The Behavior of Niobium During Core Formation

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Abstract

During the formation of the Earth, the planet accreted chondritic proportions of refractory elements, including niobium (Nb), lanthanum (La) and tantalum (Ta), and it is therefore concluded the bulk Earth has chondritic ratios of La/Nb and Nb/Ta. Based on previous studies, only sub-chondritic abundances of Nb have been found within the silicate Earth (crust plus mantle), thus there is an undiscovered Nb-rich reservoir. I propose Nb exists in the Earth's core due to its siderophilic or chalcophilic tendency during core formation. In order to test this hypothesis, I will analyze iron meteorites (analog samples of the cores of asteroids) using a laser ablation ICP-MS. This study will focus on the analyses of metal phase and sulfides from Canyon Diablo, Nedagolla, and Hoba to determine if these iron meteorites do indeed have abundances of Nb within them.

Table of Contents

Introduction

In the beginning, there was a cloud of dust and gas a few light years in diameter. The cloud collapsed possibly due to a shockwave from an exploding nearby star impacting the cloud. As the cloud collapsed, the temperature increased due to conservation of energy[1]. The collapsed cloud of swirling hot gas and dust is known as the solar nebula with a protosun at its center. The protosun became so hot that fusion started in its core and became a G2 V star (G2 is the spectral type- our Sun is yellow and V is the luminosity class- our Sun is a main sequence star with a luminosity of 1)[1]. As the solar nebula shrank, it rotated faster and faster due to the conservation of angular momentum. This rotation kept all the material in the solar nebula from collapsing in on the Sun. Then the solar nebula flattened into what is known as the protoplanetary disk[1]. Because of static electricity, the hot dust began to accrete together to first form chondrities, the oldest, undifferentiated meteorites in the solar system[2]. Some chondrities went on to form planetesimals (small, rocky bodies that have differentiated into a crust and core) approximately 10 million years after their formation[3] (if they were hot enough), but could not form into a planet (ex: an asteroid: a small, rocky planetesimal or a broken part of a planetesimal found primarily in between the orbits of Mars and Jupiter and at the Lagrange points in Jupiter's orbit.)[1]. Then some planetesimals went on to form protoplanets. As gas was removed from the solar system due to the Sun's solar winds[1], some of the nine planets we see today, which formed from protoplanets, were able to capture some of the gas and thus created atmospheres. The Earth's gravity was strong enough to capture the gas to form an atmosphere[1]. The Earth then differentiated into the inner core, outer core, mantle and crust > 50 million years after Earth's formation[3]. According to McDonough (2000), the core formed < 30 Ma after Earth's formation based on tungsten (W) isotopes.

Earth's Reservoirs[4]

Reservoir	Radius (km)	Mass (kg)	Volume (cu.km)
Inner Core	2886.79 ± 10	9.675E+24	7.606E+09
Outer Core	2888.01 ± 5	1.835E+24	1.694E+11
Crust and Mantle	6371.01 ± 0.02	4.043E+24	9.138E+11

All chondrities are stony meteorites coming from the crust or crust-mantle boundary of planetesimals. Stony meteorites can be broken up into 3 categories: chondrities, carbonaceous chondrities, and achondrities. Chondrities contain chondrules (rounded bits of glassy rock) and silicates. Most chondrities are depleted in volatile elements (elements that condense out at temperatures usually < 600K) due to heating. This depletion in volatiles suggests chondrities come from the crust of large planetesimals. Chondrities make up approximately 82% of falls, meteorites that were not witnessed falling to Earth and were thus found some time later. On the other hand, carbonaceous chondrities contain chondrules, silicates, and volatile compounds. Carbonaceous chondrities are the most primitive form of meteorites with an age of 4.56 Ga. Since they were still able to retain their volatiles, carbonaceous chondrities most likely come from the crust of smaller and cooler planetesimals. Carbonaceous chondrities make up approximately 4% of falls. On the other hand, achondrities have no chondrules or volatile compounds due to excessive heating which melted the chondrules. Excessive heating suggests achondrities come from the crust-mantle boundary of large planetesimals. Achondrities make up 8% of falls.

