TRACE ELEMENT GEOCHEMISTRY OF ACHONDRITIC METEORITES

A DISSERTATION

Submitted in partial fulfillment of the
Requirements for the award of the degree

of

INTEGRATED MASTER OF TECHNOLOGY
in
GEOLOGICAL TECHNOLOGY

By
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MAY 2019

DECLARATION OF AUTHORSHIP

I hereby solemnly declare that the work presented in this dissertation thesis titled "**Trace element geochemistry of achondritic meteorites**" submitted by me in partial fulfillment of the requirements for award of the degree '**Integrated Master of Technology**' in '**Geological Technology**' to the **Department of Earth Sciences, IIT Roorkee**, is an authentic record of my own work carried out during the period May 2018 to April 2019, under the supervision of **Dr. Nachiketa Rai**, Department of Earth Sciences, Indian Institute of Technology, Roorkee. The matter embodied in this dissertation has not been submitted by me for the award of any other degree in any other institute.

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This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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Any accomplishment in life merits a support structure which requires the efforts and support of many people. This bears a deeper meaning when it comes to the case of students, lacking expertise, insight and the knack of going about doing things. This dissertation is no different from what is mentioned above.

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ABSTRACT

Geochemical modelling of major and trace element data (EMP and LA-ICPMS) from Achondritic meteorite samples (ureilites) for Ca, Mg, Al, Si, Fe with Sc, Cr, Mn, Fe, Co, Ni, Zn, Ga, REE, W, Re, Os, Ir, and Au is presented. Data for bulk samples as well as different phases present in the samples such as Olivine, Fe-Ni metal and sulphide phases were considered. In the bulk samples the refractory siderophile concentrations range from approximately 0.1 to 1.0 times CI chondrites while the volatile siderophiles range from about 0.07 to 0.3 times CI chondrites which indicates the separation/ loss of a metal phase enriched in those elements as well as loss due to early volatilization processes. For the Fe-S and Fe-Ni phases the siderophile elements are considerably high when compared to olivine and bulk sample analyses for those elements. However, normalized concentrations of several siderophile elements are still subchondritic which may indicate that these metallic and sulphide phases represent a second generation of metallic melt separation in the parent body. Rare earth elements (REEs) in bulk ureilites are quite depleted indicating a separate silicate melt phase.

CONTENT

LIST OF FIGURES

LIST OF TABLES

Introduction

4.1) Meteorites:

A meteorite is a rock formed elsewhere in the solar system that rotates for a long time around the sun or on a planet (meteorites). It was finally caught by the earth's gravitational field and fell like a solid object on the earth. Most of these objects burn up in the atmosphere and are very small, and only a few larger ones that survive the journey through the atmosphere reach on the Earth as meteorites. These pieces reach the inner part of the solar system where the Earth travels by collisions and gravitational interactions. Our planet collides with thousands of these small pieces of this material everyday. Some of these are the scattered or isolated brighter shooting stars and fireballs that can be visible any night. Occasionally they have been large enough to produce impact craters such as meteor crater in Arizona.

The most primitive meteorite specimens are believed to be the samples of most primitive(pre-planetary) material in the Solar Nebula. Some meteorites are so primitive that they contain traces interstellar dust, which survived thermal processing in the solar nebula. Thus, meteorites provide information about the chemical and physical properties at different locations within the solar nebular disk, as well as constraints about time scales and physical processes involved in the formation and evolution of objects in the solar system.

Meteorites play an important role in our understanding of the chemical composition of the solar system because, in addition to the samples returned from the Moon, they are the only samples of extraterrestrial matter that can be studied in terrestrial laboratories.

The most commonly used parameters for the classification of meteorites are petrology(texture, mineralogy and mineral composition), whole rock chemical composition and O-isotopic composition. Most meteorites are predominantly composed of the silicates, sulfides, and metal on the basis of which their classification (Weisberg et al., McCoy., Krot., 2007) is done.

4.2) Importance of Meteorites:

1. How our solar system has evolved to the sun and the planets of today and how the effects of meteorites could affect our future.

2. Primitive meteorites provide information about the chronology of events and conditions in the first solar system as well as hints on the proportions of the elements present in the entire solar system.

3. Geochemical fractionation of elements. A process of distributing and distributing bonding elements that extends our knowledge of the order in which meteorite elements, their parent and solar systems were formed.

4.3) Achondritic Meteorites:

Majority of the rocks that are formed by the igneous processes are identical to the achondrites that are present on the earth. The achondritic meteorites are formed nearby planet's surface and big asteroidal bodies by the process which is identical to the formation of igneous rocks. These meteorites are quite helpful in knowing the ancient solar-system process i.e. the differentiation and reprocessing which the parent body of the rocks went through. One hypothetical study of the achondrites which are primitive show that they underwent partial melting as they went above the parental bodies' solidus temperature and no crystallisation from the melt occured. When it is present in the molten state, these can be derived from the unachieved isotopic equilibrium of parent body planetary differentiation.

4.4) Ureilites:

Grouping of around two hundred species of the achondrites which are primitive are known to be ureilite. The chemistry of the lithophiles in addition to their mineralogy and texture strongly indicate that they are formed from the achondrites which underwent strong fractionation process but they do have low Oxygen-isotopic wt% and do not obey the trend of a mass depend fractionate process which characteristically show that the planets underwent differentiation. These achondrites do not contain feldspar but are known to contain a little amount of diamond of the preterrastrial time(Vdovykin G.P. et al., 1969). They are entirely reduced and are known to be formed at significantly large pressure values subjected to a longer time interval. They are known to contain less quantity of cpx having darker veins passing through it and ultramafic rock content with grains of ol which are large. The carbon rich veins can be upto ten percent of the meteorite with the weight percent of the carbon can be as much as six percent. The veins are a result of shock experienced by the graphite(which was consequently crystallize with the silicate) which results in its redistribution. They are known to contain iron sulphide, Cr and shows a depletion in the LREE (Goodrich et al., 2007; Krot et al., 2003).

Literature Review

5.1) Importance of trace elements:

In geology the trace elements are known to have a variety of uses. It is a fact that to classify the rocks and solve various hypothetical issues which concern the evolutionary system of magama the major elements play a vital role but because various phases include or exclude trace elements with selectivity on a large scale than they actually do with major elements, so to igneous fractionation processes the trace elements are far sensitive than the major elements. As a result of the same, using the trace elements the evolution of the melt and from where it is originated can usually be better constrained. In a mineral sample it would be extremely laborious and highly expensive to analyze all the trace elements which are present. Although new work is done on regular basis, past experience shows a vital role of trace elements in igneous petrology. The geochemical behavior provides the basis to classify the trace element. There are a few important trace elements (Strontium, Titanium, Vanadium, Chromium, Maganese, Cobalt, Nickel, Copper, and Zinc), in addition to it is the lanthanides (mostly the REE), and Rubidium, lead, Thorium,Uranium etc.
The value of the distribution coefficient . But in case of trace elements, the value of KD can range over several orders of magnitude (for example garnet has the range of KD values that varies from 0.04 to 6.950). As a consequence, the trace elements as compared to major elements can be several times very sensitive to the process of distribution and fractionation.

$$KD=Cs/Cl$$

where Cs and Cl are trace element concentration in the solid part and the liquid, respectively (in ppm or wt. %).

Conversely, the trace element that shows a very small D value is concentrated in the liquid part preferentially and will ultimately reflect the proportion of liquid at a given state of melting or of the crystallisation, as it's concentration varies inverse of amount of liquid that is diluting it.

5.2) Application of trace elements in igneous systems:

Fractional crystallize or partial melt shows greater change in many trace-element in terms of large distributn coefficient. With continuation of this process the concentration of these elements tends to fluctuate by larger amounts, so this method can be used to examine their efficiency. Another use-case of this method is for identifying the source-rock/mineral showing fractional crystallize or partial melt behaviour. This method is dependent of estimating the amount of trace element still left in the liquid after mineral is fractionated to a specific degree. This technique has another use-case for the determination of the extent of partial melt required for production of particular types of lava for a certain rock type. This method is thus quite efficient and recommended for ascertaining model of partial melt vs fractional crystallize. Eg. Rare Earth Element nomenclature denotes typically a way to separate mantle-derive melts originating from different-pressure source.(Winter, 2014, p. 165).

The amount of magma-produce by partial melt from source rock is dependant on the phase occurrence trend and amount in them due to their distinct chemical attributes. For instance, namely element like Strontium shows much larger fractionation in feldspars belonging to the plagioclase family. When Plagioclase is absent from source-rock, Strontium exists in liquid part and is present in greater enrichment for magma showing minor amounts of partial melt. When Plagioclase is actually present, it will capture Strontium, so lesser enrichment of Sr in magma, till the time Plagioclase is melted.

At different-different levels of depth in the mantle, partial melting occurs which causes a result in the form of production of primary basalt. For lesser amounts of depth (40-80 km), there is instead the production of Plagioclase Iherzolite (spinel form), with increase in depth to 80km, the plagioclase iherzolite is of garnet form. As Plagioclase, its spinel/garnet concentrates Strontium, Vanadium+Chromium, and other rarer metals (heavy rare earth elements), respectively, magma resulting due to lesser amounts of partial melt at shallower depths will have lesser amounts of Strontium, those at medium depth will have less of Vanadium and Chromium, while magma at depths greater than eighty kilometer contain less of Heavy Rare Earth Elements. Minute amounts for studied element for distinct forms of primary magma lead us to infer their production by different degree of partial melt at distinct depth in earth’s mantle. Henry Law correlates this activity directly to their existing amounts at the site of concentration, i..e twice the amount of Nickel in system extends to 2x the amount for all the phase. This does not infer the same concentrate amount of Nickel for all phase as fractionation for trace element. Instead, these amounts are varying in a proportional manner to the systems amount. Eg. for Nickel concentrate amount in Olivine= 300ppm, 80ppm opx., amounts go 2x to 800 & 160 ppm.

For this reason, trace concentration ratios play a more critical role than individual trace compositions to identify specific mineral roles in a meteorite. For example, in the case of garnet, the HREE ratio Yb divided by LREE La would be a good indicator of the slope of the REE diagram. The absolute values of La or Yb vary depending on the pebble effect, but also on the total concentration of REE at the source, and we can not distinguish these effects in a rock sample from the concentration of Yb or L alone.

Since La and Yb should behave in the same way with the exception of garnet, a low La / Yb ratio is more likely to affect garnet. Likewise, the Eu ratio on the neighbouring Sm indicates an Eu anomaly and thus the involvement of the plagioclase. Although these examples of EEE illustrate this point, the complete EEE diagram is usually more informative. As a more practical example, the K / Rb ratio was used to illustrate the importance of amphibole in ultramafic well rock, such as Peridotite hornblende, show. In magical assemblages, K and Rb behave in the same way, so that their ratio should be nearly constant for all mafic rocks. Almost all K and Rb must therefore be in amphibole, which has a D of about 1.0 for K and 0.3 for Rb. Since D is smaller than Zk in the amphibole, fusion of a group containing hornblende (assuming residues of the hornblende are present) results in a reduction of the K / Rb ratio in the spindle compared to it in the original rock. Since all other factors are equal, the magma produced by the partial fusion of an amphibious rock would have a K / Rb value lower than a magma coming from a source without amphibole. Of course, high values of K or Rb also indicate absolutely a source of amphiboles, but they may also be due to other causes, e.g. Plagioclase or an alkaline-enriched liquid. The ratio is more informative than the amphibole due to the different D-values for this mineral. The fractional crystallization of an amphibian would also result in a low K / Rb ratio in the released liquid. Another example concerns the incompatible pair Sr and Ba. These incompatible elements tend to be enriched in the first partial melt products or residual liquids after fractionated crystallization. The effect is obviously selective, depending on the mineral phases involved in the process.

In all previous cases, by means of ratios, the idea is to find a mineral with a single pair of elements for which there is a relatively high value of D for one element and a relatively low value of D for an element. The ratio of these elements is therefore only sensitive to the liquid / crystalline fractionation associated with this particular mineral. There are several applications of trace element in petrology, some of which are not specific to minerals. For example, the ratio of two highly incompatible element in a series of magmas produced in a volcanic center of fractional crystallization should be the same because the crystallizing minerals eliminate very little. However, if the volcanic rocks come from different sources or sources, the ratio would be more variable. These are just a few examples of the use of specific trace elements. The table is a Green (1980) abstract of several important trace element used as petrogenetic tracers to try to identify the minerals involved in differentiation or partial melting. These elements can inform us about a single analysis of the entire rock, but they are much more reliable when used in variational graphs for a range of rocks associated with a wide range of compositions in the same area. A decrease in these elements for a number of rocks causes the division of a phase in which they are concentrated. High concentrations of a trace element in parental magmas can reflect the high concentration of this element in the source rock, thus helping to limit the mineralogy of the source area.

Trace elements may also be used to identify the paleotectonic setting of some volcanic rocks (i.e. to determine where they are bursting). In this case, rather than absolute concentrations of trace elements (which may have been affected by post-magmatic processes such as atmospheric change, alteration, or metamorphism), relatively immobile trace element ratios are used.

5.3) Spider Diagram:

In this diagram, the concentration of the trace elements which are incompatible are normalized to their estimated amount present in the ideal carbonaceous chondritic samples(CI chondrites). Since during the early stages of the core formation a few of those elements were discarded, it resulted in the increased amount of these elements in the early mantle which is sometimes known as the concentration effect but the bulk earth absolute concentration of these elements may be approximately similar to the chondritic values. The schemes which are being used to normalize(early mantle, chondritic meteorite etc.) as well as the elements differ for the variants applied in the construction of spider diagram. The abscissa which shows the order in which the different elements are aligned may be different for various authors (Wood et al., 1979; Sun, 1981; Thomson, 1982,1984). It wholly depends on how the author estimates the incompatibility of various elements that follows a general trend of decreasing from left to right. When the process of partial melting and fractional crystallize of the mafic-intermediate takes place the elements that are being chosen are mostly the incompatible ones. There are some exception with the Strontium being compatible in the presence of plagioclase, and titanium with iron-titanium oxide. The low abundance of these elements are indicative of these minerals.

OBJECTIVE

The main objective of this project is modelling the trace element geochemistry of different phases present in selected Achondrite samples DaG1000a. This involved consideration of the different phases present, major element compositions of bulk samples and individual phases, and trace element distribution in different phases.

METHODOLOGY

The techniques that were used for imaging and geochemical analysis were:

7.1) SEM (Scanning Electron Microscope):

Scanning Electron Microscopy (SEM) is a test process that analyzes a sample with an electron beam to produce an enlarged image for analysis. The method is also referred to as SEM analysis and SEM microscopy and is used very efficiently in microanalysis to identify the various phases present. Electron microscopy is performed at high magnification, produces high-resolution images and precisely measures very small features.

7.2) EPMA(Electron Probe Microanalysis):

It is used to determine the composition of the main elements. EPMA works by bombarding a microvolume of a sample with a beam of focused electrons (typical energy = 5-30 keV), collecting the x-ray photons emitted by the various elemental species. Since the wavelengths of these X-rays are characteristic of the transmitting species, the sample composition can be easily identified by recording the WDS (Dispersive Wavelength Spectroscopy) spectra. WDS spectrometers work according to Bragg's law and use different mobile and shaped single crystals as monochromators.

7.3) LA-ICPMS(Laser Ablation-Inductively Coupled Plasma Mass Spectrometry):

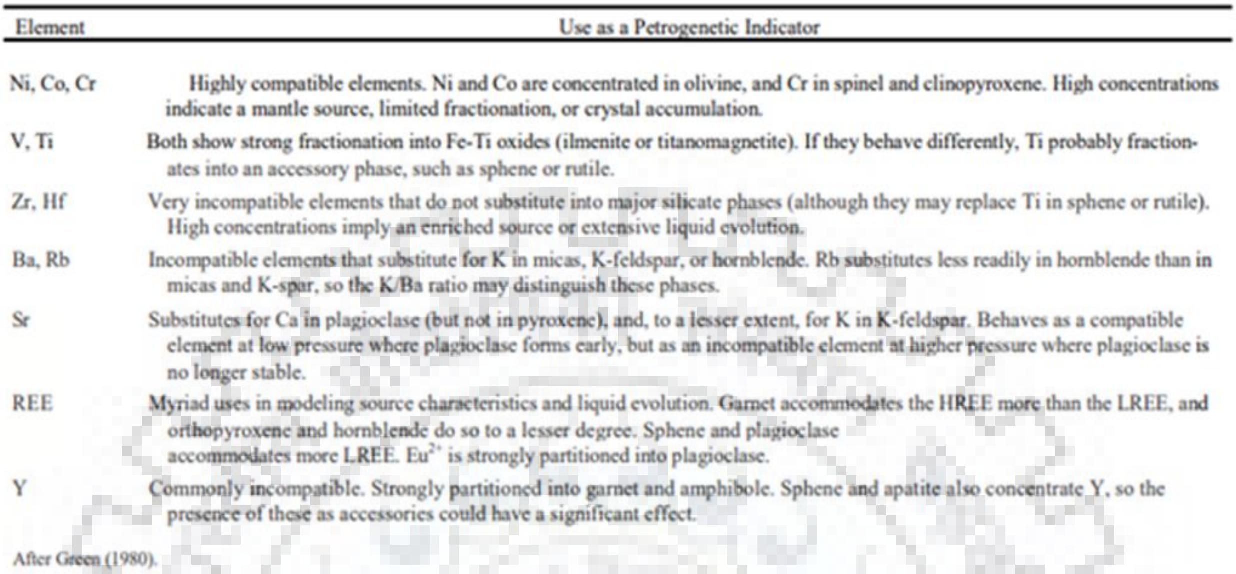
LA-ICPMS (Inductive Coupling Laser Ablation Plasma Mass Spectrometry) is a powerful analytical technology that enables highly sensitive elemental and isotopic analyzes directly on solid samples.

LA-ICPMS starts with a laser beam focused on the surface of the sample to create fine particles - a process called laser ablation. The removed particles are then transported to the secondary excitation source of the ICPMS instrument, where they are disrupted and ionized. The excited ions in the plasma torch are then introduced into a mass spectrometer detector which allows both elemental and isotopic analysis.

7.4) Trace element modelling:

Elemental concentrations in bulk rock sample, as well as individual phases such as olivine, Fe-Ni metallic phase, Sulfide phases were normalized to chondritic values (McDonough and Sun, 1995) which are considered to the building blocks of all rocky bodies in the solar system. A double normalization method with respect to CI chondrite values and a refractory lithophile element was used to analyse the respective depletion/ enrichment factors in the individual phases, as well as bulk rock sample. Mg was chosen as the refractory lithophile element for investigating the trace element systematics in this work. Being a refractory element, Mg would not be susceptible to loss due to volatilization during early high temperature processes, and being lithophile Mg would not move into the metallic iron rich melt that would separate from the parent body during differentiation. For example, considering the bulk sample or a silicate phase, after double normalization to CI and RLE, a refractory lithophile element would ideally show a value of 1.0 in contrast to any other volatile element which would show a value <1.0 due to decreased concentration from volatile loss. For bulk sample and silicate phases, any element with chalcophile or siderophile character would also show a normalized value <1.0 due to fractionation into a sulphide or metallic phase. A similar normalization approach when applied to metallic or sulphide phases may show normalized values >1.0 showing enrichment of these elements in the metallic or sulphide phases compared to the undifferentiated CI chondrites. Rare Earth Elements in olivine phases are indicators of whether these are residual mantle olivines after losing out a silicate melt during mantle partial melting.

A Brief Summary of Some Particularly Useful Trace Elements:



Element	Use as a Petrogenetic Indicator
Ni, Co, Cr	Highly compatible elements. Ni and Co are concentrated in olivine, and Cr in spinel and clinopyroxene. High concentrations indicate a mantle source, limited fractionation, or crystal accumulation.
V, Ti	Both show strong fractionation into Fe-Ti oxides (ilmenite or titanomagnetite). If they behave differently, Ti probably fractionates into an accessory phase, such as sphene or rutile.
Zr, Hf	Very incompatible elements that do not substitute into major silicate phases (although they may replace Ti in sphene or rutile). High concentrations imply an enriched source or extensive liquid evolution.
Ba, Rb	Incompatible elements that substitute for K in micas, K-feldspar, or hornblende. Rb substitutes less readily in hornblende than in micas and K-spar, so the K/Ba ratio may distinguish these phases.
Sr	Substitutes for Ca in plagioclase (but not in pyroxene), and, to a lesser extent, for K in K-feldspar. Behaves as a compatible element at low pressure where plagioclase forms early, but as an incompatible element at higher pressure where plagioclase is no longer stable.
REE	Myriad uses in modeling source characteristics and liquid evolution. Garnet accommodates the HREE more than the LREE, and orthopyroxene and hornblende do so to a lesser degree. Sphene and plagioclase accommodates more LREE. Eu^{2+} is strongly partitioned into plagioclase.
Y	Commonly incompatible. Strongly partitioned into garnet and amphibole. Sphene and apatite also concentrate Y, so the presence of these as accessories could have a significant effect.

After Green (1980).

Samples considered in this study

Analysis of achondrite meteorite samples DaG1000 were considered. Major phases in these samples were found to be silicate mineral olivine, along with FeS and Fe-Ni metallic phases.

DATA SETS:

Na	Mg	Al	K	Ca	Sc	Ti	V	Cr
mg/g	wt%	wt%	mg/g	wt%	ppm	mg/g	ppm	mg/g
0.769325	23.1232	0.316857	0.056504	1.047064	9.77955	0.4303	125.1782	5.754722
0.428567	12.88121	0.176511	0.031477	0.583286	5.44788	0.239707	69.73286	3.205774
0.528205	15.876	0.217549	0.038795	0.718896	6.714473	0.295437	85.94525	3.951094
0.6608	19.86133	0.27216	0.048533	0.89936	8.4	0.3696	107.52	4.942933
0.468246	14.07383	0.192854	0.034391	0.637291	5.952278	0.2619	76.18915	3.502585
0.703072	21.13189	0.28957	0.051638	0.956893	8.937358	0.393244	114.3982	5.259139
0.391659	11.77191	0.161311	0.028766	0.533055	4.978721	0.219064	63.72763	2.929701

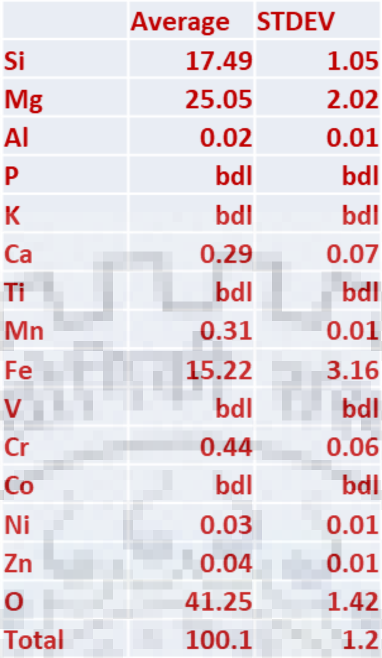
Mn	Fe	Co	Ni	Zn	Ga	As	Se	Sb
mg/g	wt%	ppm	ppm	ppm	ppm	ppm	ppm	ppb
4.776767	13.7131	127.7861	1127.908	352.0638	1.838555	0.317292	0.347717	39.55285
2.660987	7.639138	71.18563	628.3221	196.1237	1.024201	0.176753	0.193702	22.03365
3.279647	9.415183	87.73577	774.4025	241.721	1.262321	0.217847	0.238737	27.15631
4.102933	11.77867	109.76	968.8	302.4	1.5792	0.272533	0.298667	33.97333
2.907357	8.346416	77.77643	686.496	214.282	1.119028	0.193118	0.211637	24.07366
4.365403	12.53216	116.7815	1030.775	321.7449	1.680223	0.289968	0.317773	36.14665
2.431828	6.981273	65.05528	574.2125	179.2339	0.936	0.161532	0.177021	20.13616

La	Ce	Nd	Sm	Eu	Tb	Ho	Lu	Hf
ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb
31.72921	412.9143	bdl	30.42527	30.42527	bdl	31.72921	15.64728	bdl
17.67534	230.0216	bdl	16.94896	16.94896	bdl	17.67534	8.716607	bdl
21.78473	283.5	bdl	20.88947	20.88947	bdl	21.78473	10.74316	bdl
27.25333	354.6667	bdl	26.13333	26.13333	bdl	27.25333	13.44	bdl
19.31183	251.3184	bdl	18.5182	18.5182	bdl	19.31183	9.523644	bdl
28.99676	377.3551	bdl	27.80511	27.80511	bdl	28.99676	14.29977	bdl
16.15318	210.2127	bdl	15.48935	15.48935	bdl	16.15318	7.965953	bdl

Re	Os	Ir	Au	Th	U
ppb	ppb	ppb	ppb	ppb	ppb
bdl	284.6936	347.7173	9.823015	bdl	bdl
bdl	158.5938	193.7024	5.472092	bdl	bdl
bdl	195.4658	238.7368	6.744315	bdl	bdl
bdl	244.5333	298.6667	8.437333	bdl	bdl
bdl	173.2774	211.6365	5.978732	bdl	bdl
bdl	260.1764	317.7727	8.977079	bdl	bdl
bdl	144.9361	177.0212	5.000848	bdl	bdl

Table 1: Data set for bulk sample.

