phone/mining-grade” ratios. However, the technologies for the extraction and enrichment for most of these elements from recycled mobile phones have not yet been developed and the mining grades of recycled electronic waste (urban mining) of the elements for which extracting technologies exist are much higher. Because of the technological challenges only one front running company for mobile phone recycling – the company Umicore - is operating in Europe (Umicore 2013). The company has developed technologies for the recovery of the precious metals Ag, Au, Pt, Pd, Rh, Ir, and Ru, special metals In, Se, Te, secondary metals Sb, Sn, and Bi and base metals Pb, Cu, and Ni from microelectronic waste. Thus, the most valuable and currently recyclable elements determined in this study are Ag, Au and In and to minor extend Cu and Ni. However, Cu and Ni form large, relative easy minable deposits in nature and, thus, their recycling is not as profitable as the recycling of the precious metals.

Table 4. Average concentrations of elements in mobile phones and Li-batteries, the weight of the elements in one mobile (79 g) and one Li-battery (22 g) and the necessary tonnage of elements to produce 1,575,000,000 mobile phones and Li-batteries.

Mobile phones				Li-batteries			
element	average concentration	weight of element in one phone	Weight of element in 1.6 bill phones	element	average concentration	Weight of element in one battery	Weight of element in 1.6 bill batteries
	ppm	g	t		ppm	g	T
C	269000	21.251	33470.3	C	264333	5.8153	9159.2
Cu	192000	15.168	23889.6	Co	171000	3.7620	5925.2
Si	53533	4.229	6660.9	Al	156967	3.4533	5438.9
Fe	46867	3.702	5831.4	Cu	102433	2.2535	3549.3
Ca	18667	1.475	2322.6	Li	19890	0.4376	689.2
Al	18200	1.438	2264.5	Ni	18710	0.4116	648.3
Ni	16150	1.276	2009.5	Mg	12367	0.2721	428.5
Sn	11770	0.930	1464.5	Fe	10267	0.2259	355.7
Zn	10520	0.831	1309.0	Si	8867	0.1951	307.2
Cr	5860	0.463	729.1	K	5667	0.1247	196.4
B	4203	0.332	523.0	N	5167	0.1137	179.0
Ba	3700	0.292	460.4	F	5067	0.1115	175.6
Nd	2627	0.208	326.8	Mn	2947	0.0648	102.1
Ti	1933	0.153	240.6	Ca	2700	0.0594	93.6
Mg	1800	0.142	224.0	Sn	1610	0.0354	55.8
Sr	1663	0.131	206.9	Ti	1567	0.0345	54.3
P	1633	0.129	203.2	P	1520	0.0334	52.7
S	1267	0.100	157.6	Cl	933	0.0205	32.3
Co	955	0.075	118.8	Na	890	0.0196	30.8
N	933	0.074	116.1	Ba	641	0.0141	22.2
Ag	915	0.072	113.9	Br	583	0.0128	20.2
Mn	676	0.053	84.1	S	400	0.0088	13.9
Pr	654	0.052	81.4	Cr	377	0.0083	13.1
F	533	0.042	66.4	B	313	0.0069	10.9
Na	437	0.034	54.3	Zn	163	0.0036	5.7
Ta	409	0.032	50.9	Pb	145	0.0032	5.0
Cl	267	0.021	33.2	Nd	101	0.0022	3.5
Au	255	0.020	31.7	As	60	0.0013	2.1
W	190	0.015	23.7	Sr	40	0.0009	1.4

Table 4. Continued

Mobile phones				Li-batteries			
element	average concentration	weight of element in one phone	Weight of element in 1.6 bill phones	element	average concentration	Weight of element in one battery	Weight of element in 1.6 bill batteries
	ppm	g	t		ppm	g	T
Dy	146	0.012	18.2	Au	35	0.0008	1.2
Br	135	0.011	16.9	V	32	0.0007	1.1
Pb	106	0.008	13.2	W	27	0.0006	1.0
Li	105	0.008	13.0	La	23	0.0005	0.8
Gd	83	0.007	10.3	Pr	23	0.0005	0.8
Ge	79	0.006	9.8	Ga	21	0.0005	0.7
Mo	75	0.006	9.4	Se	16	0.0003	0.5
As	64	0.005	8.0	Sb	10	0.0002	0.3
In	56	0.004	6.9	Nb	10	0.0002	0.3
Ga	38	0.003	4.8	In	9	0.0002	0.3
V	36	0.003	4.4	Bi	7	0.0002	0.2
Sb	25	0.002	3.2	Mo	6	0.0001	0.2
Se	18	0.001	2.2	Dy	6	0.0001	0.2
Y	17	0.001	2.2	Ta	4	0.0001	0.1
La	14	0.001	1.7	Gd	4	0.0001	0.1
Ho	13	0.001	1.6	Y	3	0.0001	0.1
Sc	12	0.001	1.5	Sm	3	0.0001	0.1
Nb	10	0.001	1.2	Rb	2	0.0000	0.1

Table 5. Average concentrations of selected elements in mobile phones and Li-batteries compared to average mining grades of natural rocks according different sources. Note, that the mining grades of recycled electronic waste (urban mining) are much higher and recycling technologies have not yet been developed for Ta and Co.

Mobile phones			Li-batteries		
element	average concentration	mining grade	element	average concentration	mining grade
	ppm	ppm		ppm	ppm
Cu	192000	8000	Co	171000	5000
Ni	16150	10000	Cu	102433	8000
Sn	11770	16000	Li	19890	15000
Ag	915	350	Ni	18710	10000
Ta	409	300	Sn	1610	16000
Au	255	4	Ta	35	4

5. Acknowledgements

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