When the Earth formed 4.56 billion years ago, it is assumed to have accreted chondritic proportions of refractory elements (elements that condense out at temperatures $\geq$ 1250K) since chondrities are the building blocks of planets. Victor Moritz Goldschmidt, "Father of Geochemistry", broke the refractory elements into 3 sub-categories: lithophile, chalcophile and siderophile. Lithophile elements bind with oxygen and are found almost exclusively in the silicate Earth (crust plus mantle), some scientists predict some lighter lithophile elements such as oxygen (O) and silicon (Si) might be in the core since the core has a lower density than predicted. Chalcophile elements bind with sulfur and are found in the core as well as the silicate Earth. Siderophile elements bind with iron and are found exclusively in the core[4]. All refractory elements exist in the same relative proportions in chondrities. It is commonly assumed the Earth's chondritic complement of Nb is found in the silicate Earth because Nb is typically considered to be a refractory lithophile element. However Wade and Wood (2001) and Humayun and Campbell (2003) have questioned whether or not Earth's Nb budget is explicitly in chondritic proportions in the silicate Earth. It is understood that lanthanum (La), a lithophile refractory element, is exclusively contained in the silicate Earth and is excluded from the core[5]. It has been tested, by doing analyses on numerous samples of the upper continental crust as well as mid-ocean ridge basalts and ocean island basalts, that the ratio of Nb/La is not in chondritic proportion within the silicate Earth[6]. Therefore, there must be an undiscovered Nb-rich reservoir within the Earth.

There are two reservoirs that may contain significant Nb:

1. Rutile-bearing refractory eclogites (metamorphic rocks containing pyroxenes and garnets) within the silicate Earth.
2. The core, where it may occur as either a siderophile element or as a chalcophile element.

Rudnick et al. (2000) examined the concentrations of Nb and tantalum (Ta) in rutile-bearing refractory eclogites formed by high-pressure metamorphism of subducted oceanic crust. Although rutile (TiO_2) is only found in the eclogites as an accessory phase, it dominates the Nb and Ta budget. They calculated the modal portion of rutile within eclogites from their bulk rock titanium (Ti) contents and discovered eclogites possess a superchondritic Nb/La ratio in all but 5 of the reconstructed eclogites. These findings support the idea that within the silicate Earth there is a Nb-rich eclogitic reservoir that can account for the Earth's chondritic Nb/La value. In contrast, Wade and Wood (2001) identified two concerns with this hypothesis: 1. In order to achieve mass balance, the eclogites must make up 6% of the mantle and 2. In ocean-island basalts (high-μ (HIMU) basalts), which contain subducted oceanic crust in their source regions, do not produce the superchondritic Nb/Ta ratio.

However, Wade and Wood (2001) performed liquid iron/ liquid silicate experiments at low (2.5 GPa) and high (25 GPa) pressures and low (1750C) and high

(2300C) temperatures under reduced conditions (i.e. at the IW buffer and below). At these conditions, the metal, in order to study the siderophile behavior of the silicon, contained between 0.07 and 16.4 weight percent silicon (Si), was placed in a magnesium oxide (MgO) capsules. Some capsules were placed in a piston-cylinder apparatus at the low pressure and low temperature end of the spectrum for 30 minutes. Other capsules were places in a multi-anvil apparatus at the high pressure and high temperature end of the spectrum for 90 seconds. These experiments demonstrated that Nb is partitioned into the metal phase relative to the co-existing silicate liquid and thus a portion of the Earth's Nb along with vanadium (V) and chromium (Cr) budget was sequestered into the core as a weakly siderophile element and predict abundances of 15-50 ppb in iron meteorites[5].

In a third and separate study, Humayun and Campbell (2002) conducted experiments on phases in iron meteorites (chunks of rock coming from the cores and surfaces of differentiated asteroids) by using a JEOL JSM5800LV Scanning Electron Microscope and a laser ablation ICP-MS system. Spot sizes from 50-100 microns size spot was used on a polished slab of iron meteorites to get a stable ion signal. Significant concentrations of Nb (count rates of 8000 cps) in troilites from IAB iron meteorites. They also discovered that Nb was not in the metal phase, but was instead hosted in coexisting sulfides along with V and Cr, thus showing that Nb in this system behaved as a chalcophile element[7].