Olivine Phase:



	Average	STDEV
Si	17.49	1.05
Mg	25.05	2.02
Al	0.02	0.01
P	bdl	bdl
K	bdl	bdl
Ca	0.29	0.07
Ti	bdl	bdl
Mn	0.31	0.01
Fe	15.22	3.16
V	bdl	bdl
Cr	0.44	0.06
Co	bdl	bdl
Ni	0.03	0.01
Zn	0.04	0.01
O	41.25	1.42
Total	100.1	1.2

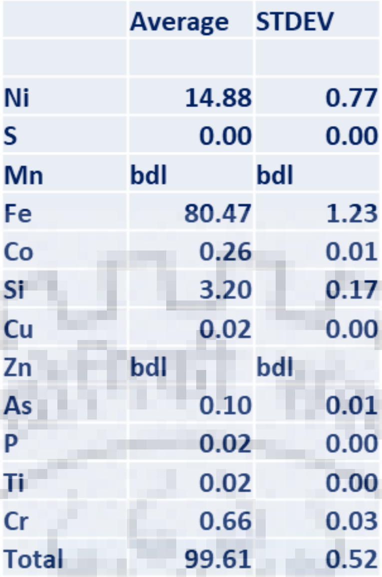
Table 2: EMPA analysis of olivine phase

Re	Os	W	Ir	Ru	Mo	Pt	Rh	Ni
	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppm
bdl	0.019447	0.003431	0.00755	0.18252	0.2653	0.024668	0.045252	77.24232
bdl	0.017484	0.003487	0.00792	0.099267	0.2172	0.030113	0.026363	159.1798
bdl	0.016949	0.003072	0.008142	0.392726	0.925252	0.032359	0.082525	65.0177
bdl	0.018327	0.002974	0.007254	0.11822	0.423239	0.024958	0.091564	65.79058
bdl	0.016025	0.003006	0.007106	0.13282	0.398266	0.028096	0.042627	169.2127
bdl	0.015924	0.00366	0.006707	0.09252	0.227868	0.022195	0.072526	111.7198

Co	Pd	Au	As	Cu	Zn	Ga	Ge
ppm	ppb	ppb	ppm	ppm	ppm	ppm	ppm
44.93737	0.116272	0.063253	0.64353	4.1293	78.63894	0.403637	1.743745
49.15273	0.031679	0.046383	0.218277	4.095637	75.63744	0.273547	1.264374
55.8373	0.117373	0.07356	0.915272	7.073838	69.56375	0.863546	4.274848
58.93636	0.0653	0.063536	0.362724	3.63784	64.63748	0.643674	2.984645
59.15263	0.036727	0.073636	0.542623	4.73949	62.63485	0.318395	2.647549
29.73636	0.015637	0.043674	0.362783	9.638495	57.67375	0.635464	0.954365

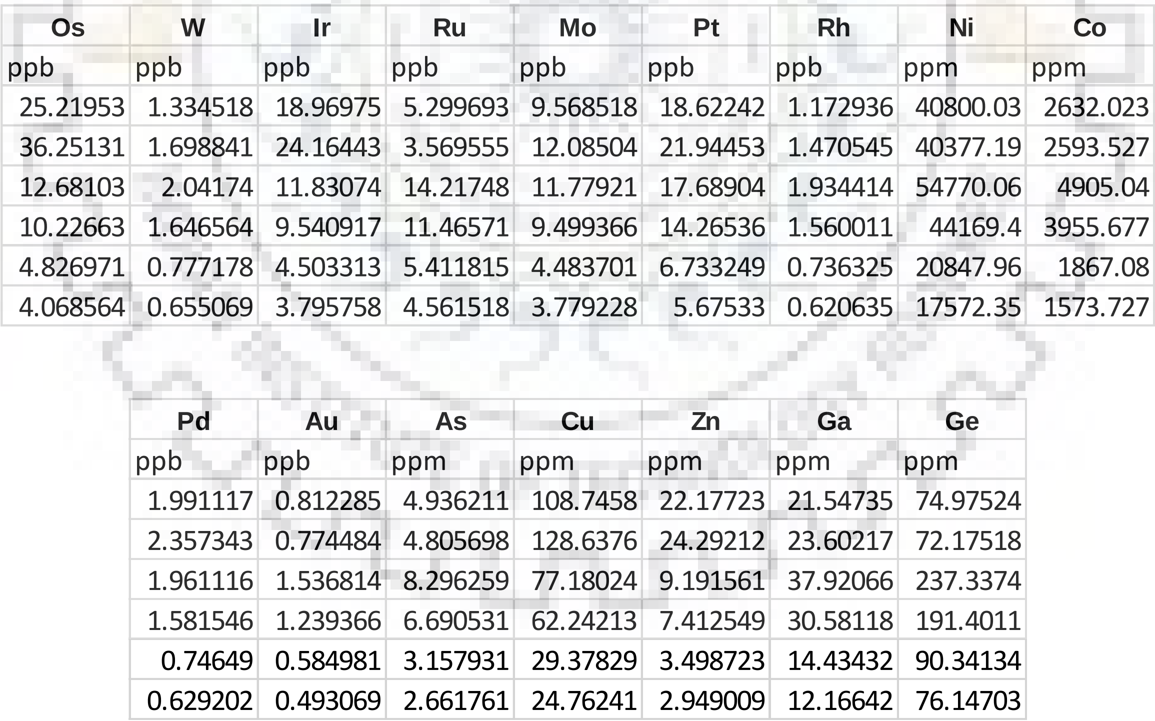
Table 3: Trace element abundance in the olivine phase.

Fe-Ni Phase:



	Average	STDEV
Ni	14.88	0.77
S	0.00	0.00
Mn	bdl	bdl
Fe	80.47	1.23
Co	0.26	0.01
Si	3.20	0.17
Cu	0.02	0.00
Zn	bdl	bdl
As	0.10	0.01
P	0.02	0.00
Ti	0.02	0.00
Cr	0.66	0.03
Total	99.61	0.52

Table 4: EMPA analysis of Fe-Ni phase



Os	W	Ir	Ru	Mo	Pt	Rh	Ni	Co
ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppm	ppm
25.21953	1.334518	18.96975	5.299693	9.568518	18.62242	1.172936	40800.03	2632.023
36.25131	1.698841	24.16443	3.569555	12.08504	21.94453	1.470545	40377.19	2593.527
12.68103	2.04174	11.83074	14.21748	11.77921	17.68904	1.934414	54770.06	4905.04
10.22663	1.646564	9.540917	11.46571	9.499366	14.26536	1.560011	44169.4	3955.677
4.826971	0.777178	4.503313	5.411815	4.483701	6.733249	0.736325	20847.96	1867.08
4.068564	0.655069	3.795758	4.561518	3.779228	5.67533	0.620635	17572.35	1573.727

Pd	Au	As	Cu	Zn	Ga	Ge
ppb	ppb	ppm	ppm	ppm	ppm	ppm
1.991117	0.812285	4.936211	108.7458	22.17723	21.54735	74.97524
2.357343	0.774484	4.805698	128.6376	24.29212	23.60217	72.17518
1.961116	1.536814	8.296259	77.18024	9.191561	37.92066	237.3374
1.581546	1.239366	6.690531	62.24213	7.412549	30.58118	191.4011
0.74649	0.584981	3.157931	29.37829	3.498723	14.43432	90.34134
0.629202	0.493069	2.661761	24.76241	2.949009	12.16642	76.14703

Table 5: Trace element abundance in the Fe-Ni phase.

Fe-S Phase:

	Average	STDEV
S	36.81	0.51
Mn	bdl	bdl
Fe	62.15	0.86
Co	bdl	bdl
Ni	0.05	0.00
Cu	bdl	bdl
Zn	bdl	bdl
As	0.07	0.01
P	bdl	bdl
Ti	0.01	0.00
Cr	0.16	0.02
Total	99.27	1.38

Table 6: EMPA analysis of Fe-S phase

Os	W	Ir	Ru	Mo	Pt	Rh	Ni	Co
ppb	ppb	ppb	ppb	ppb	ppb	ppb	mg/g	ppm
0.390057	0.516237	0.612799	0.519397	11.72568	0.876466	0.250708	5047.008	390.249
0.453529	0.542783	0.283679	0.516987	6.914841	2.629314	0.315849	5512.342	673.6752
0.557364	0.372829	0.296464	0.551785	3.09354	1.496864	0.244433	8075.213	596.0196
0.363839	0.27188	0.796366	0.308333	9.18033	4.801457	0.271016	9195.649	283.4223
0.219926	0.532627	0.406755	0.438188	4.223226	2.951344	0.304072	1656.892	205.7713
0.332929	0.482929	0.518904	0.424542	1.997081	1.55485	0.383079	3155.692	496.7242
0.210043	0.37289	0.37895	0.507244	8.036647	0.763873	0.296462	4170.151	492.7753
0.621609	0.163784	0.306478	0.443756	3.697098	1.008903	0.328703	2837.291	106.4709
0.253784	0.093664	0.286478	0.465191	1.748285	2.02045	0.238672	4028.96	165.9581
0.406268	0.483995	0.398677	0.510913	1.785355	0.992615	0.300686	2741.227	351.9523

Pd	Au	As	Cu	Zn	Ga	Ge
ppb	ppb	ppm	ppm	ppm	ppm	ppm
0.261818	0.352627	7.728282	542.1795	19.28293	6.829292	17.38833
0.192883	0.178282	6.278282	302.629	17.93939	1.289292	19.73838
0.252728	0.467272	4.262728	219.9089	80.8239	2.728292	20.72828
0.172828	0.618182	5.827273	636.9358	98.92929	2.182892	12.82828
0.261718	0.418182	4.627282	530.8472	56.83393	1.937733	14.28284
0.78292	0.727283	5.272728	261.6141	49.98394	1.639393	14.78283
0.927273	0.378283	5.082829	428.8344	38.93939	1.377383	12.78283
0.82727	0.172728	9.18394	326.4872	47.93939	2.839383	10.82929
0.582829	0.129394	8.728292	493.3538	48.83939	1.972828	10.18384
0.628823	0.267283	3.827263	257.5718	30.38939	5.289393	14.78839

Table 7: Trace element abundance in the Fe-S phase.

Normalization of the elemental abundance values:

The normalization of the data set values for a particular phase or for the bulk of the sample is done by the following method:

$$\text{Normalized Value} = \frac{X(\text{bulk or phase})/Mg(\text{bulk})}{X(\text{Ref.})/Mg(\text{Ref.})}$$

Where,

X(bulk or phase) = concentration of element in the bulk or the phase for which the calculation is to be done

Mg(bulk) = Concentration of Mg in the bulk(average value)

X(Ref.) = Concentration of that element in the CI chondrites

Mg(Ref.) = Concentration of Mg in the CI chondrites

Now here Mg is taken in the ratios calculated since it is a refractory lithophile element and when the abundance of Mg is normalized with the CI Chondrites its value comes out to be nearly equal to 1.

Normalized value of element abundance:

Lithophile	Normalized Values	Siderophile	Normalized Values	Chalcophile	Normalized Values
Na	0.062953	Mn	1.001753	Zn	0.473957
Mg	1	Fe	0.316182	Ga	0.0834
Al	0.15376	Co	0.106658	As	0.071576
K	0.042863	Ni	0.04483	Se	0.00691
Ca	0.472401	Os	0.242472		
Sc	0.689408	Ir	0.318929		
Ti	0.408129	Au	0.029282		
V	0.932868				
Cr	0.90627				
La	0.055872				
Se	0.00691				
Eu	0.225531				
Sb	0.117904				
Ho	0.242519				

Table No. 8 - Normalized Values of the elements in the bulk of the sample

element			Normalized value			
Os	0.029285	0.042095	0.014725	0.011875	0.005605	0.004724
W	0.008165	0.010394	0.012492	0.010074	0.004755	0.004008
Ir	0.023722	0.030218	0.014795	0.011931	0.005632	0.004747
Ru	0.004247	0.002861	0.011394	0.009189	0.004337	0.003656
Mo	0.000627	0.000792	0.000772	0.000622	0.000294	0.000248
Pt	0.010491	0.012363	0.009965	0.008036	0.003793	0.003197
Rh	0.005134	0.006436	0.008467	0.006828	0.003223	0.002716
Ni	2.21093	2.188016	2.967957	2.393514	1.129739	0.952236
Co	2.995184	2.951376	5.581826	4.501472	2.124695	1.790866
Pd	0.00206	0.002439	0.002029	0.001636	0.000772	0.000651
Au	0.003301	0.003148	0.006246	0.005037	0.002377	0.002004
As	1.518189	1.478048	2.55161	2.05775	0.971258	0.818655
Cu	515.6264	609.9447	365.9558	295.1257	139.2993	117.4128
Zn	0.040705	0.044587	0.016871	0.013605	0.006422	0.005413
Ga	1.332631	1.459715	2.345265	1.891342	0.892714	0.752452
Ge	1.376131	1.324738	4.356205	3.513068	1.658168	1.397639

Table No. 9 - Normalized values of various elements in Fe-Ni Phase in the sample.

RESULTS

Graphs for abundance of various elements in Bulk of the Sample:

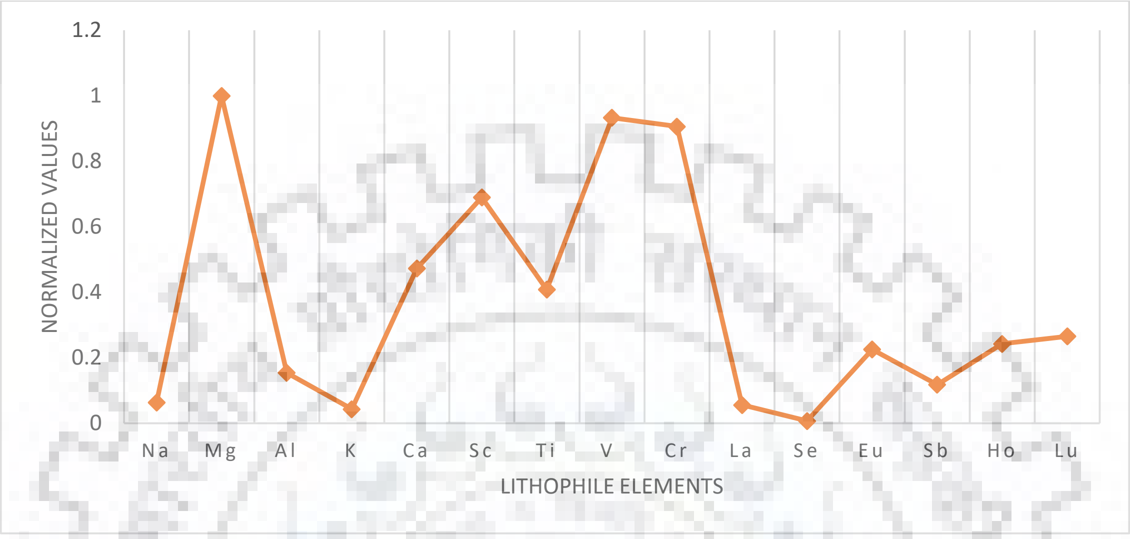


Figure 1: Abundance of Lithophile elements in Bulk of the Sample

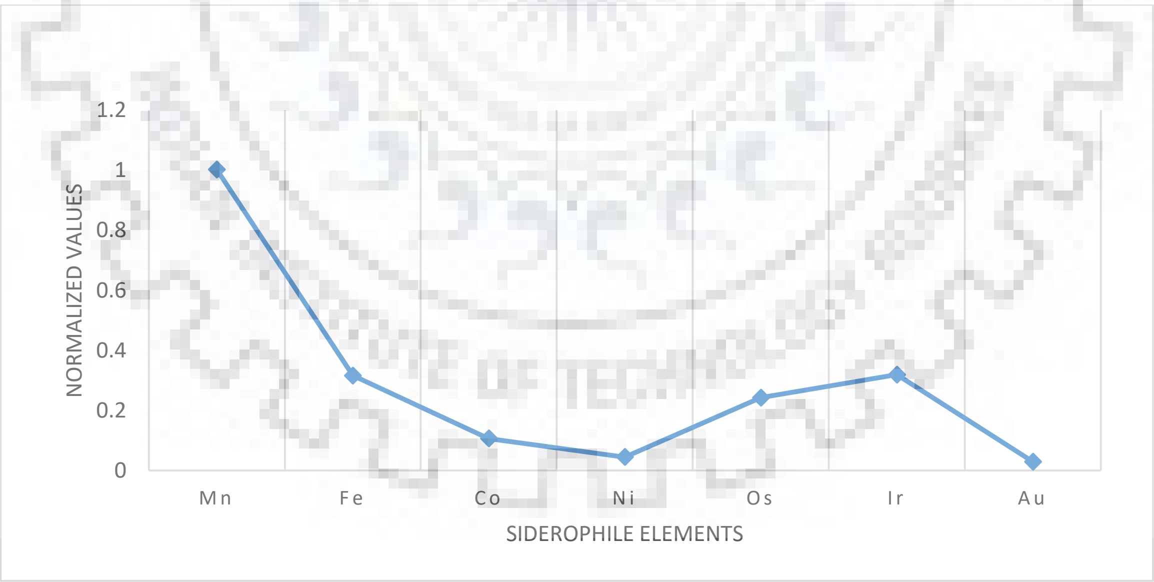


Figure 2: Abundance of Siderophile Elements in Bulk of the sample.

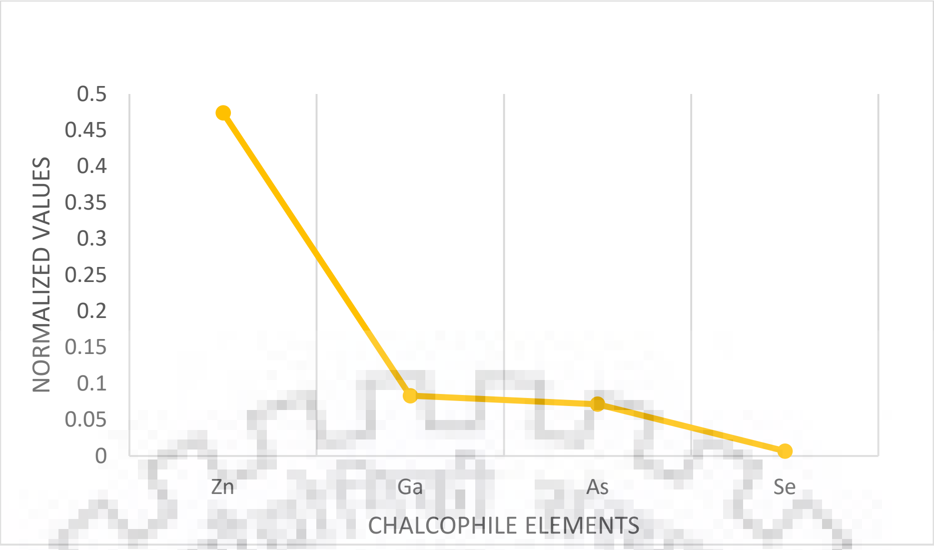


Figure 3: Abundance of Chalcophile elements in Bulk of the Sample

Graphs for abundance of siderophile elements in Olivine:

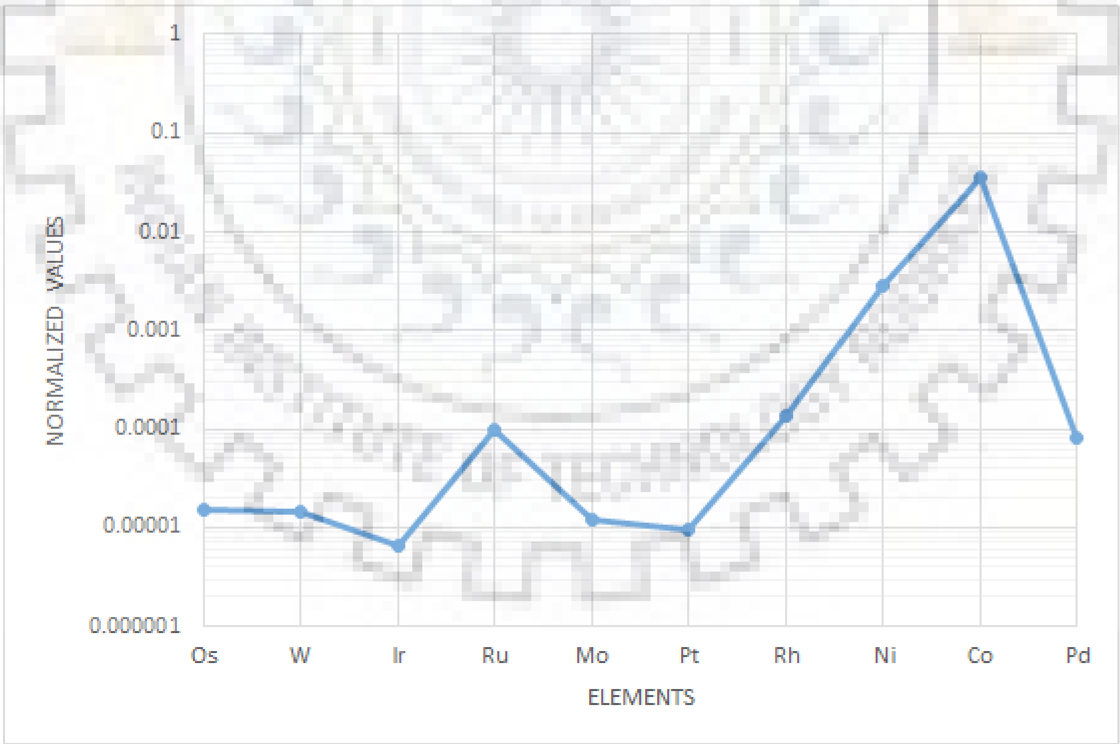


Figure 4: elemental abundance of data set 1

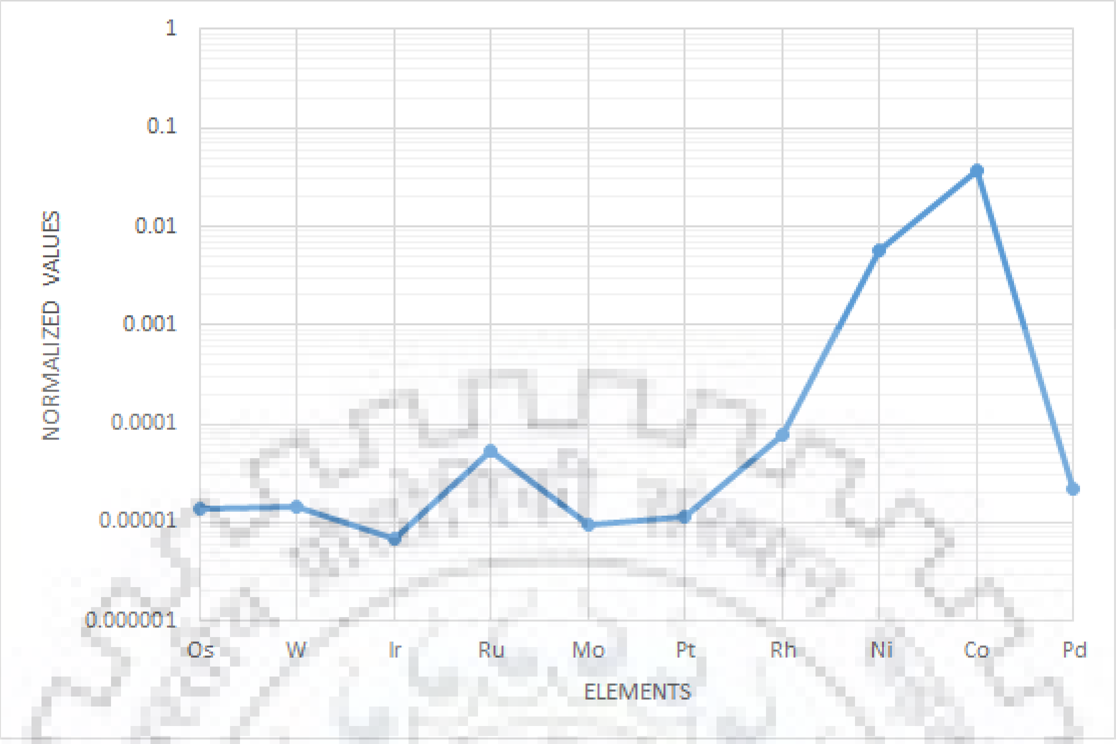


Figure 5: elemental abundance of data set 2

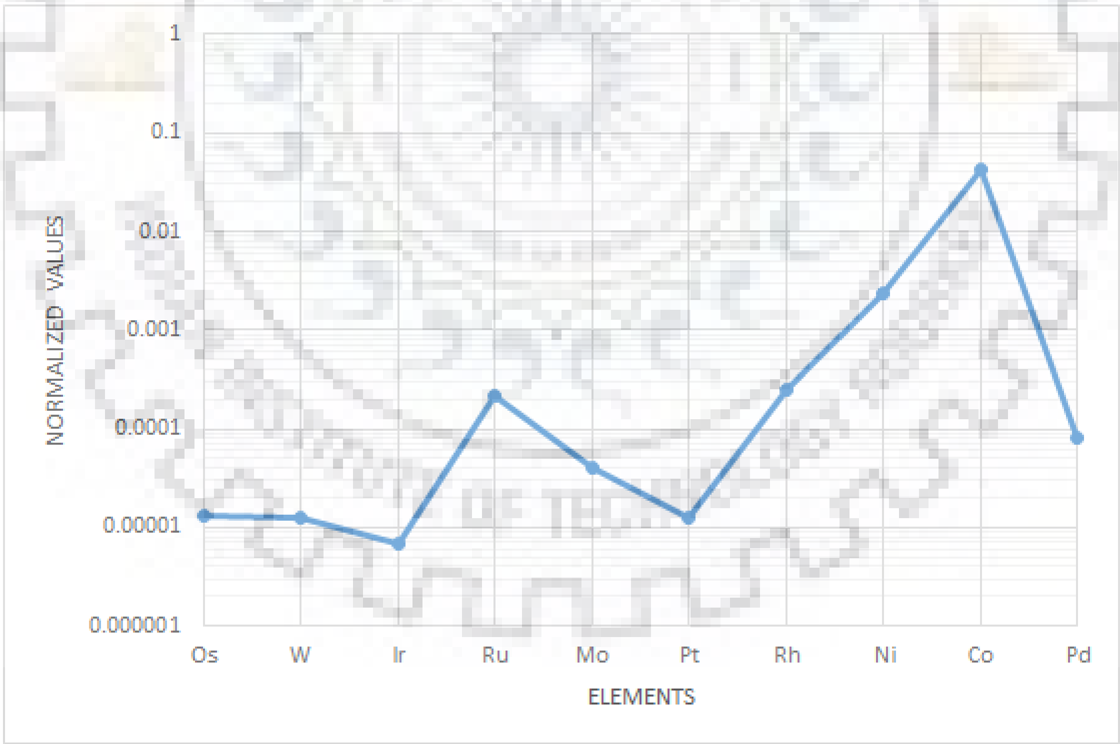


Figure 6: elemental abundance of data set 3

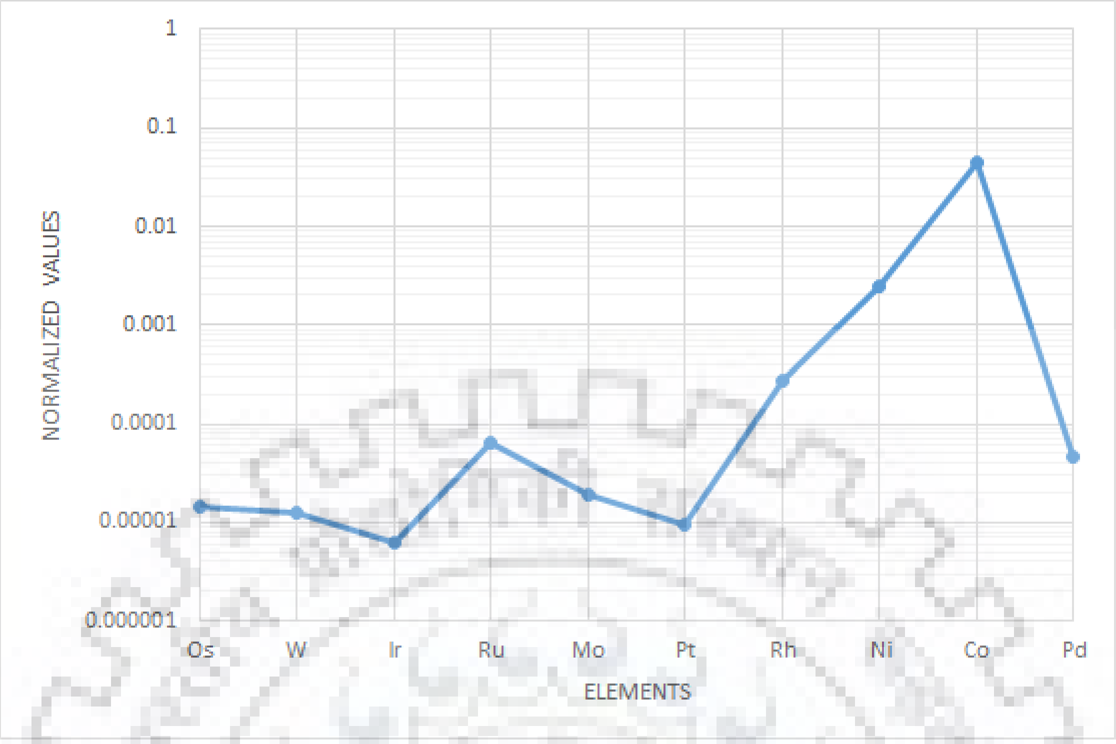


Figure 7: elemental abundance of data set 4

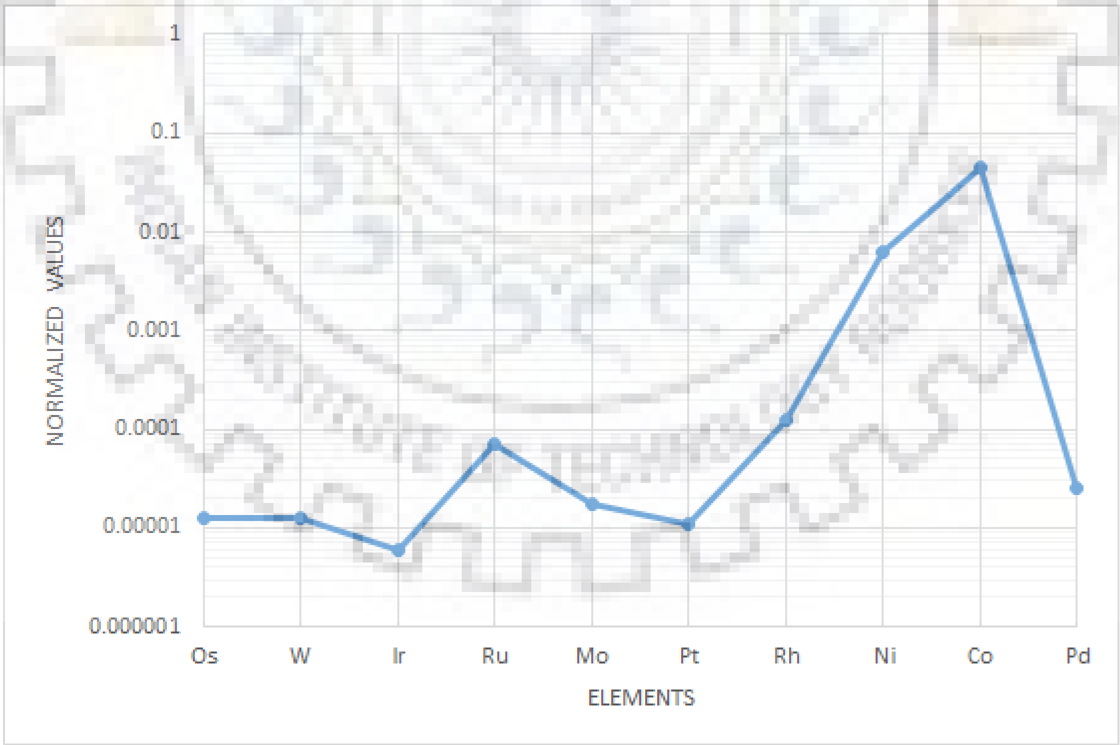


Figure 8: elemental abundance of data set 5

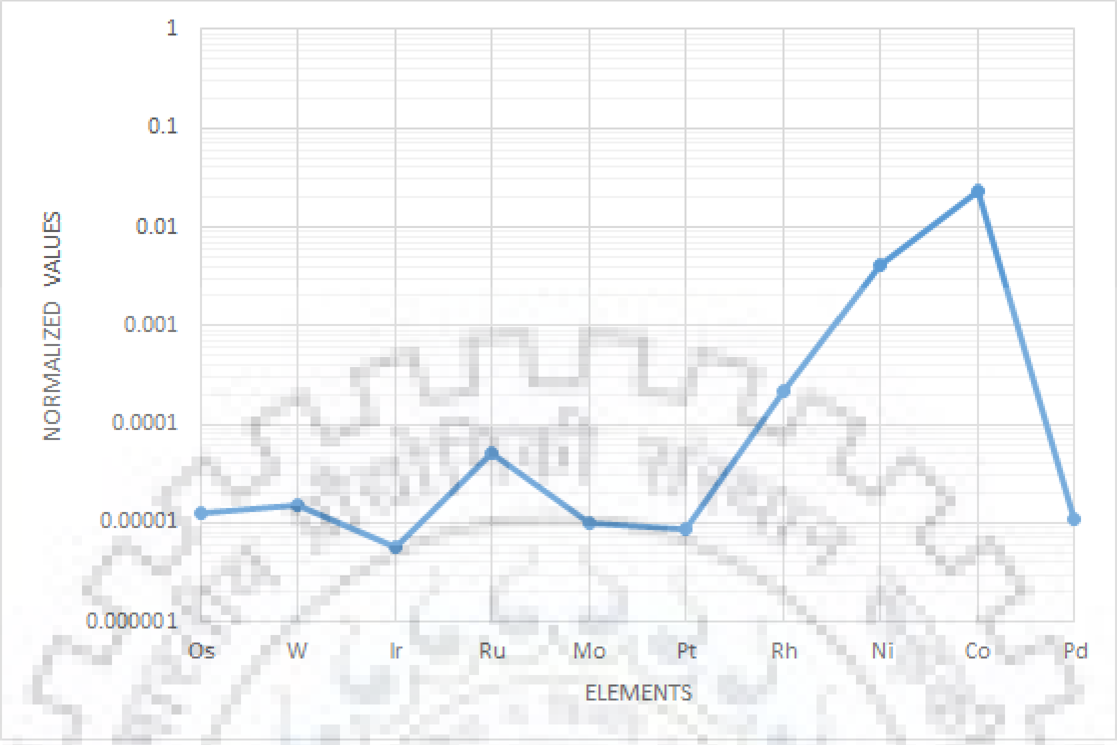


Figure 9: elemental abundance of data set 6

Graphs for abundance of chalcophile elements in olivine phase:

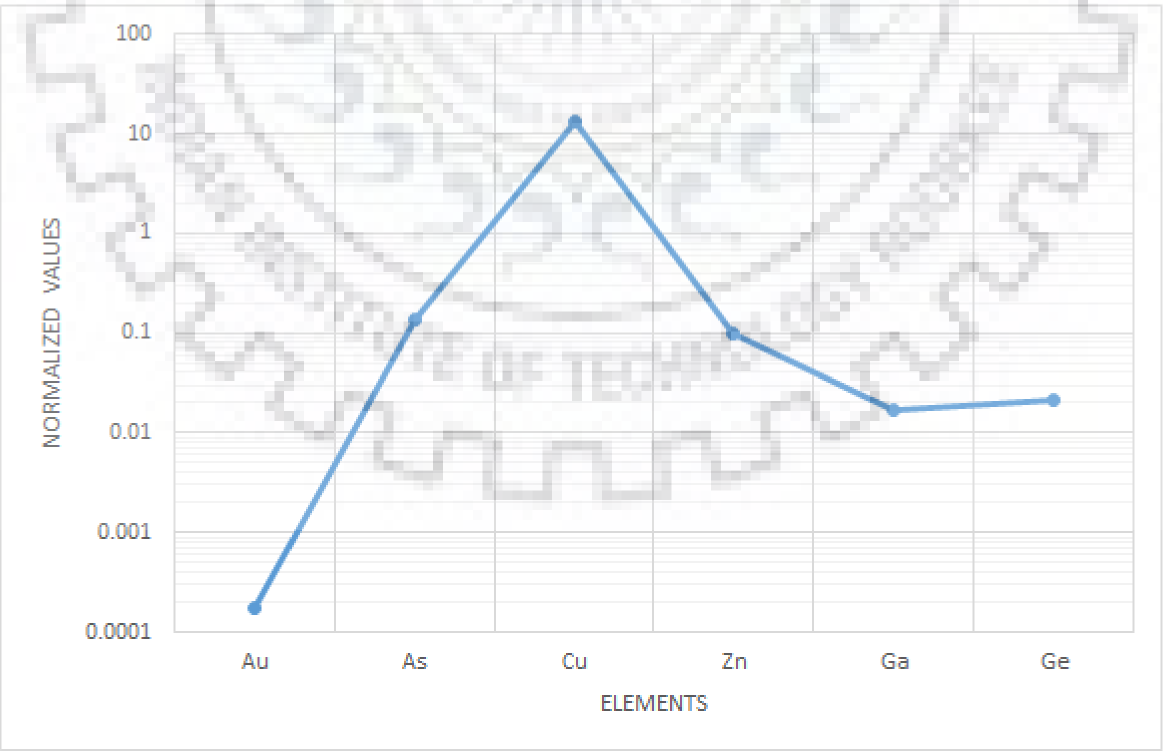


Figure 10: elemental abundance of data set 1

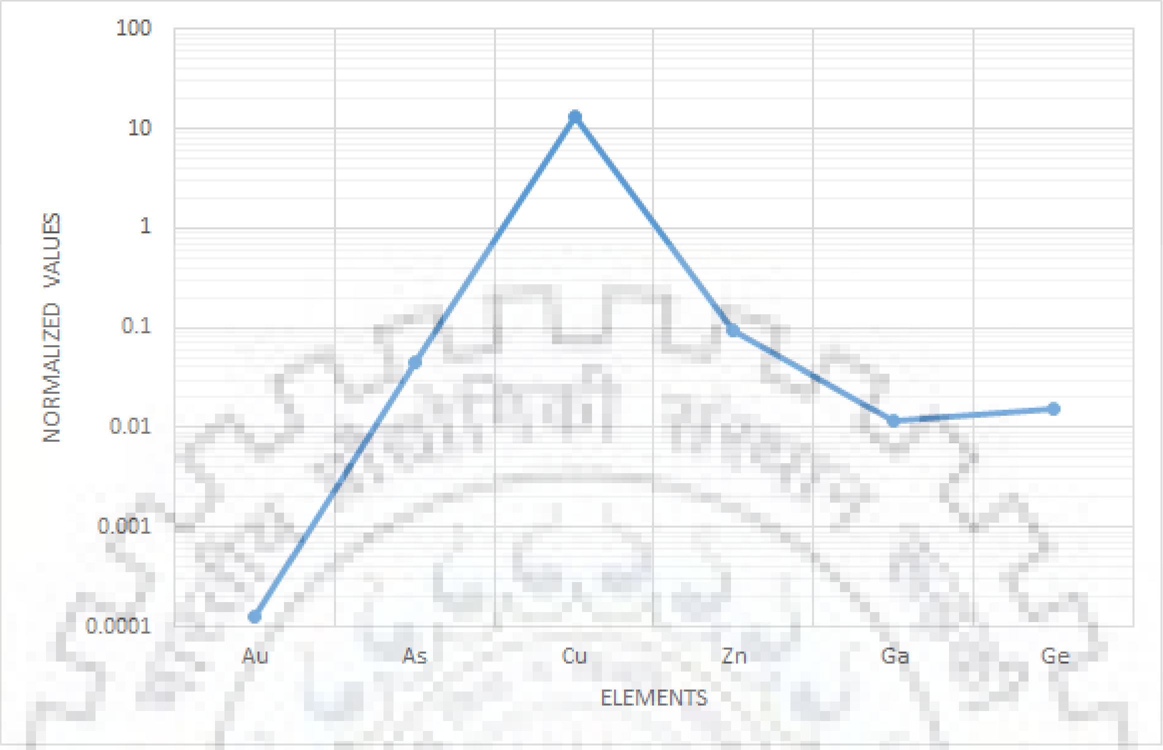


Figure 11: elemental abundance of data set 2

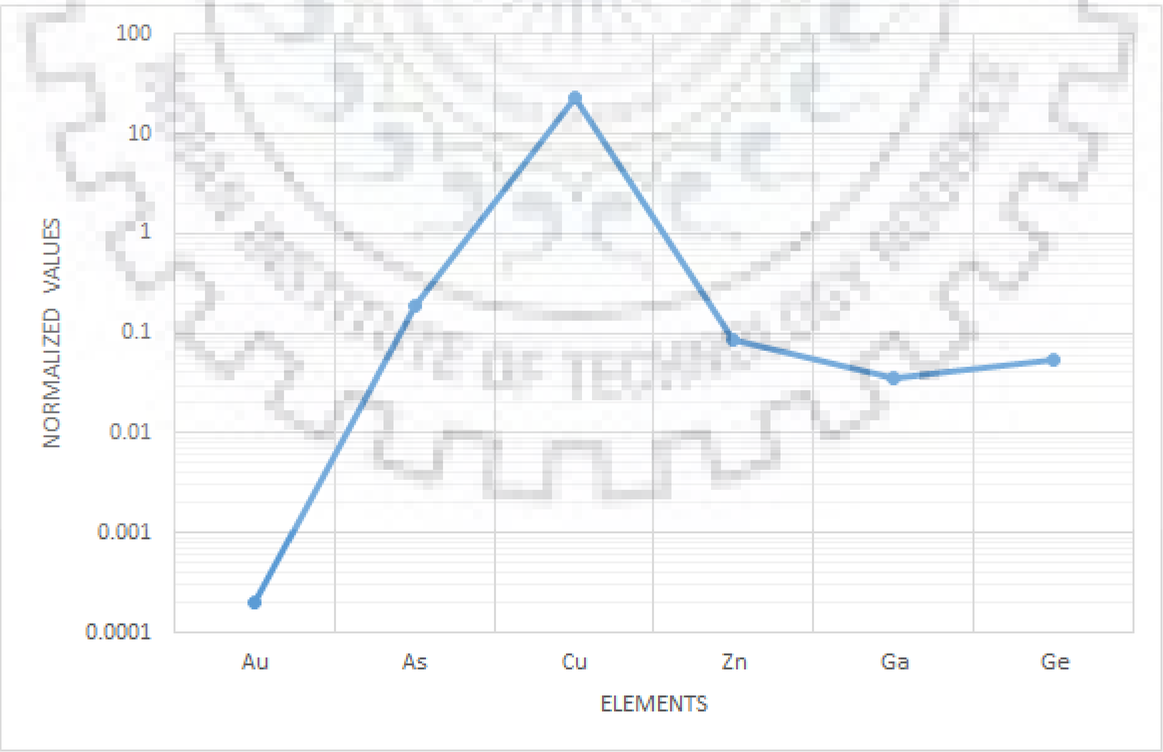


Figure 12: elemental abundance of data set 3

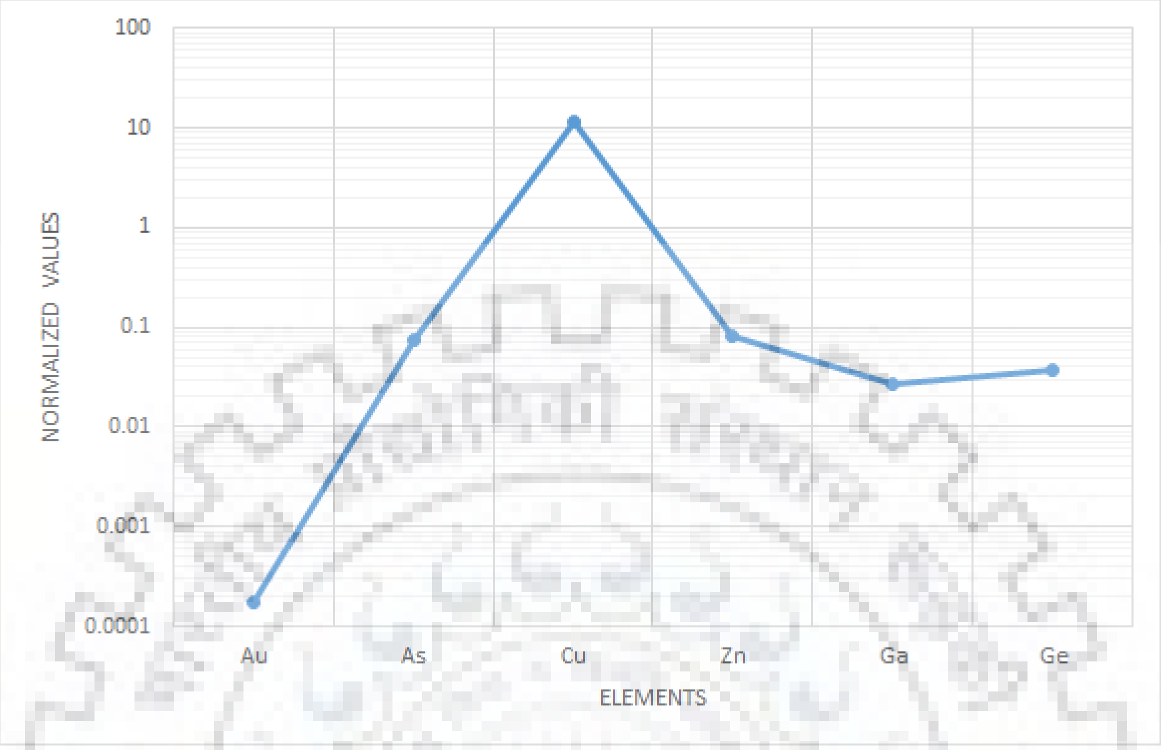


Figure 13: elemental abundance of data set 4

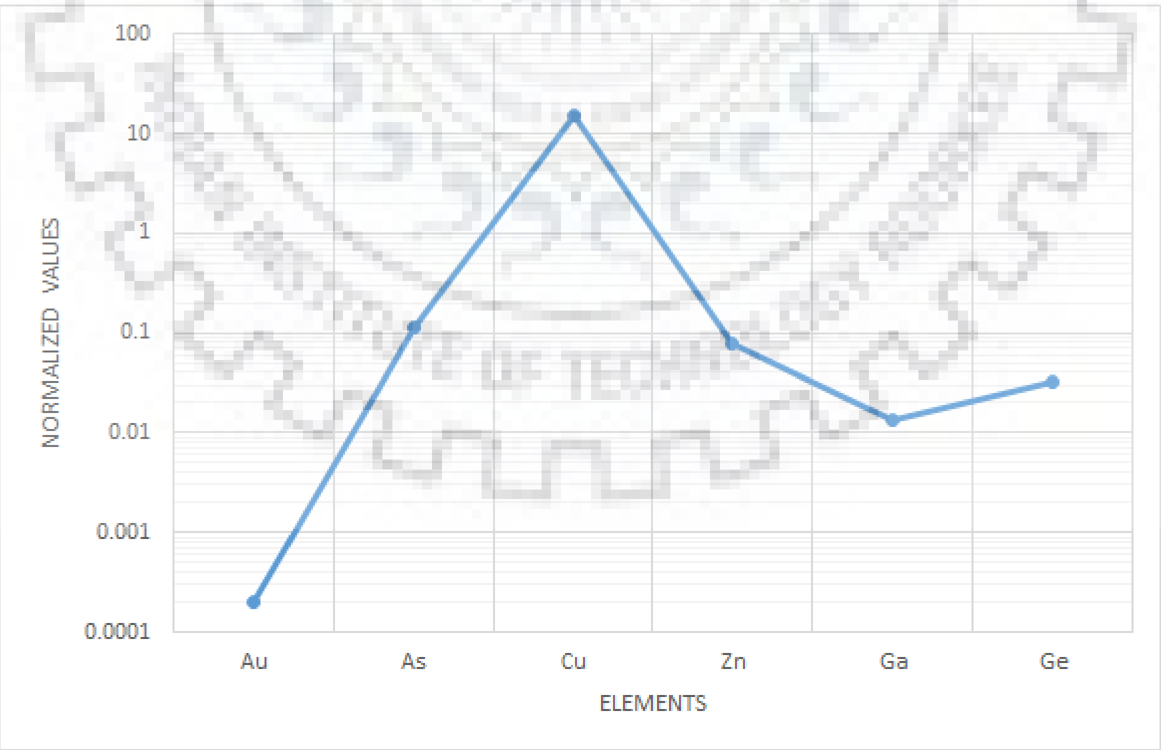


Figure 14: elemental abundance of data set 5

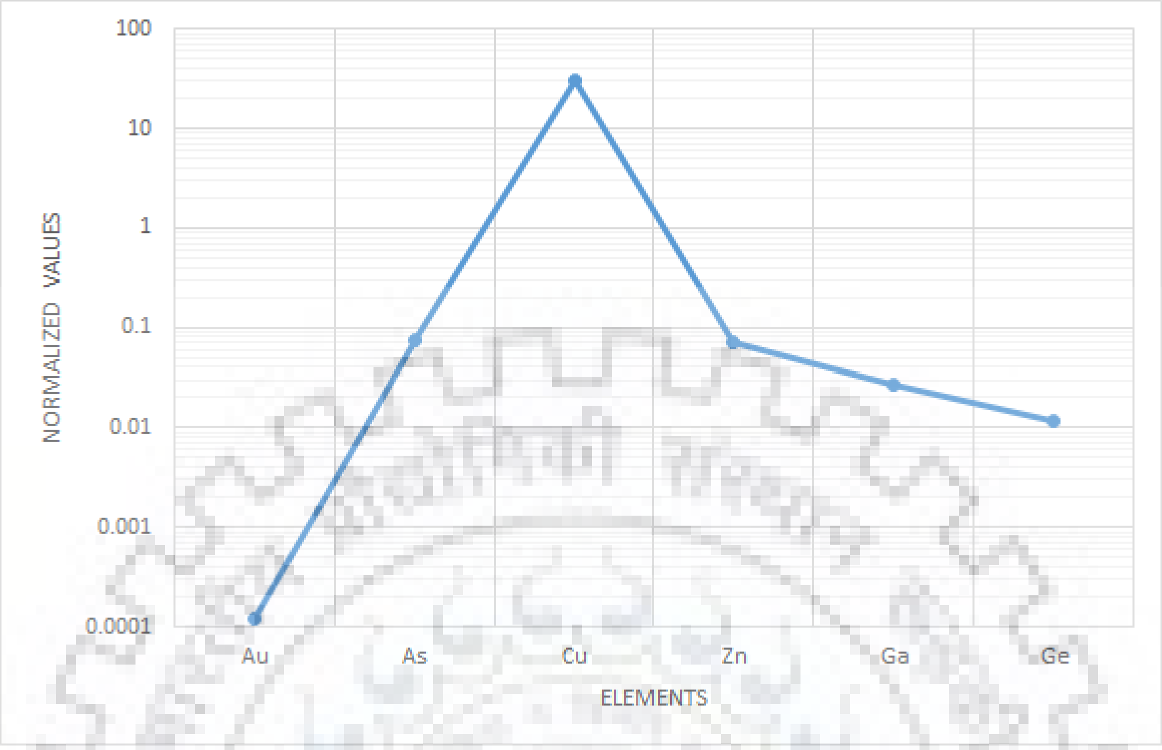


Figure 15: elemental abundance of data set 6

Combined graph for the different data sets above of siderophile and chalcophile element abundance in the olivine phase:

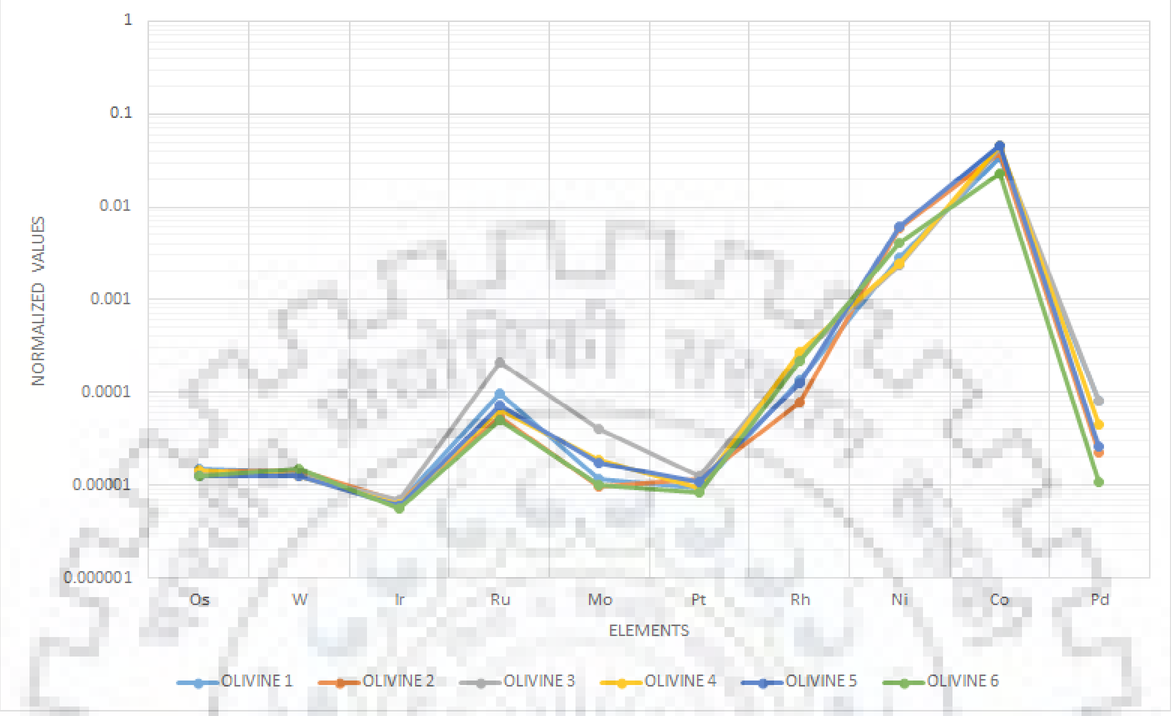


Figure 16: Graph for the elemental abundance of siderophile elements in the olivine phase

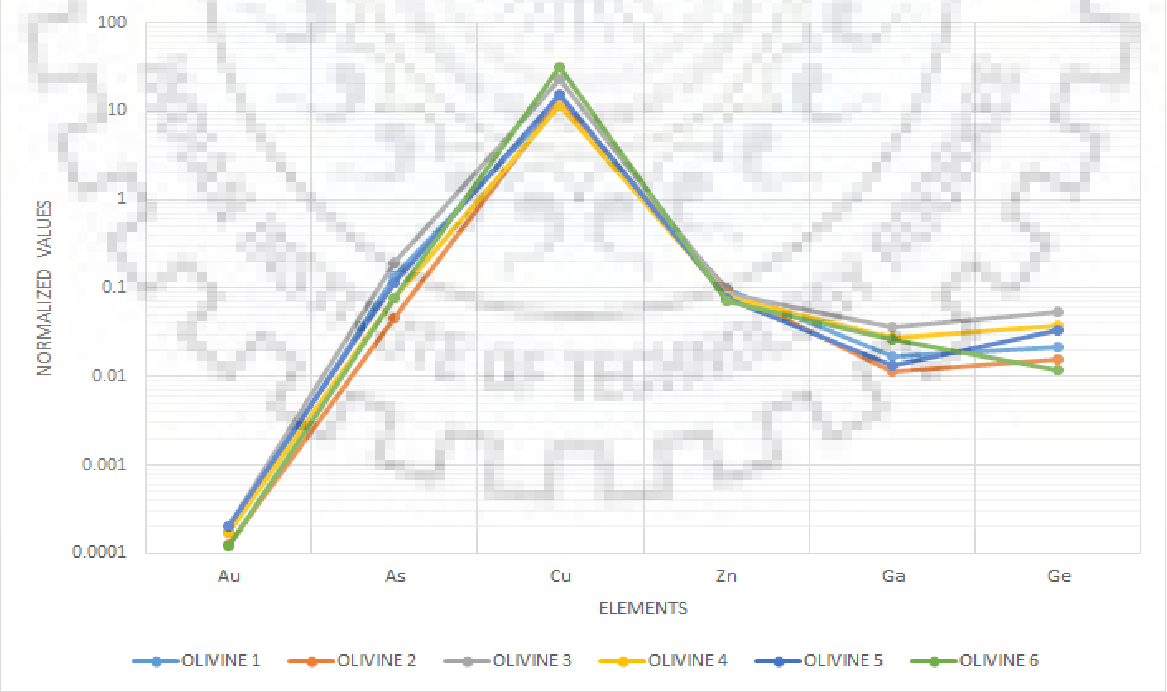


Figure 17: Graph for the elemental abundance of chalcophile elements in the olivine phase

Graphs for abundance of siderophile elements in Fe-S phase:

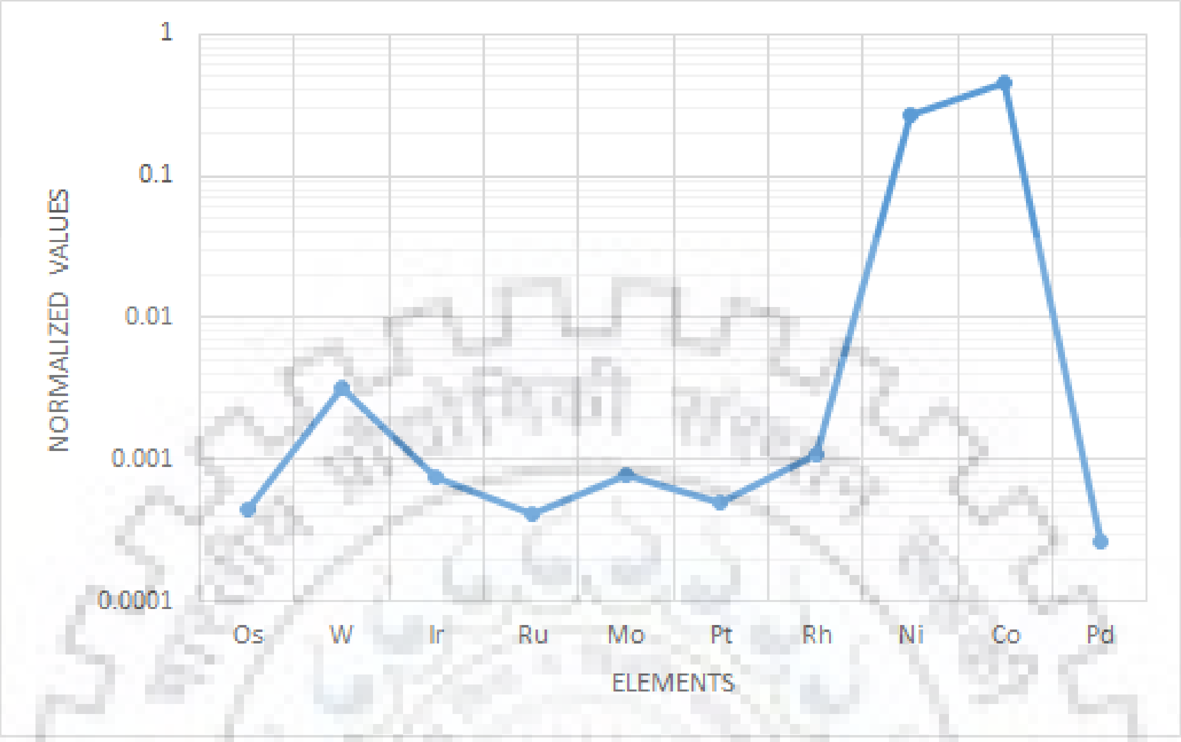


Figure 18: elemental abundance of data set 1

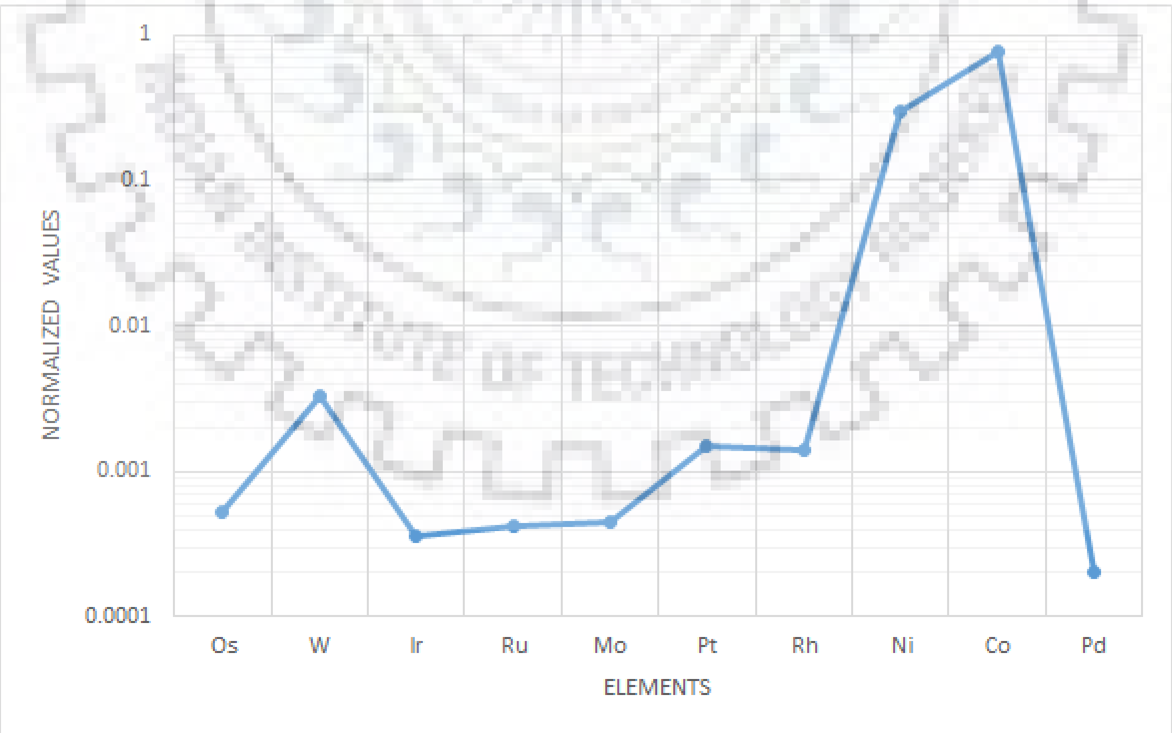


Figure 19: elemental abundance of data set 2

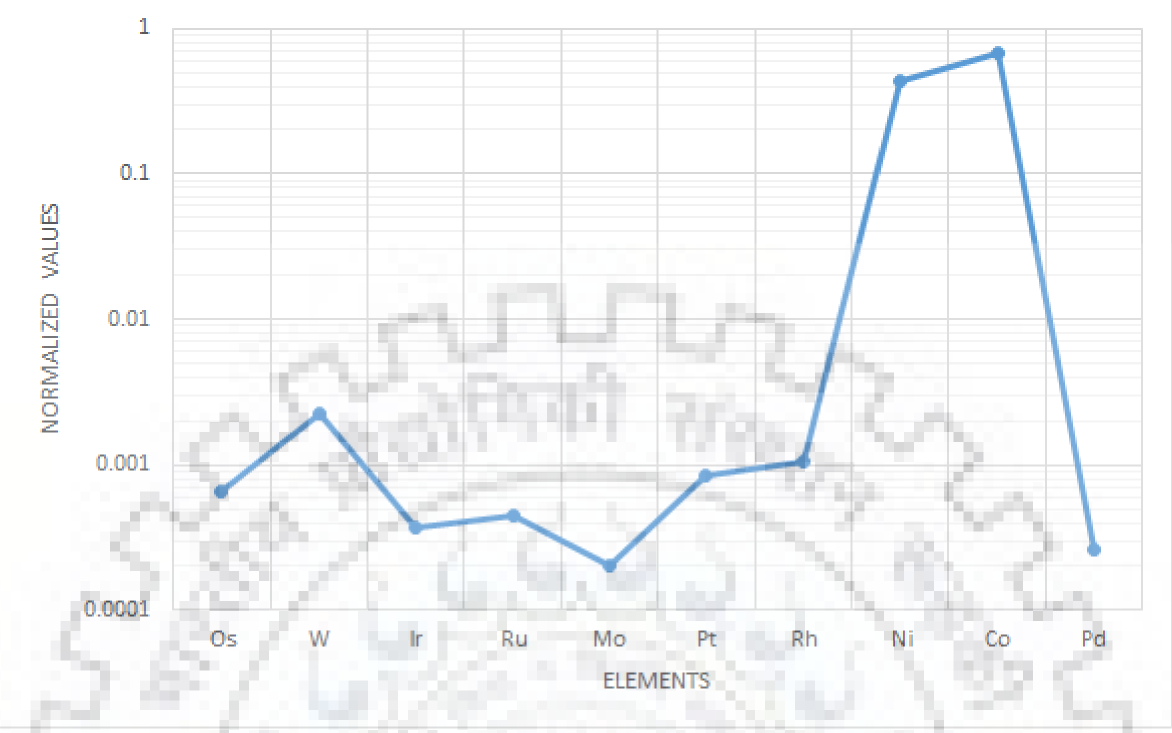


Figure 20: elemental abundance of data set 3

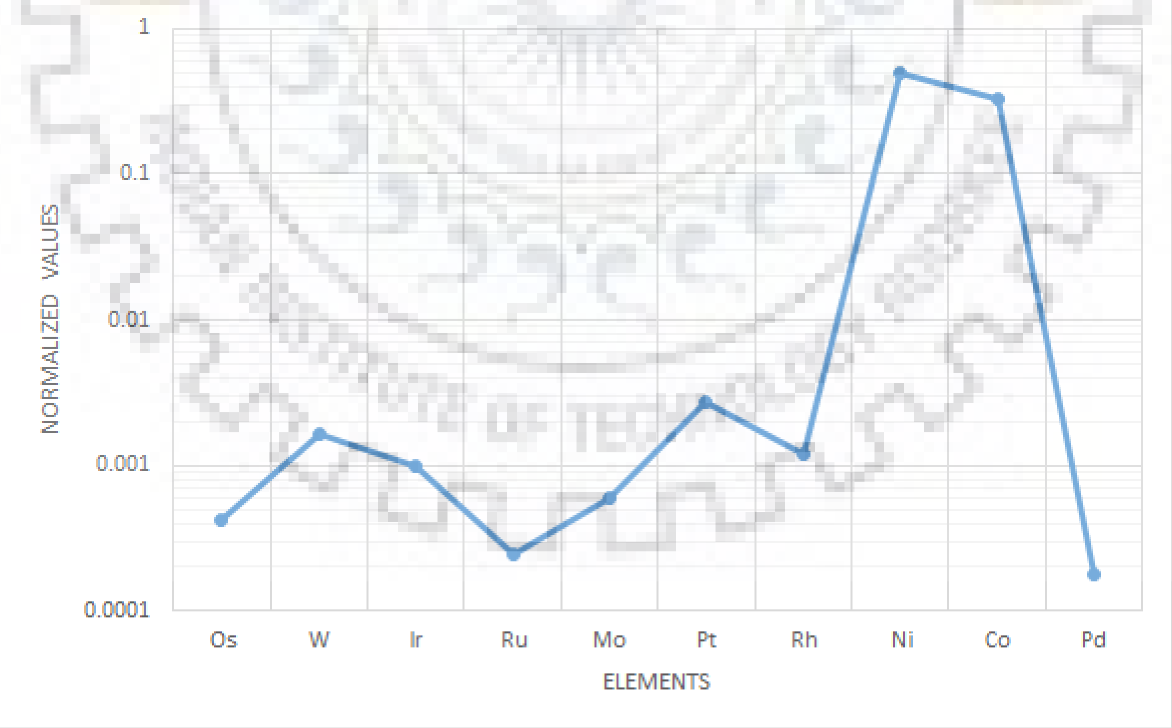


Figure 21: elemental abundance of data set 4

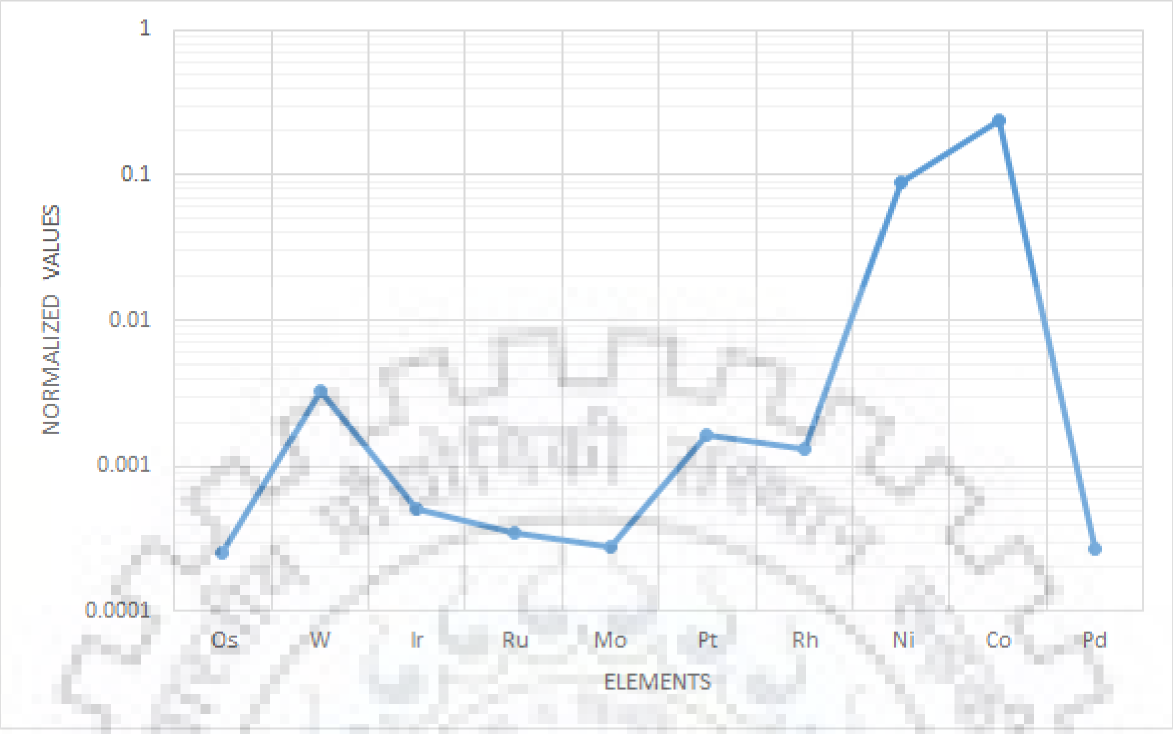


Figure 22: elemental abundance of data set 5

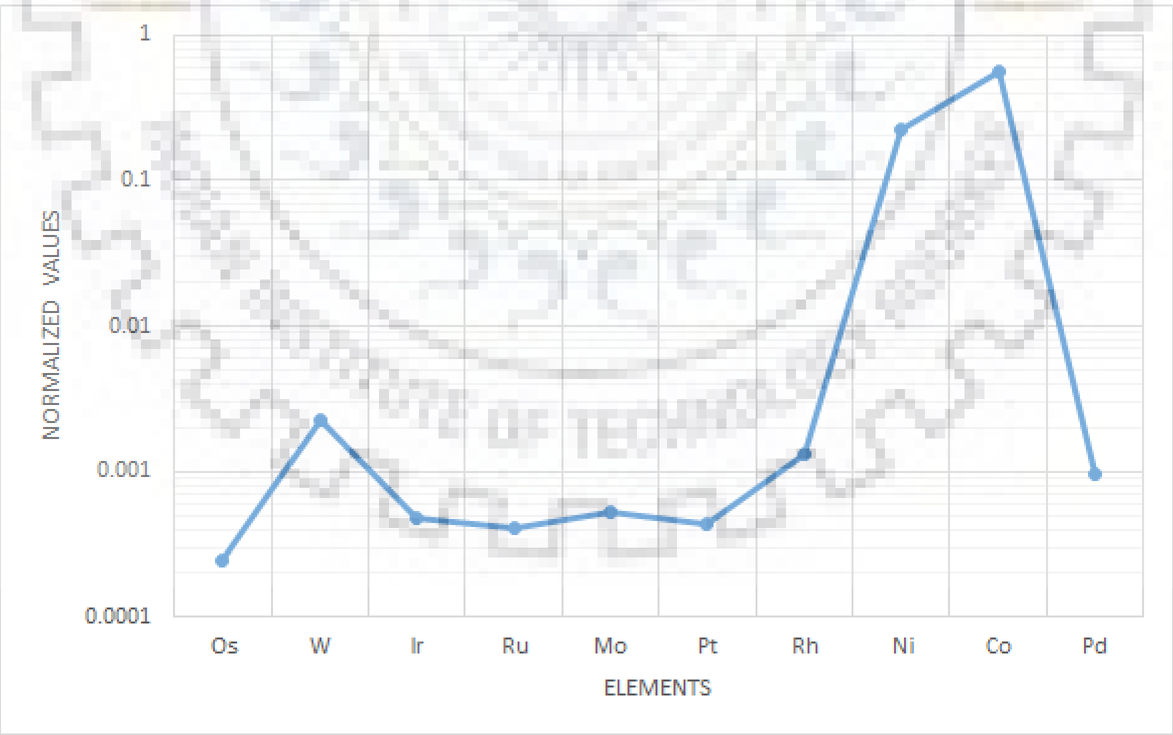


Figure 23: elemental abundance of data set 6

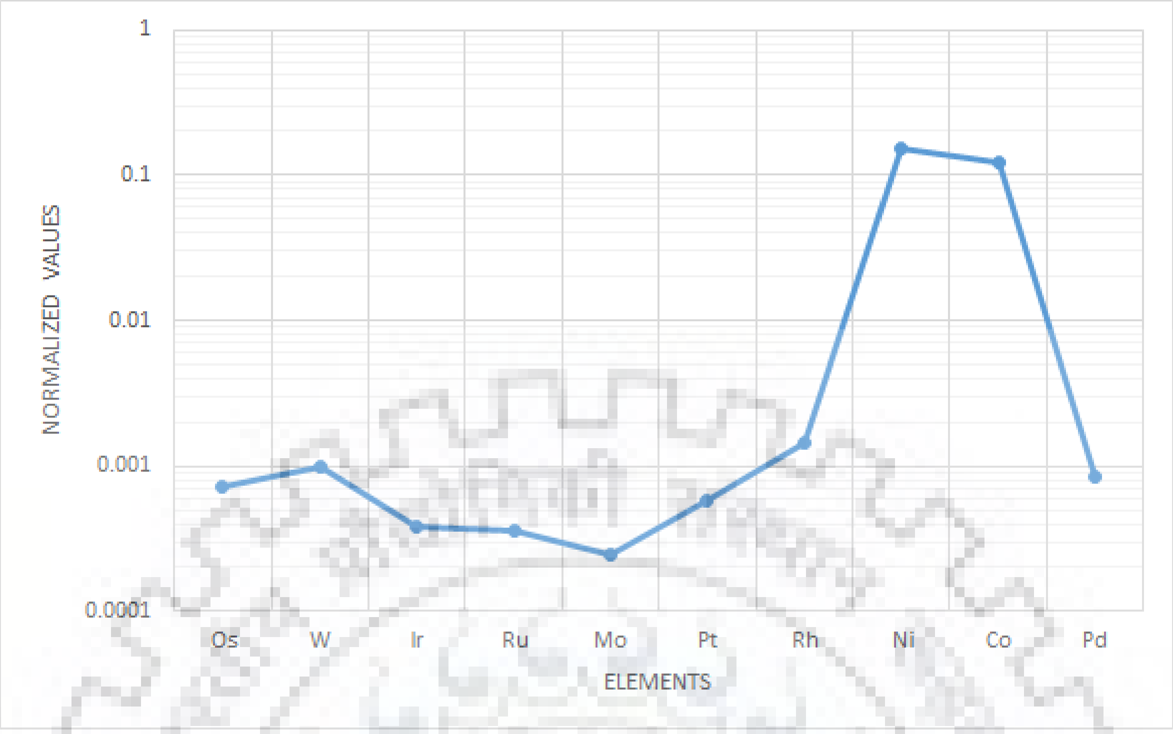


Figure 24: elemental abundance of data set 7

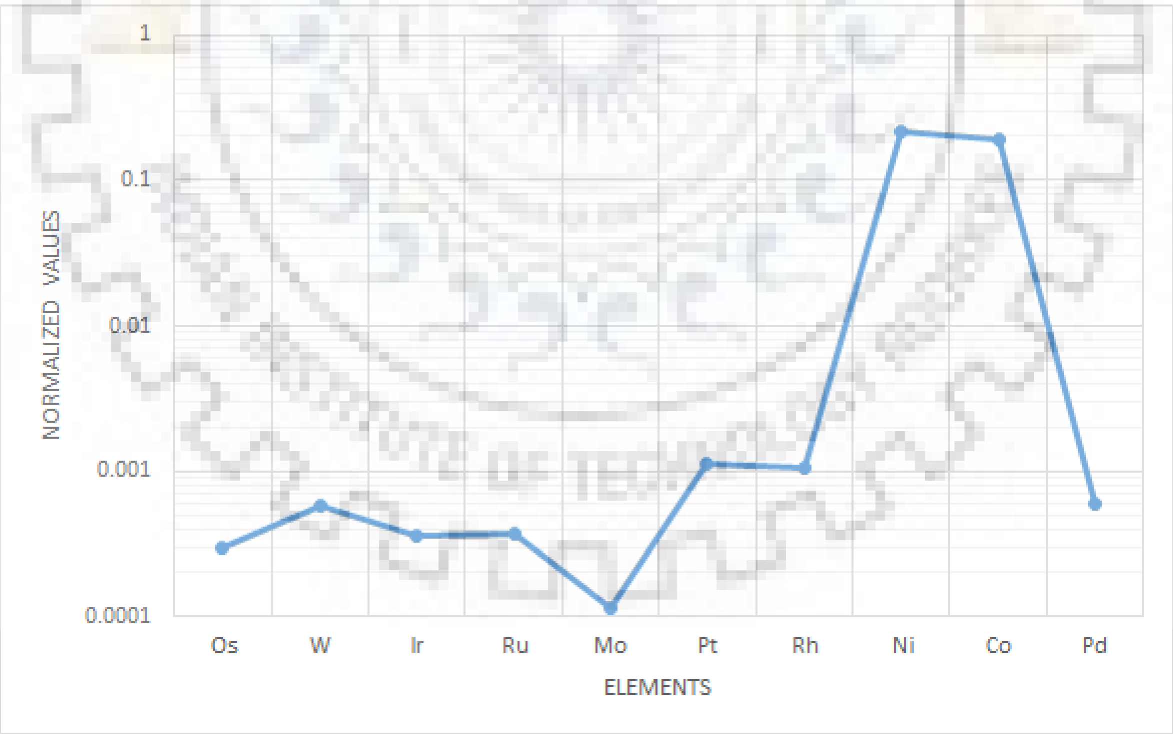


Figure 25: elemental abundance of data set 8

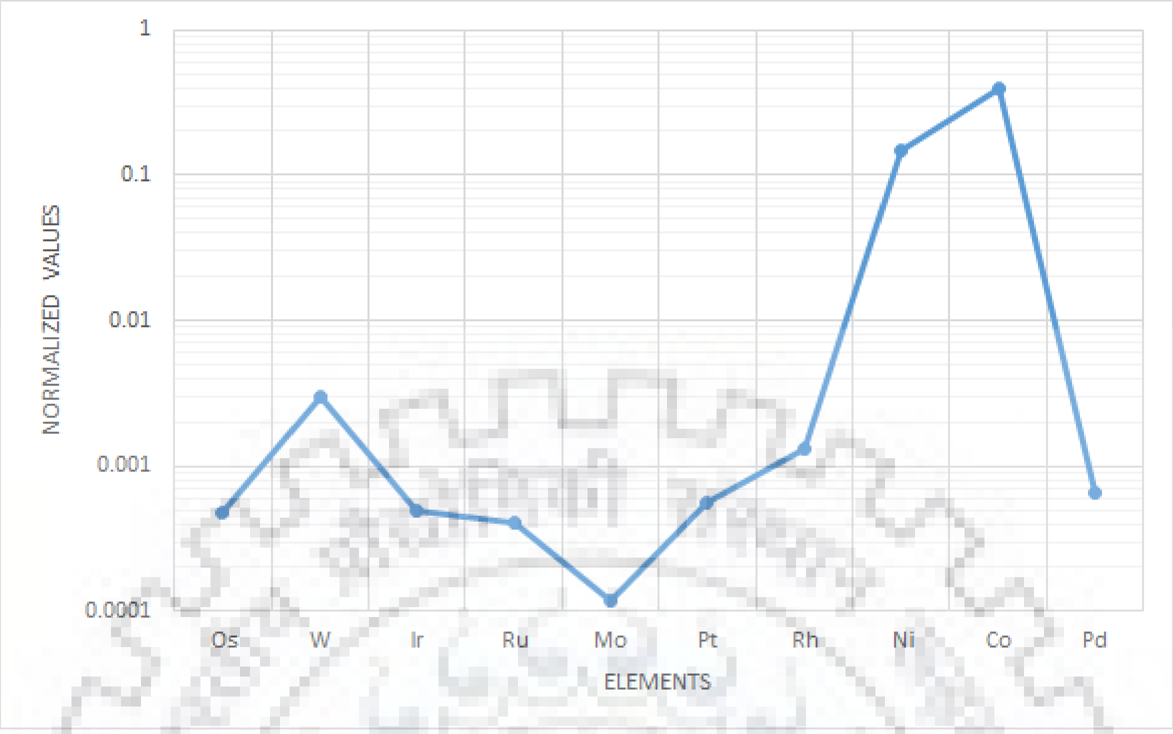


Figure 26: elemental abundance of data set 9

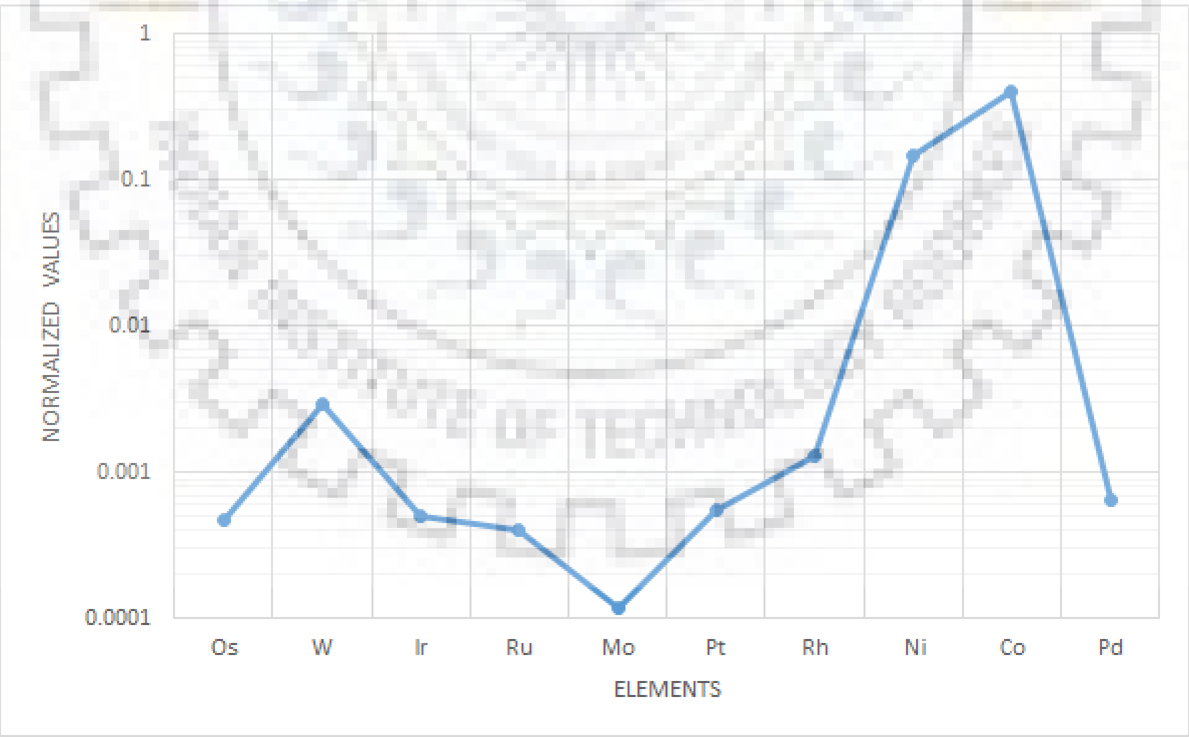


Figure 27: elemental abundance of data set 10

Graphs for abundance of Chalcophile elements in Fe-S phase:

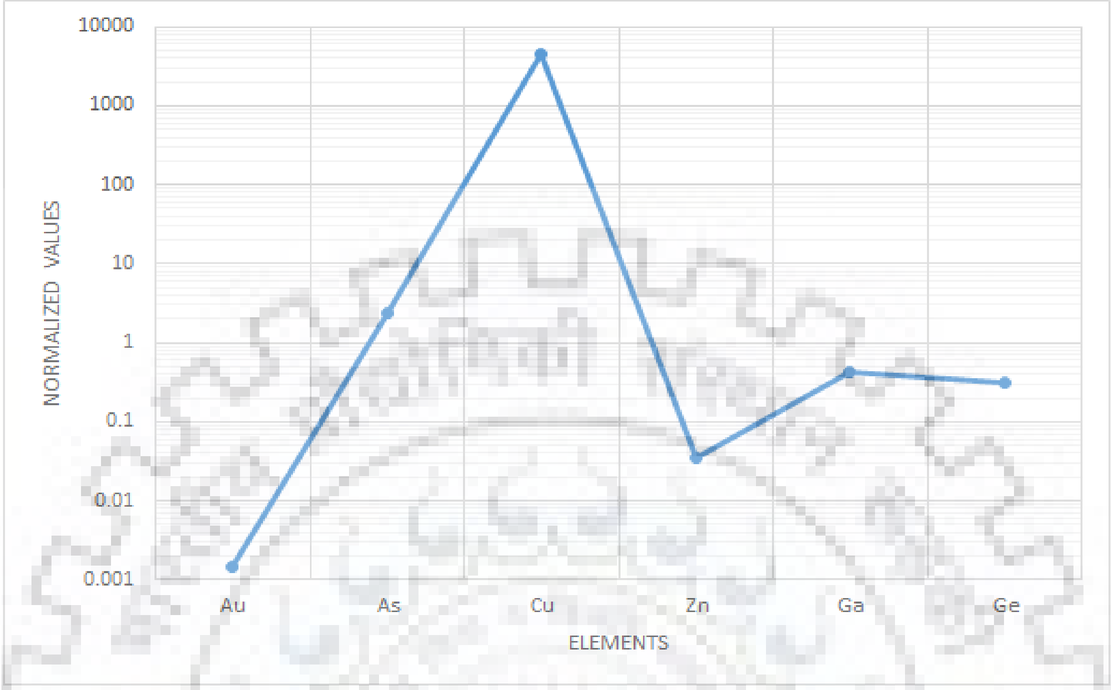


Figure 28: elemental abundance of data set 1

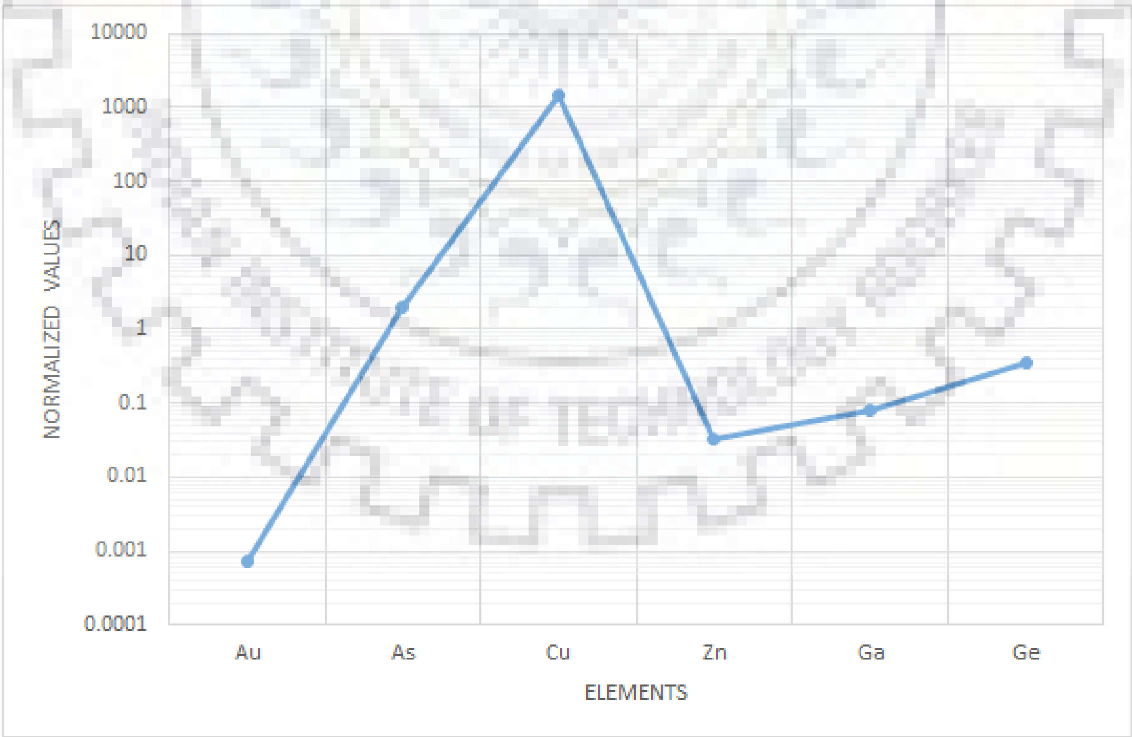


Figure 29: elemental abundance of data set 2

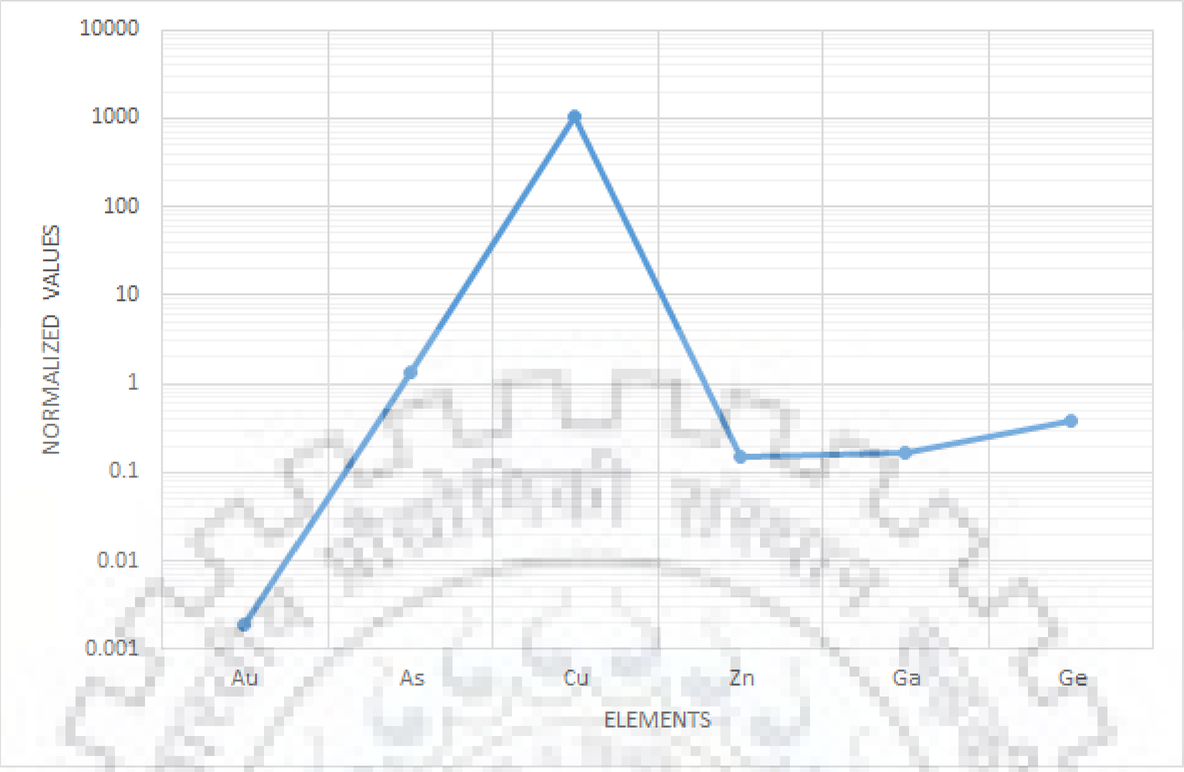


Figure 30: elemental abundance of data set 3

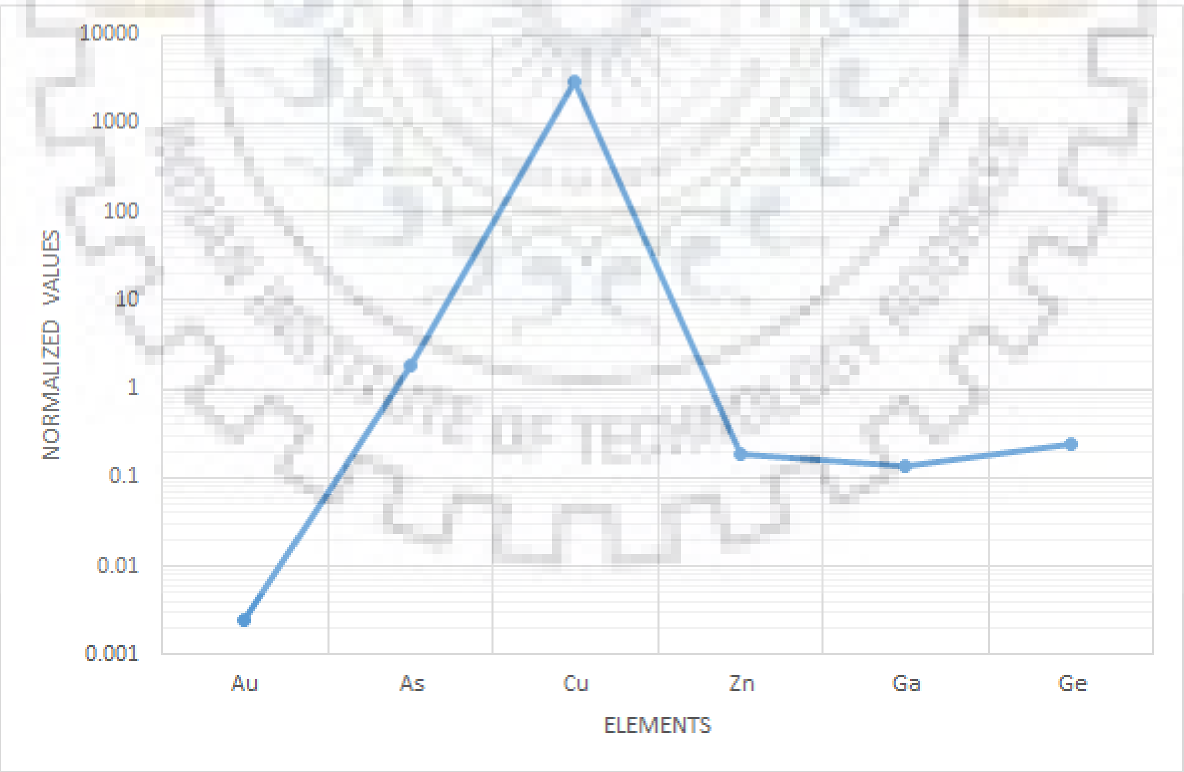


Figure 31: elemental abundance of data set 4

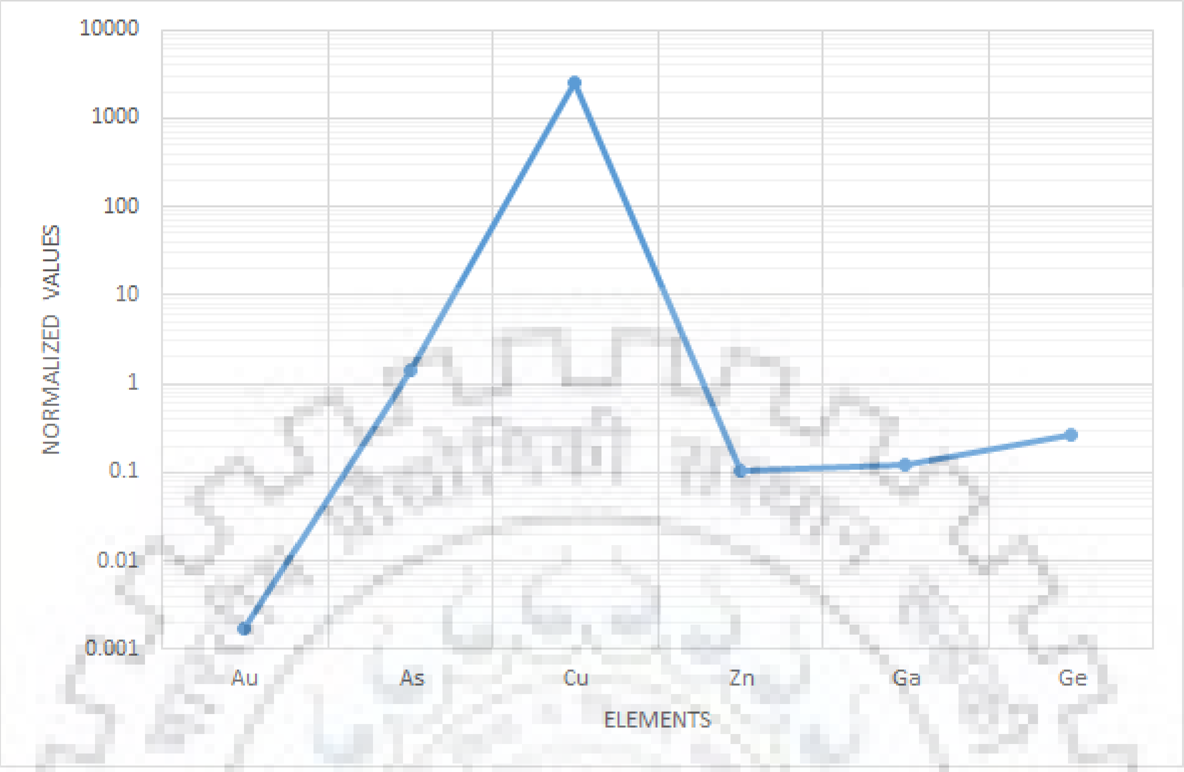


Figure 32: elemental abundance of data set 5

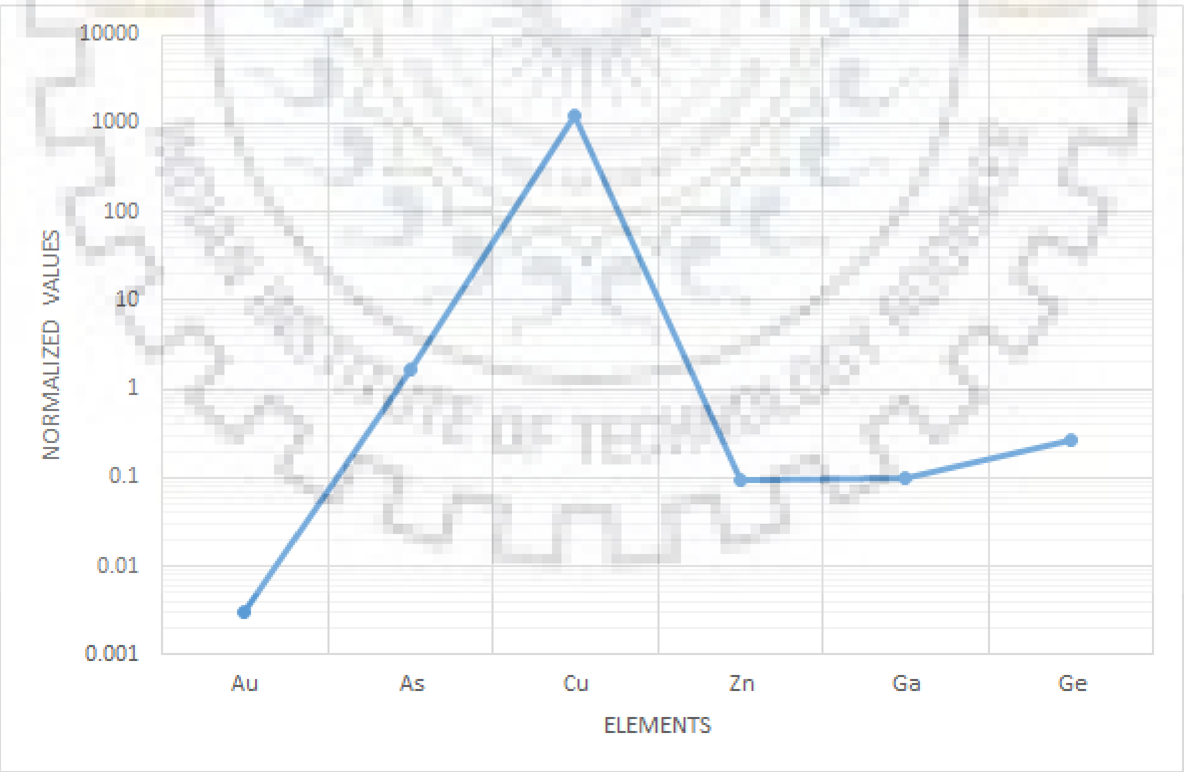


Figure 33: elemental abundance of data set 6

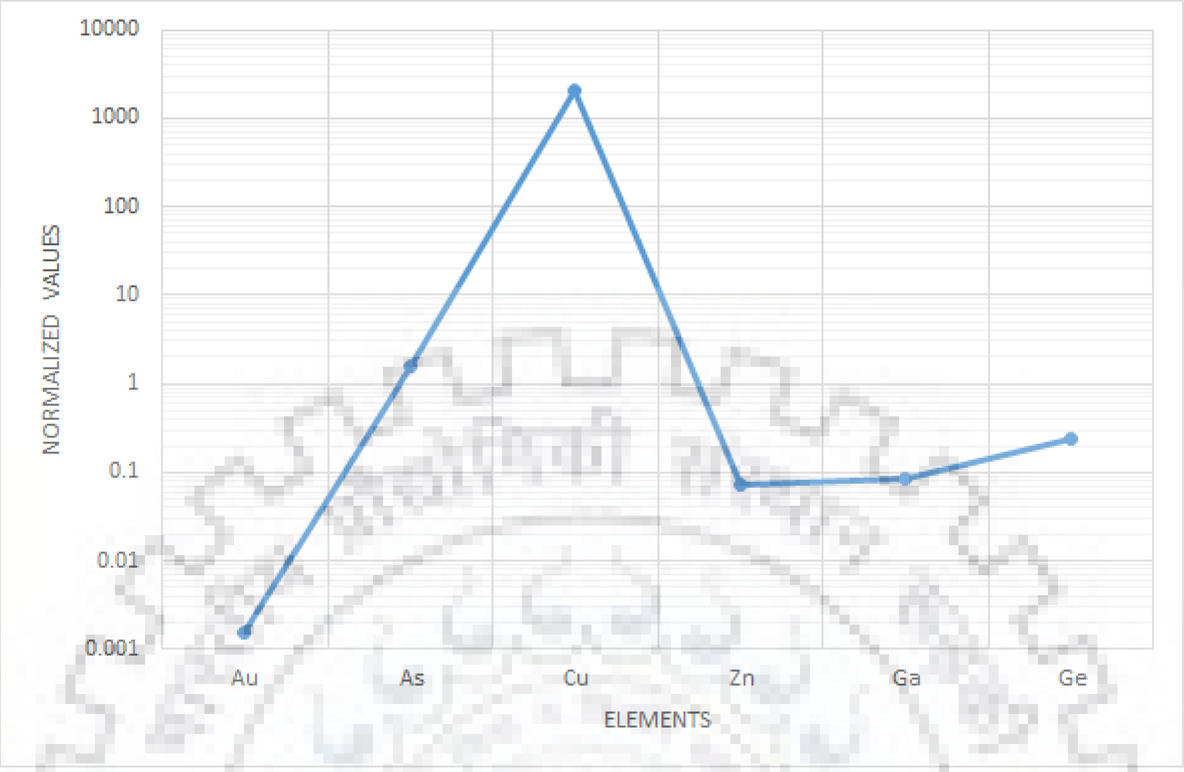


Figure 34: elemental abundance of data set 7

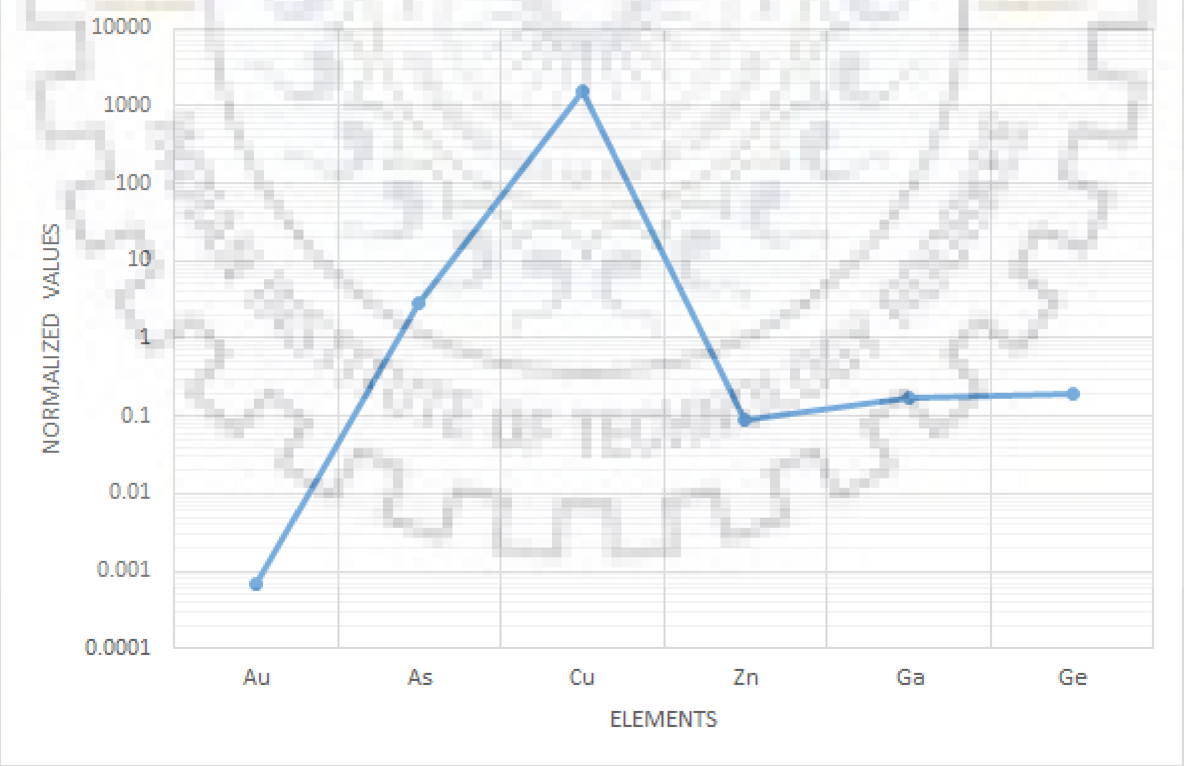


Figure 35: elemental abundance of data set 8

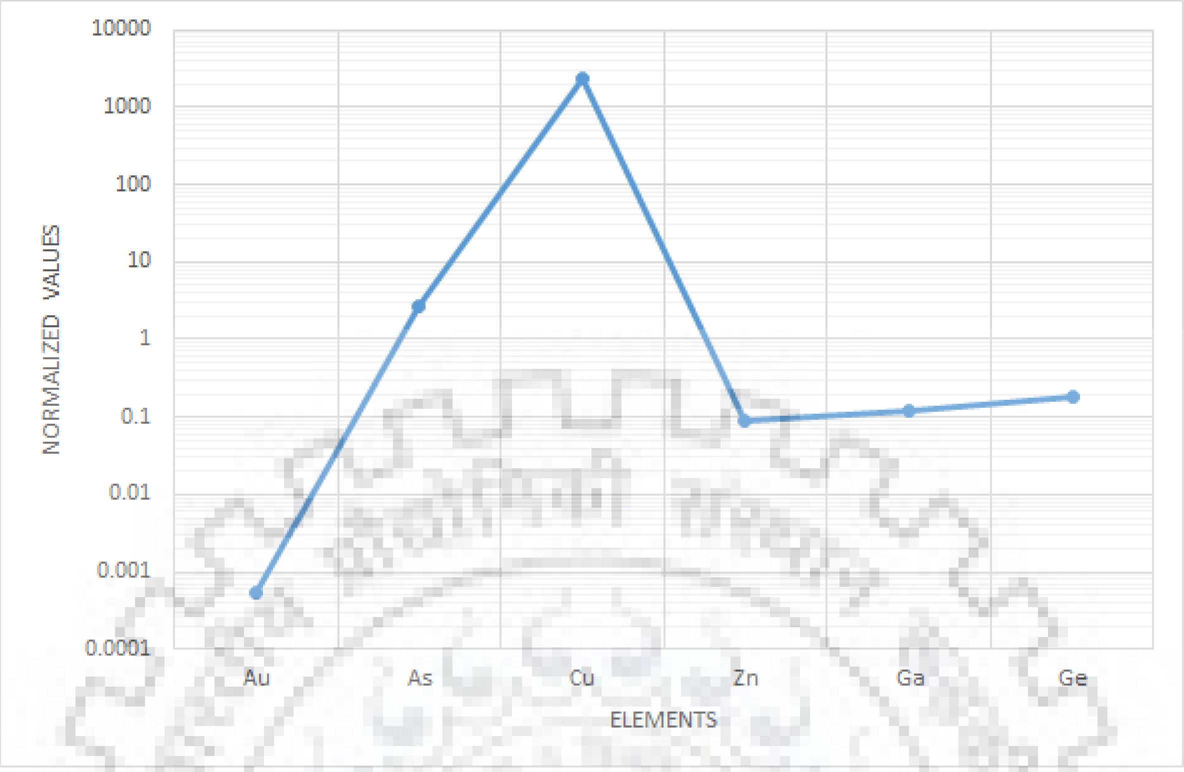


Figure 36: elemental abundance of data set 9

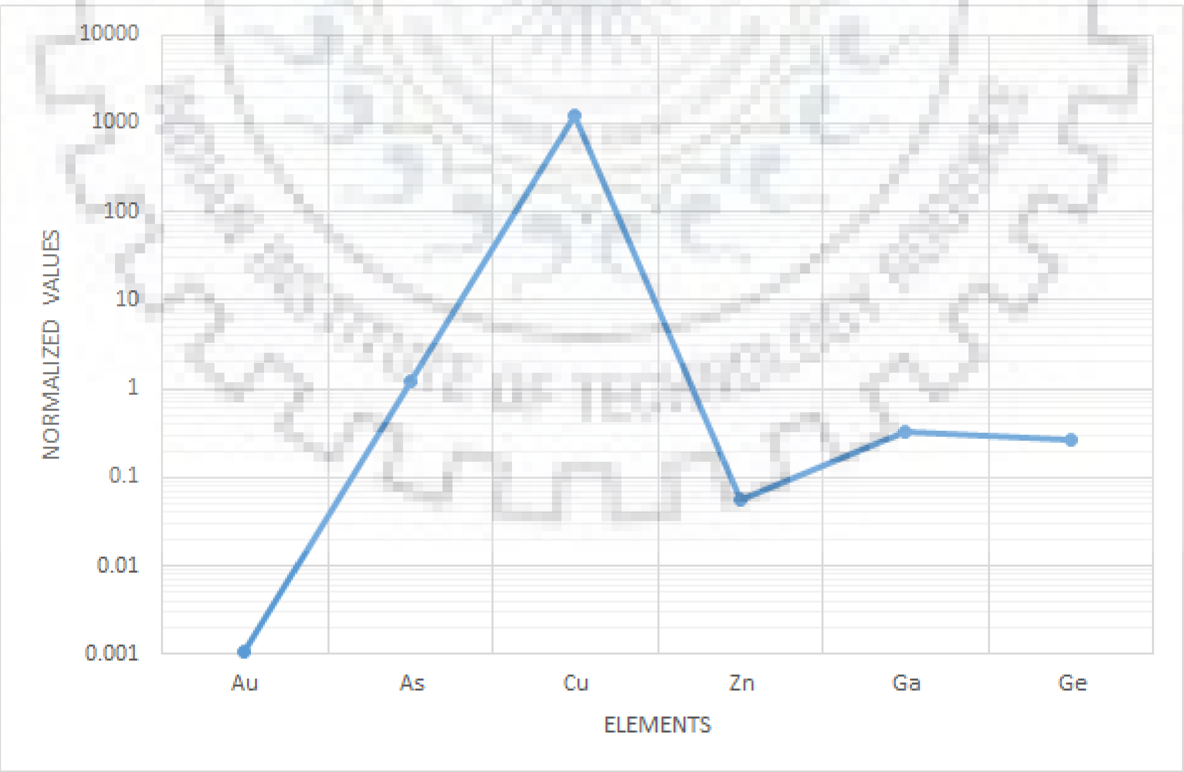


Figure 37: elemental abundance of data set 10

Combined graph for the different data sets above of siderophile and chalcophile element abundance in the Fe-S phase:

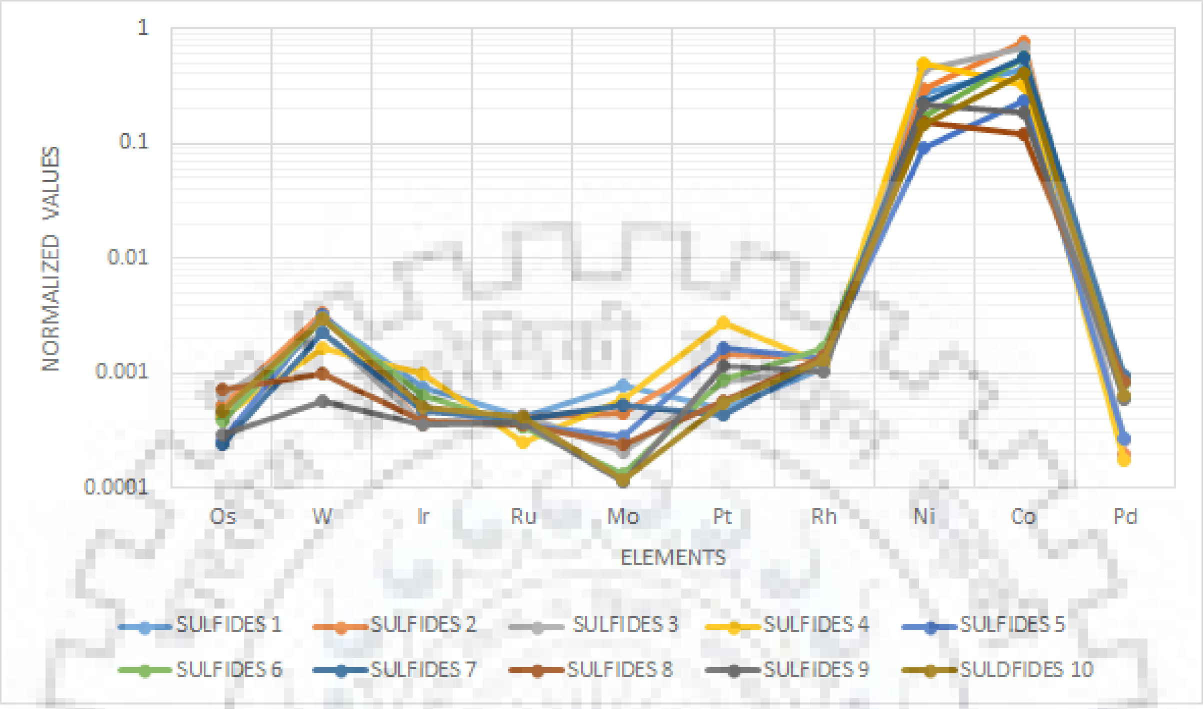


Figure 38: Graph for the elemental abundance of siderophile elements in the Fe-S phase

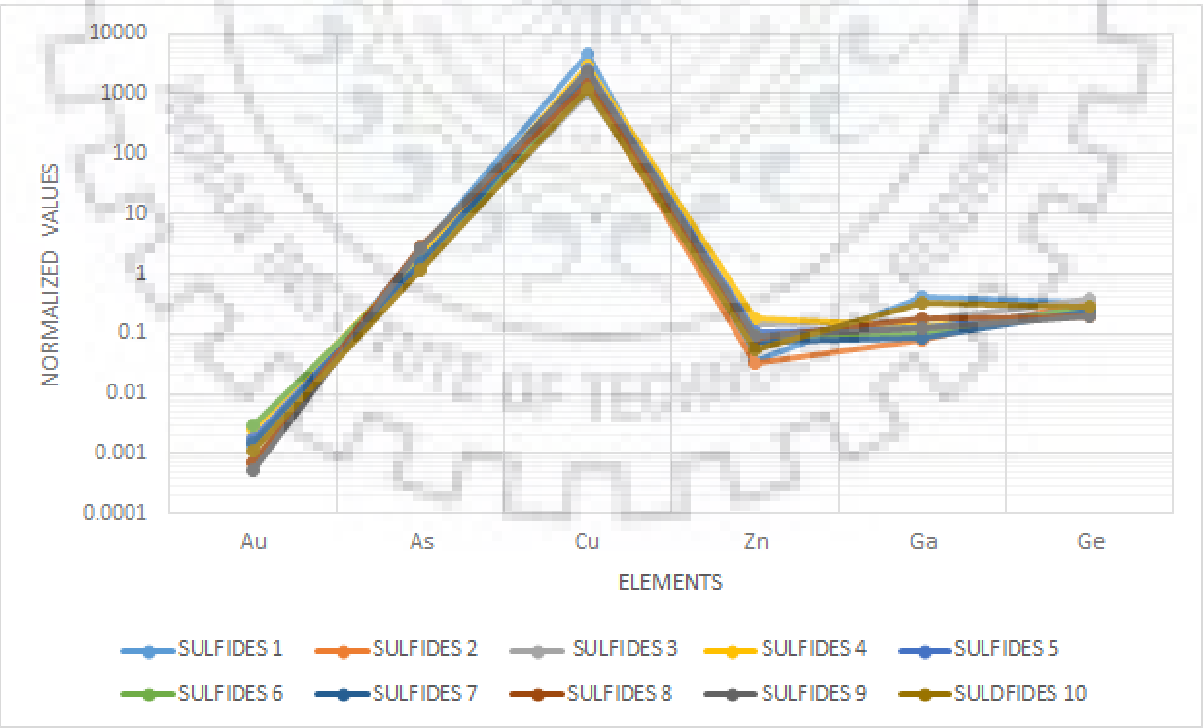


Figure 39: Graph for the elemental abundance of chalcophile elements in the Fe-S phase

Graphs for abundance of siderophile elements in Fe-Ni phase:

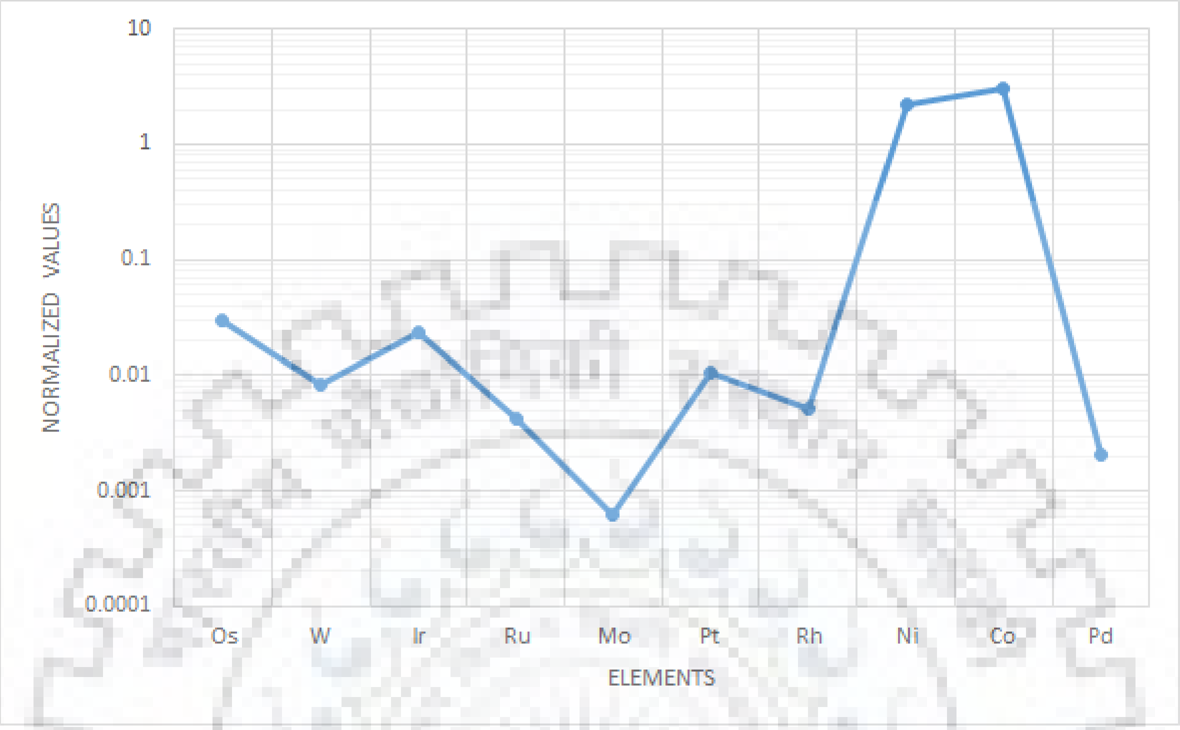


Figure 40: elemental abundance of data set 1

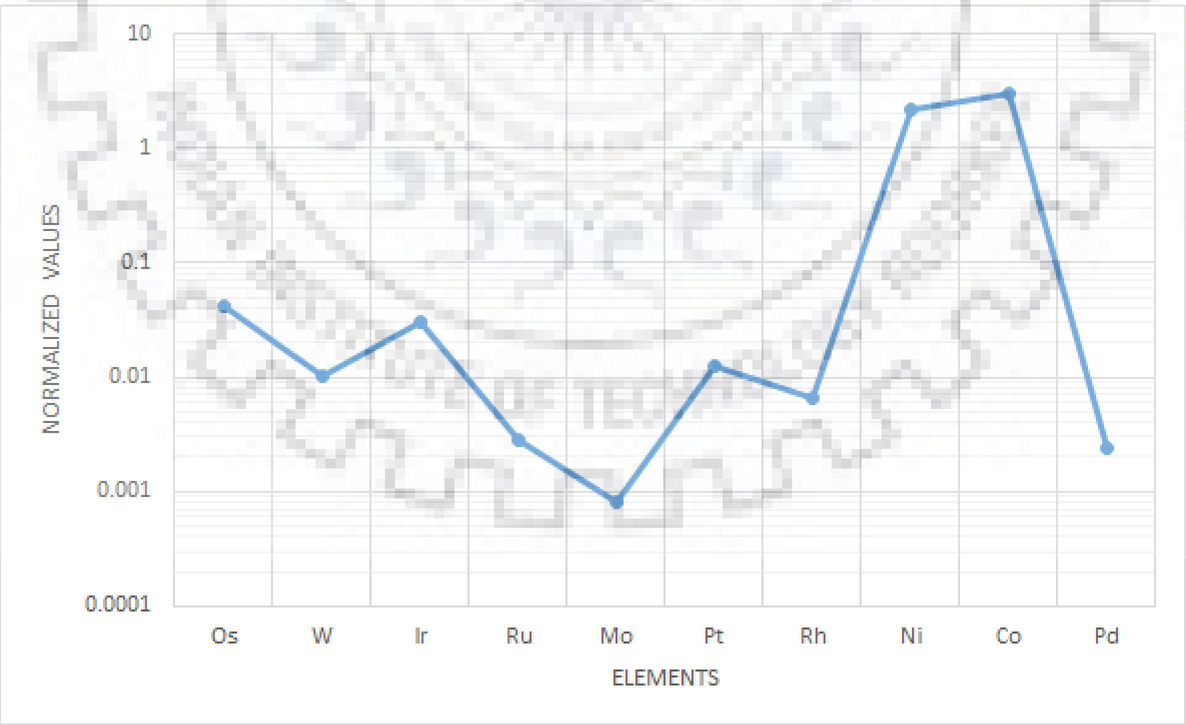


Figure 41: elemental abundance of data set 2

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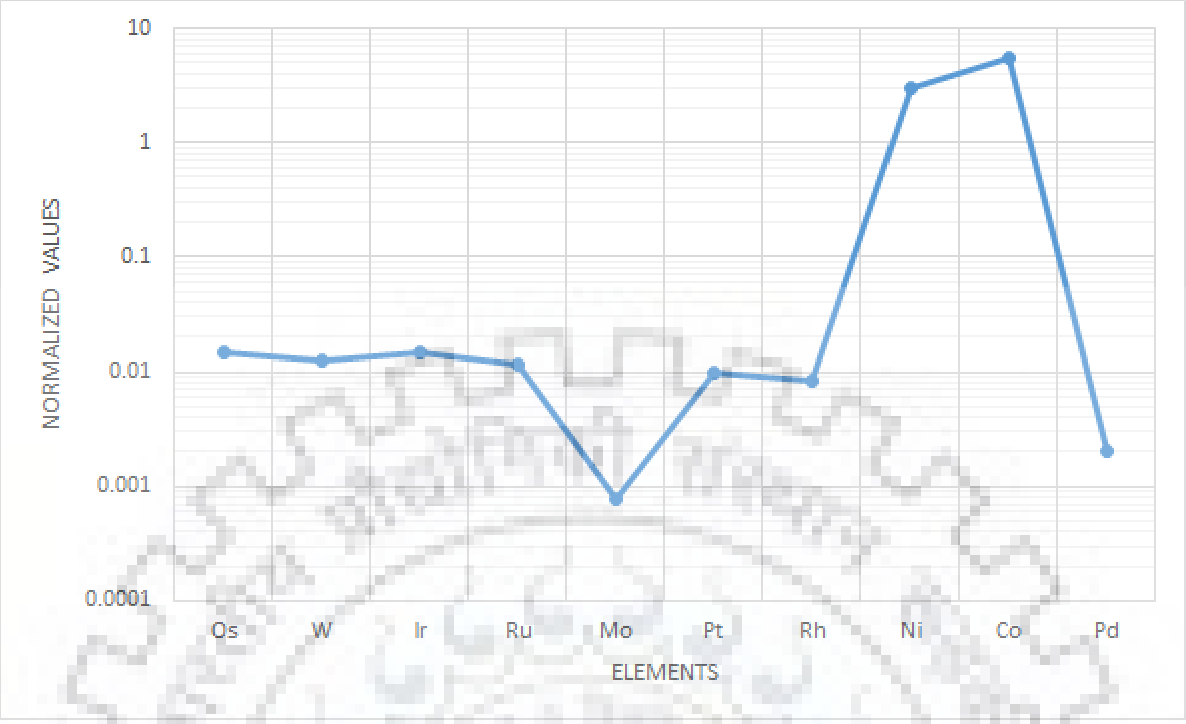

Figure 42: elemental abundance of data set 3

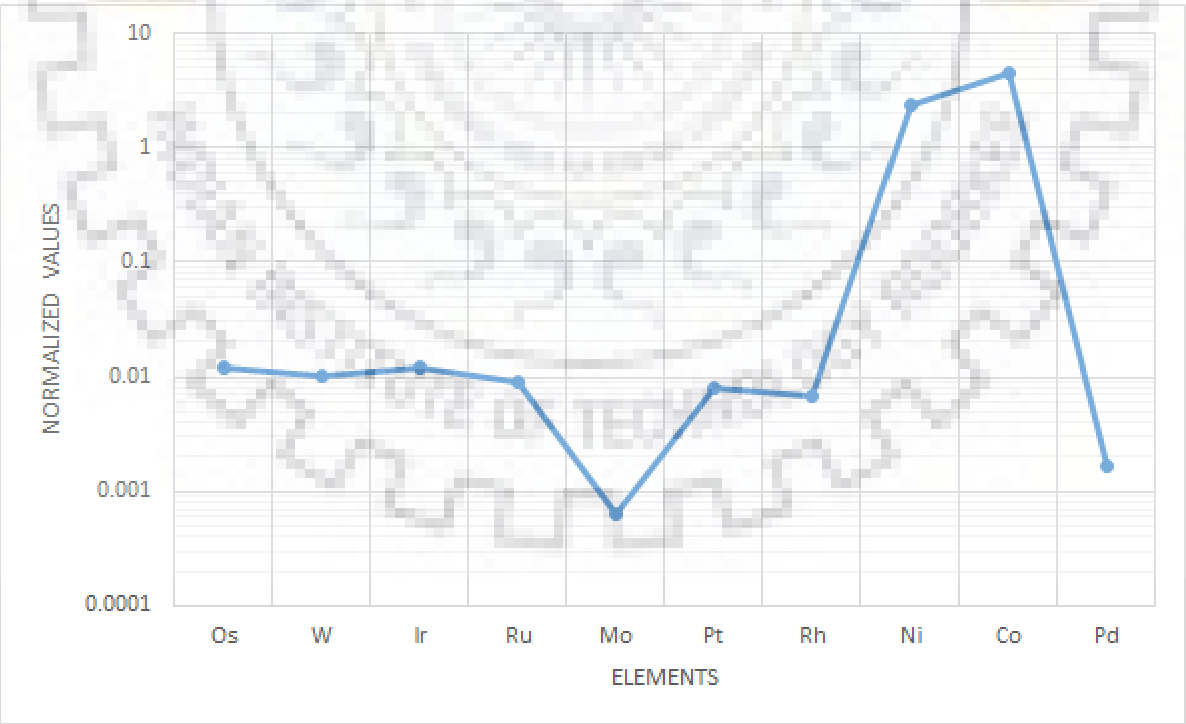

Figure 43: elemental abundance of data set 4

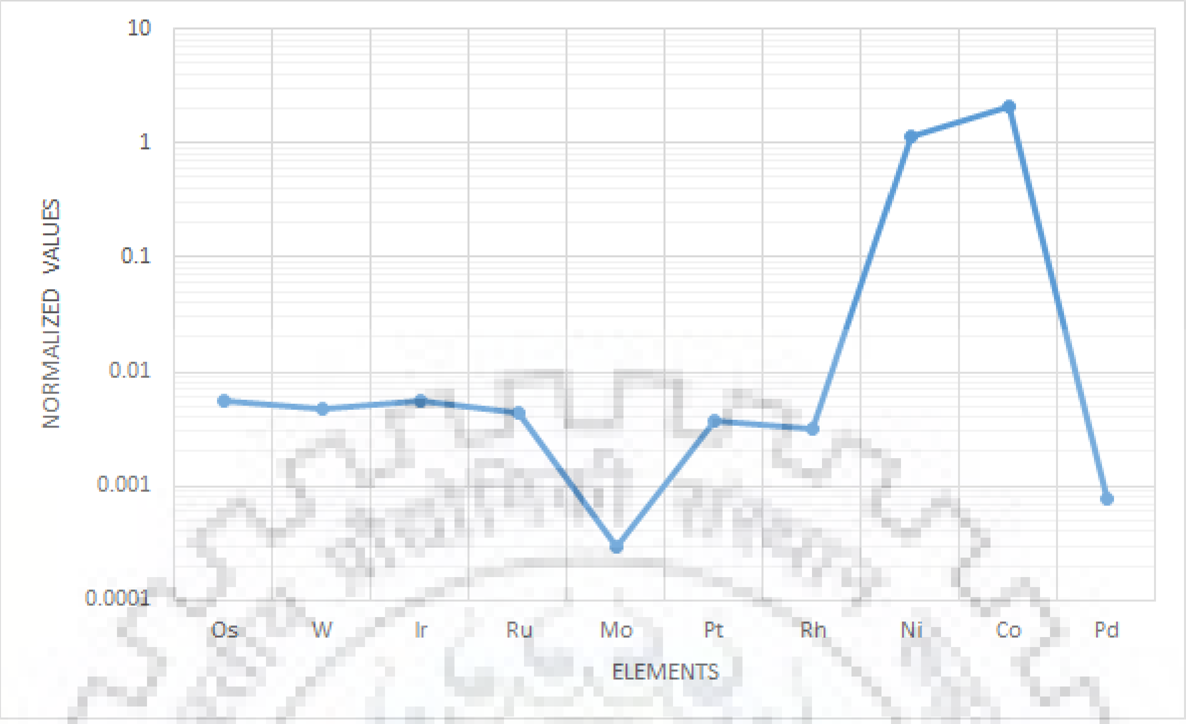

Figure 44: elemental abundance of data set 5

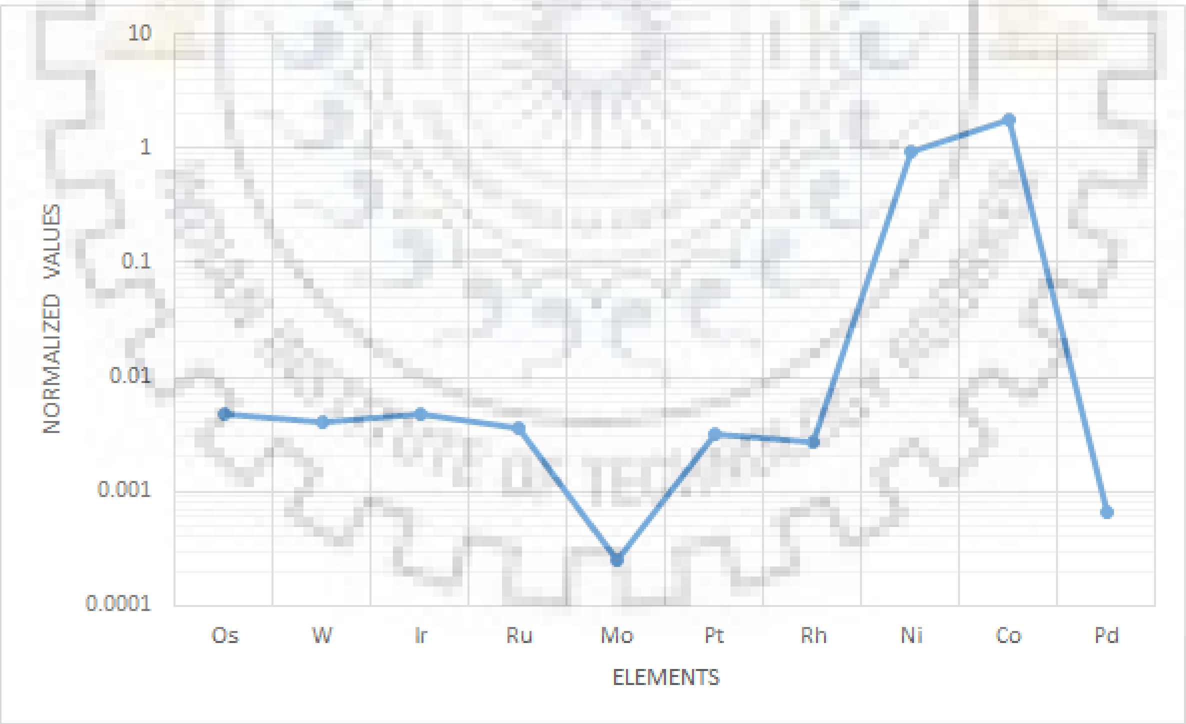

Figure 45: elemental abundance of data set 6

Graphs for abundance of chalcophile elements in Fe-Ni phase:

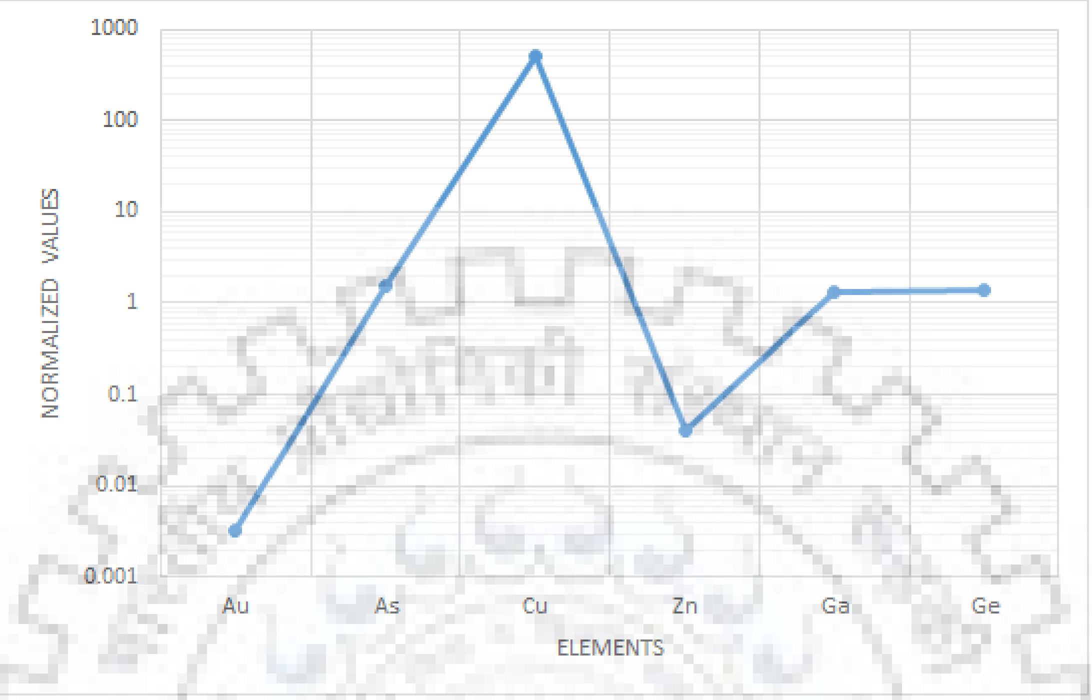

Figure 46: elemental abundance of data set 7

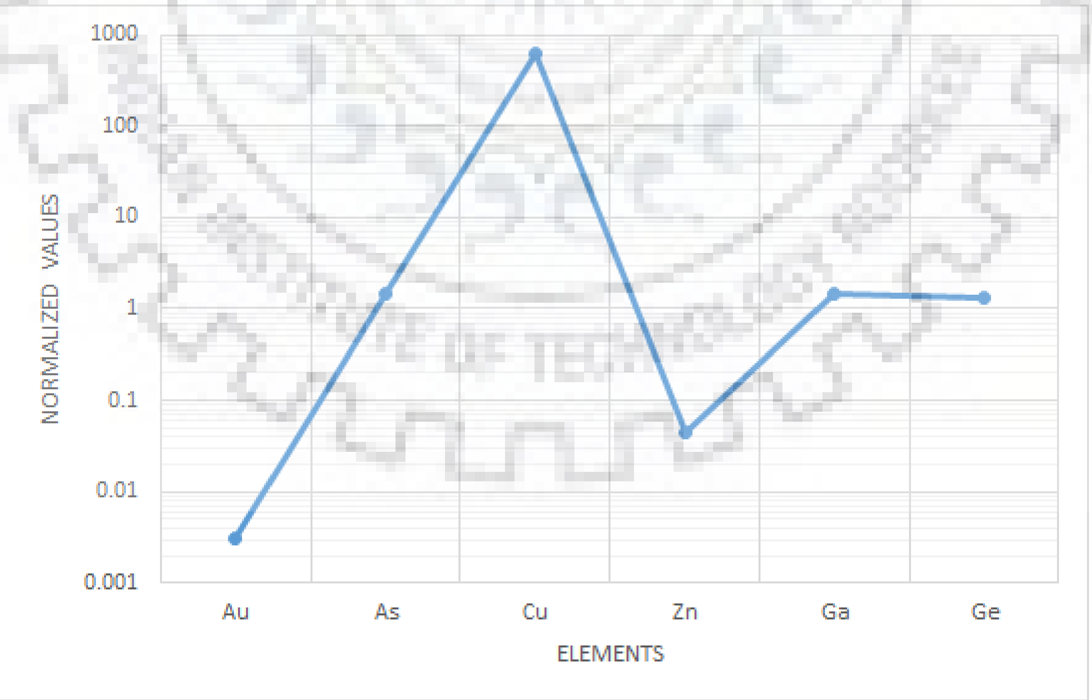

Figure 47: elemental abundance of data set 8

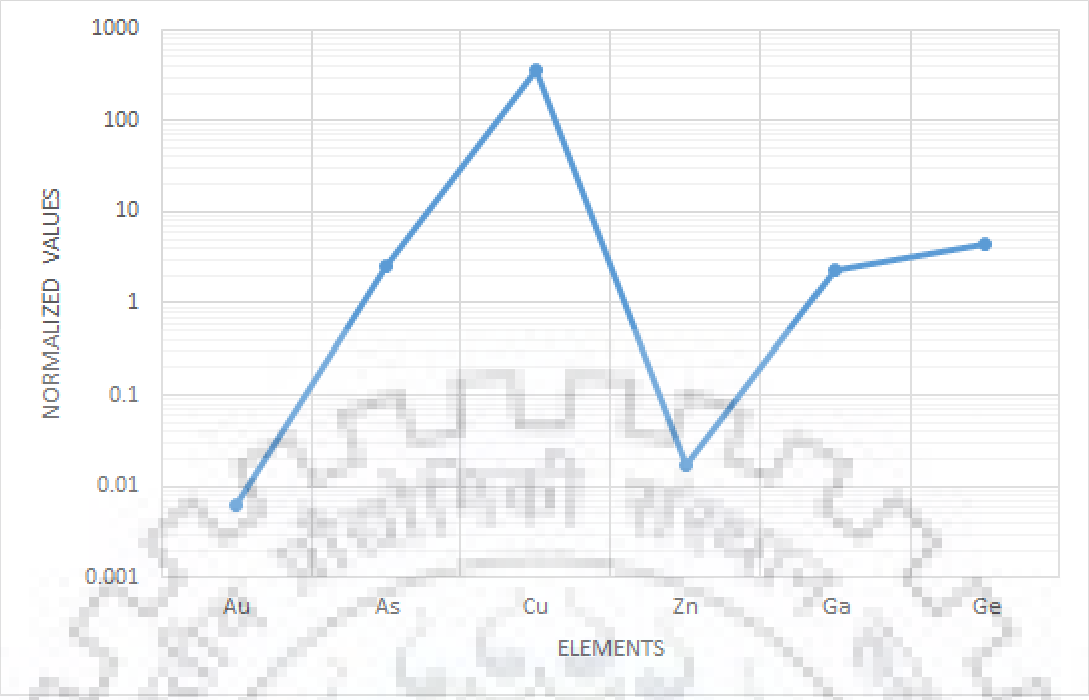

Figure 48: elemental abundance of data set 9

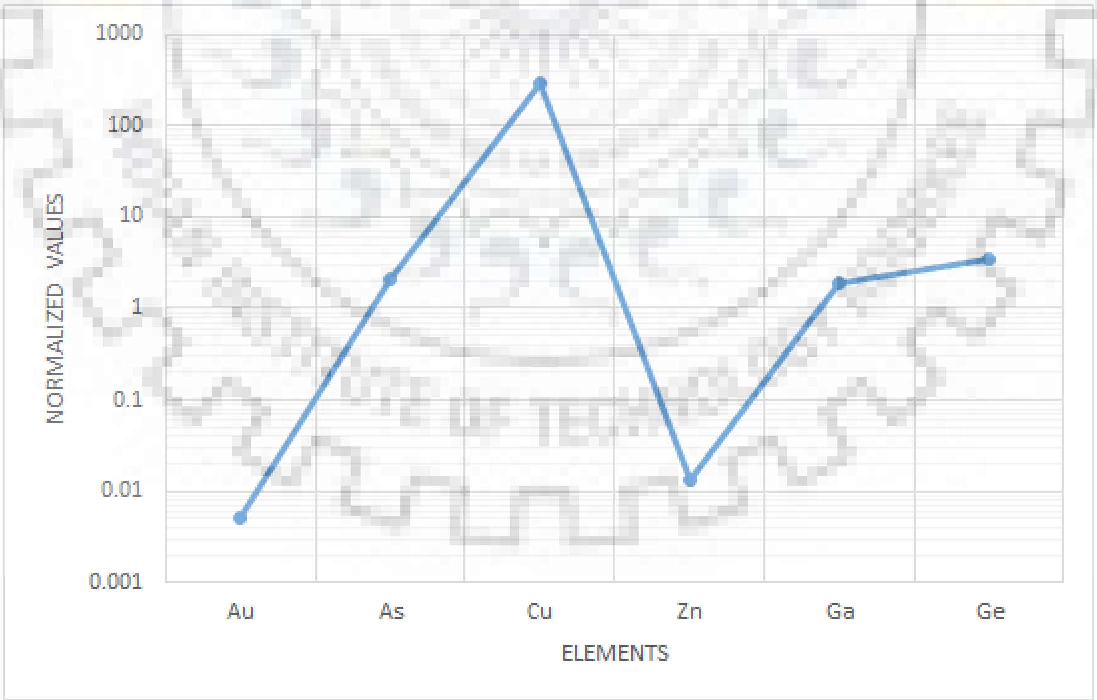

Figure 49: elemental abundance of data set 10

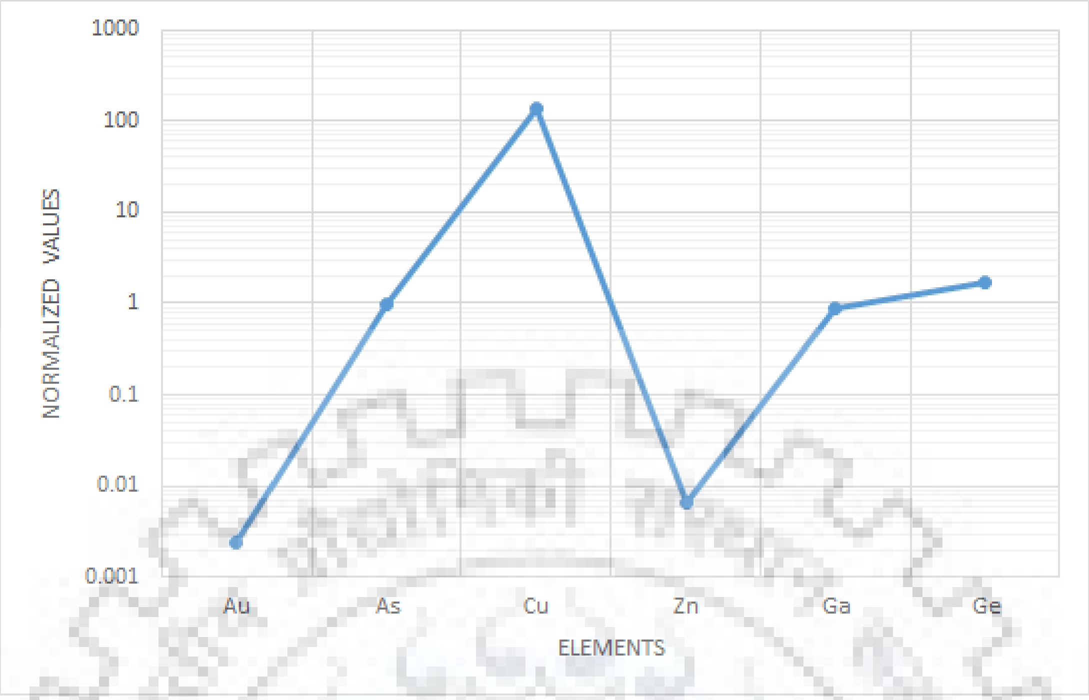

Figure 50: elemental abundance of data set 11

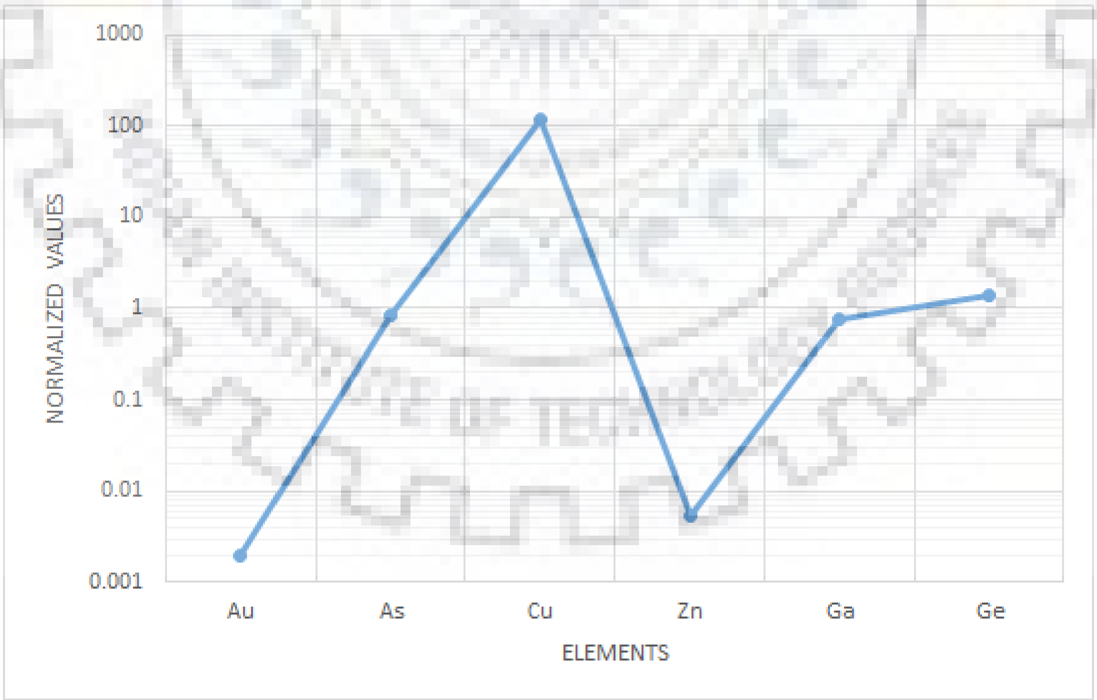

Figure 51: elemental abundance of data set 12

Combined graph for the different data sets above of siderophile and chalcophile element abundance in the Fe-Ni phase:

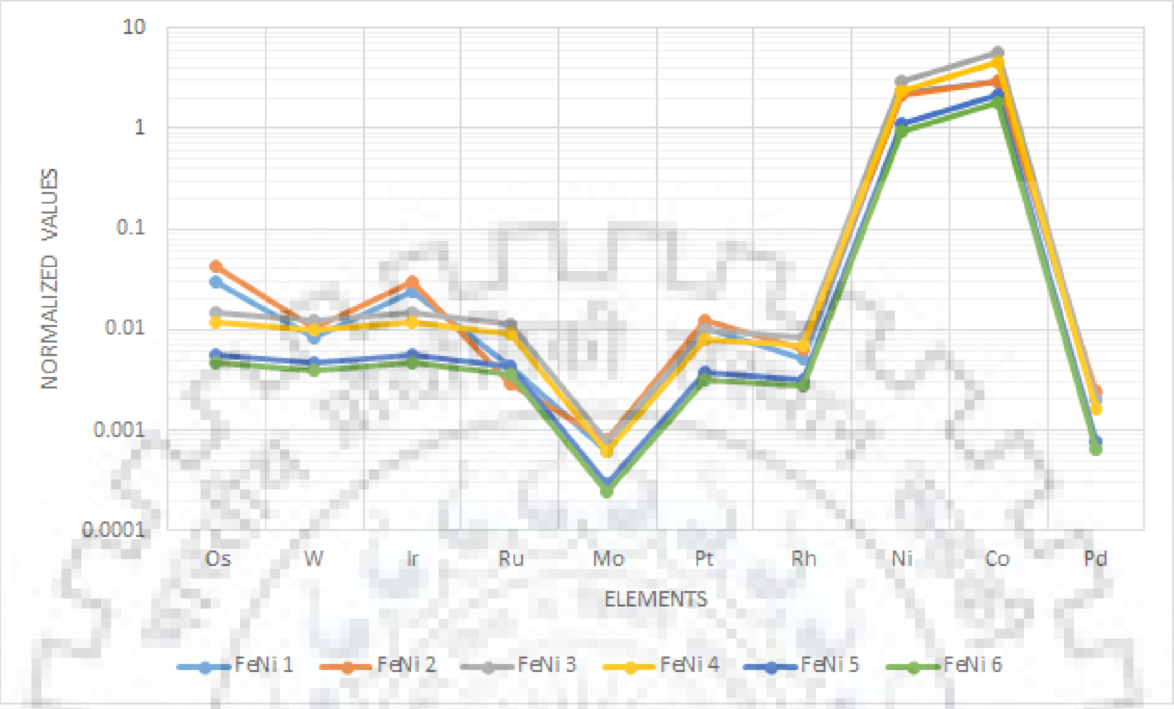

Figure 52: Graph for the elemental abundance of siderophile elements in the Fe-Ni phase

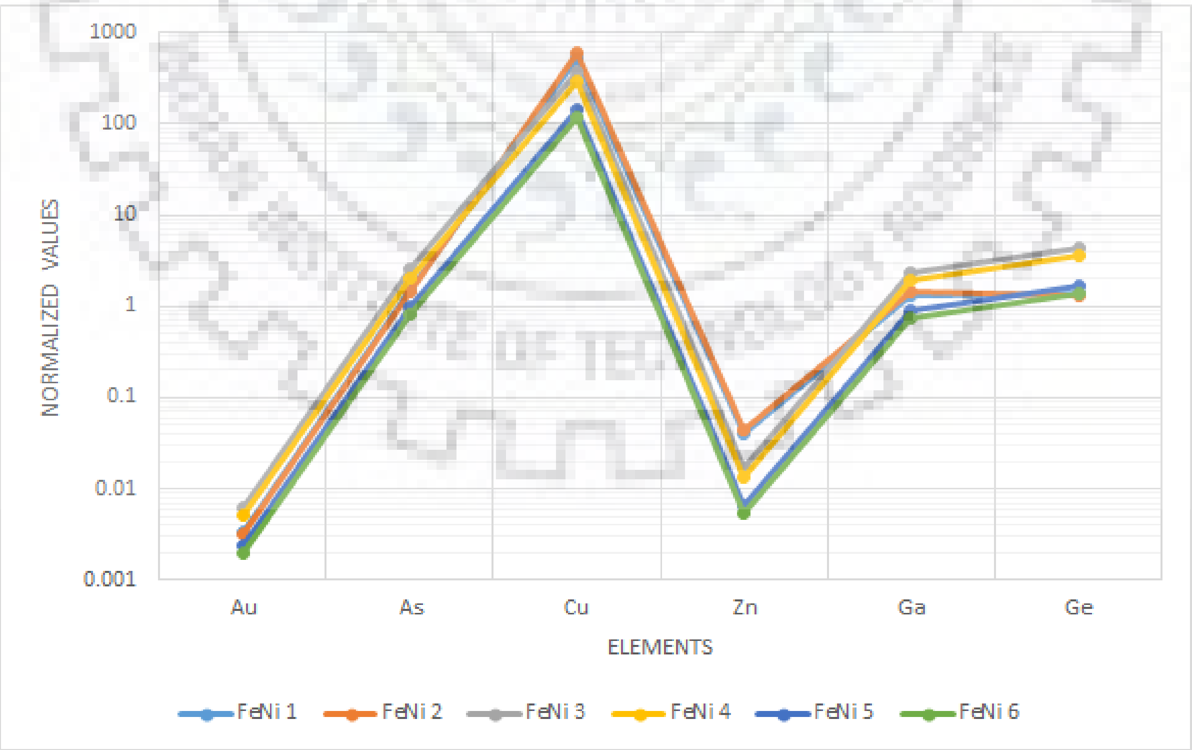

Figure 53: Graph for the elemental abundance of chalcophile elements in the Fe-Ni phase

Conclusion and Discussion

Trace element analysis of achondrite sample DaG 1000 (bulk samples, major phases such as olivine, Fe-Ni metal and Fe-sulphide phases) has been presented in this project. Refractory siderophile concentrations range from approximately 0.1 to 1.0 times CI chondrite values (McDonough and Sun, 1995) while the volatile siderophiles range from about 0.07 to 0.3 times CI chondrite values which clearly indicates the loss of a metal phase enriched in those elements as well as loss due to early volatilization processes. For the Fe-S and Fe-Ni phases the siderophile elements are considerably high when compared to olivine and bulk sample analyses for those elements. However, normalized concentrations of several siderophile elements are still sub-chondritic which may indicate that these metallic and sulphide phases represent a second generation of metallic melt in the parent body under high temperatures and reducing conditions. Rare earth elements (REEs) in bulk ureilites and olivines are quite depleted indicating a missing silicate melt phase enriched in REEs.

Table 2, 4 and 6 shows the EPMA analysis of the major phases olivine, Fe-Ni metal and Fe-sulphide respectively in sample DaG1000. In olivine Mg ranges between 25.05 ± 2.02 (wt%), Fe between 15.22 ± 3.16 (wt%), Si between 17.49 ± 1.05, O between 41.25 ± 1.42, other elements such as the Ca, Cr, Al etc. which are present in minor concentration.

The Fe-Ni metal phase mainly consist of iron and nickel, and the rest are present in minor concentration. Value of Fe ranges between 80.47 ± 1.23 (wt%), Ni ranges between 14.88 ± 0.77. And in Fe-S phase as well the major abundance is of the iron and sulphur with Fe ranging between 62.15 ± 0.86 (wt%), S between 36.81 ± 0.51 (wt%).

Table 3 shows the trace element abundances in olivine phase. These values were normalized by the method mentioned above and then the combined graphs (Figure 16 and 17) were plotted for the different data sets of siderophile and chalcophile element abundance in the olivine phase. When we study the graph of siderophile elements(Figure 16) we observe that there is in general depletion of these elements but we see a spike at Ru, Rh, Ni and Co with the abundance of Ni and Co on the higher side when compared to the other elements which might due to the moderately siderophilic nature of these elements.

Now, when we go through the graph (figure 17) of the chlacophile elements we find that the abundance of Cu and Zn (much less than Cu) is higher which might be due to the reason that they do not form volatile hydrites, while the elements Zn, Ga are somewhat lithophile in nature and form strong bonds with oxygen and occurs in silicates/metals. But since Ga is volatile in nature so it is depleted more as compared to Zn (moderately volatile). The graph also shows high depletion of Au.

Table 5 shows the trace element abundances in Fe-Ni metal phase. These values were normalized by the method mentioned above and then the combined graphs(Figure 52 and 53) were plotted for the different data sets of siderophile and chalcophile element abundance in the Fe-Ni phase.When we study the graph(Figure 52) of siderophile elements it shows a much higher concentration of these elements when compared to olivine since it’s a metallic phase while there is a spike in the abundance of Ni and Co which is expected as we study the Fe-Ni phase and its normalized value is greater than 1 so its abundance is more relative to CI chondrites. We observe that there is a depletion of Mo as compared to other elements.

Now, when we go through the graph(figure 53) of the chlacophile elements we find that the abundance of Cu is much higher since it is one of the most metallic chalcophile elements and readily combines to form Sulfides while there is depletion of Zn, Ga, Ge because of their volatile nature.

Table 7 shows the trace element abundances in Fe-S phase. These values were normalized by the method mentioned above and then the combined graphs (Figure 38 and 39) were plotted for the different data sets of siderophile and chalcophile element abundance in the Fe-S phase. The abundance of the siderophile elements(Figure 38) in this phase is higher compared to olivine phase but lower than the Fe-Ni phase as well their normalized value is less than 1 so they are depleted when compared to CI chondrites abundance.

Now the abundance of Cu in this phase is much higher when compared to the other phases because of the higher concentration of sulphur and great affinity of Cu for sulphur to form sulphides.

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