Method of Analysis

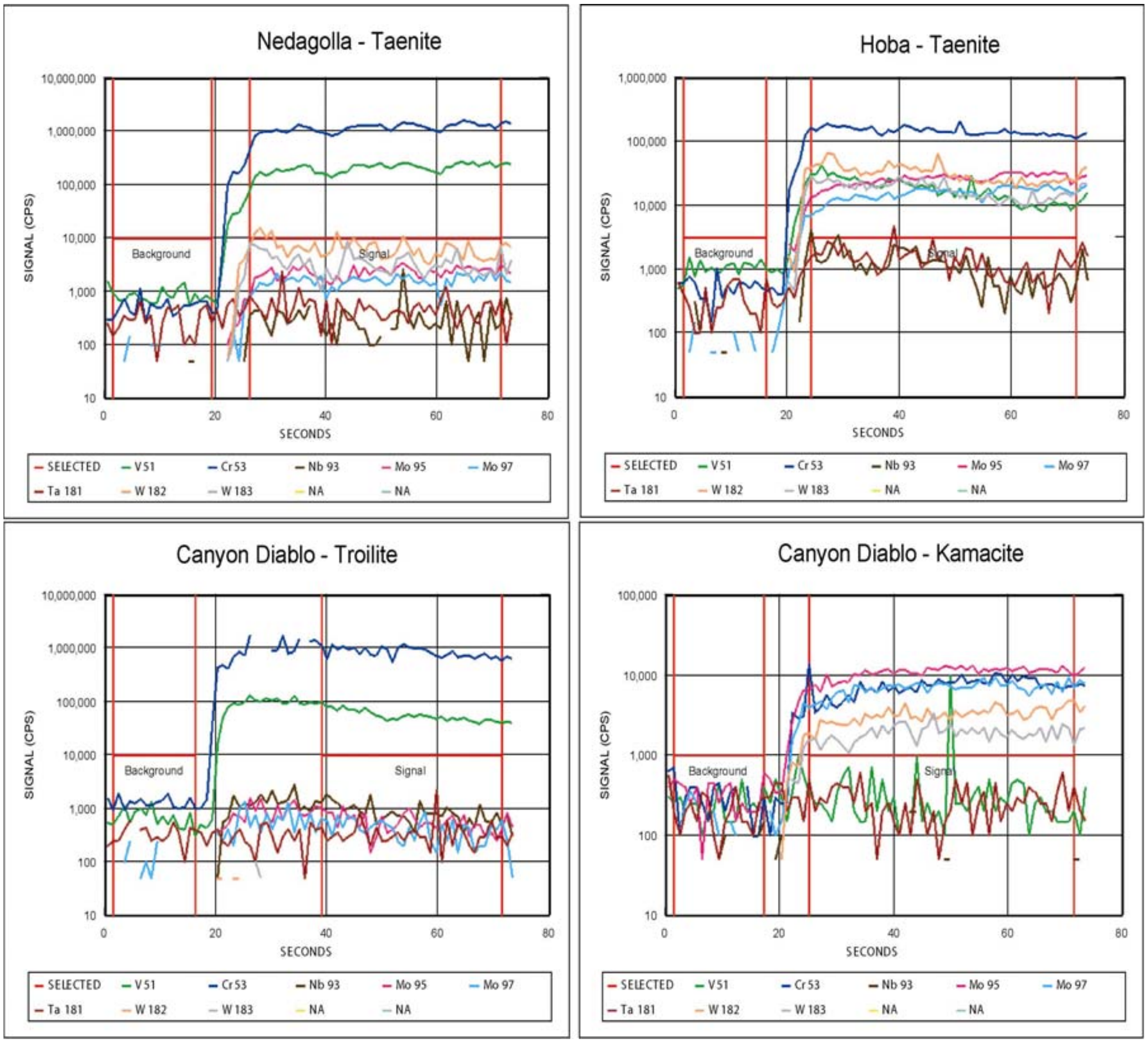
A laser ablation ICP-MS (Element 2) spot analysis was conducted on iron meteorites (differentiated meteorites) to their Nb, V, Cr, and other elements contents. These data were used to test the hypothesis of whether or not Nb exists in the core as a siderophile or chalcophile. The iron meteorites chosen for analysis are Hoba, Nedagolla, and Canyon Diablo. Hoba, of the IVB chemical group[8], is a magmatic iron meteorite, from a planetesimal core. Hoba is part of the ataxite structural class because it has greater than 12% Ni and is made almost entirely of taenite[9]. Hoba is the largest meteorite ever found and thus must have entered the Earth at a shallow angle in order to stay very well intact. Canyon Diablo, of the IAB chemical group[8], is a non-magmatic[10] iron meteorite, from the surface of a planetesimal probably due to an impactor hitting the surface causing melting and eventually recrystallization. Canyon Diablo is part of the coarse to medium octahedrite structural class because it has 6% to 12% Ni, made up primarily of taenite and kamacite, and has the Widmanstatten pattern[9]. Even though Canyon Diablo is a non-magmatic meteorite, when the impactor hit the surface of the planetessimal, elements were sequestered into the metal or sulfide phases depending on their behaviors. Nedagolla, probably of the IVB chemical group (although often listed as ungrouped[11]), is most likely a magmatic iron meteorite. Nedagolla also is part of the ataxite structural class. Thus 2 of the 3 meteorites represent specimens from the cores of differentiated planetesimals, whereas Canyon Diablo is likely to have come from a partially differentiated asteroid interrupted as it began to for a iron core and silicate-rich crust. These samples were selected to present us with a broad range of metal-forming conditions in order to evaluate the greater potential of P-T-X-fO_2 conditions under which Nb behaves either a siderophile or chalcophile element.

Asteroids are rocky planetary bodies ranging between < 1 km to approximately 1,000 km in diameter (e.g. Ceres). Even though asteroids are far smaller than the Earth and have lower equilibration pressures for core formation than the Earth's, the fact both planetary bodies experienced equilibration, they can therefore be compared to one another. Due to the uncertain pressures in the cores of asteroids, the Earth's Moon, with a core pressure of 11GPa, will be the upper limit since if all the asteroids in the solar system were coalesced together they would be roughly half the size of Earth's Moon. On the other hand, both asteroids and Earth experienced similar high temperatures to cause liquid iron differentiation. Some time later after formation, those asteroids were torn asunder, breaking up the core and sending those iron meteorites crashing to the Earth's surface[1]. Since a differentiated asteroid is essentially a miniature planet, it would be expected to find those same elevated abundances of refractory elements within Earth's core.

A laser ablation inductively coupled plasma mass spectrometer (LA-ICP-MS) spot analysis was conducted on the 3 meteorites as well as 4 standards. The LA-ICP-MS uses high temperature (6000-7000K) plasma discharge to create positively charged ions. That is achieved by laser ablating the samples into a powder form, which is then injected into the base of the plasma. As the powder is injected into the base of the plasma, it is heated and turned into a gas that is atomized and ionized, removal of an electron causing a positive charge. When the sample finally gets to the base of the plasma, it is in the form of excited atoms and ions representing the elemental constituents of the sample. If enough of these ions generated, it can be detected by the ICP-MS (Element 2)[12]. For the purposes finding Nb, V, Cr, and other elements contents in the iron meteorites, two spot analyses on Nedagolla, two spot analyses on Hoba, 4 spot analyses on Canyon Diablo troilites (sulfides), and 4 spot analysis on Canyon Diablo metals. The silicate glass standard, NIST 610, was also analyzed (4 spots). Each ablation analyses consisted of a 15 second cycle, during which a background spectrum was accumulated, followed by a 1 minute cycle of laser ablation. Before each new meteorite was ablated, 5 minutes were allowed to flush the machine with helium (He) gas (flowing through the $3cm^3$ cell at 1L/min) in order to avoid contamination from the previous sample that was ablated. For each meteorite and standard, the concentrations of ^{51}V, ^{53}Cr, ^{93}Nb, ^{95}Mo, ^{97}Mo, ^{181}Ta, ^{182}W, and ^{183}W were determined. Each spot was ablated for 45 seconds and the results were then imputed into the computer. The size of the spot varied between 40-100 microns, the percent varied between 52-95%, and the power of the laser varied between 8-20 hertz. After all the samples were analyzed, the results were saved and printed. Tungsten was used at the internal standard when processing the data with LAMTRACE (Longerich et al 1996).

Presentation of Data and Analysis of Uncertainty

Meteorite Graphs



Concentration of Various Elements in the Meteorites

	Nedagolla 100um, 70%, 10Hz	Nedagolla 100um, 70%, 10Hz	Hoba 100um, 70%, 10Hz	Hoba 100um, 70%, 10Hz
V	19	29	2.9	2.2
Cr	1028	1746	254	214
Nb	0.067	0.032	0.143	0.128
Mo	1.5	1.5	20	20
Mo	1.2	1.7	20	20
Ta	0.098	0.014	0.088	0.063
W	2.5	1.9	11	9
W	2.8	1.9	11	8
	Canyon Diablo Troilite, 65um, 65%, 10Hz	Canyon Diablo Troilite, 55um, 55%, 10Hz	Canyon Diablo Troilite, 40um, 55%, 8Hz	Canyon Diablo Troilite, 40um, 52%, 8Hz
V	47	73	49	41
Cr	b.d.	7500	7500	7500
Nb	0.62	0.81	0.53	0.42
Mo	2.0	3.6	2.3	1.8
Mo	1.95	3.0	2.5	2.0
Ta	b.d.	0.002	0.023	0.017
W	1.43	b.d.	b.d.	b.d.
W	0.83	b.d.	b.d.	b.d.
	Canyon Diablo, 100um, 70%, 10Hz	Canyon Diablo, 100um, 90%, 20Hz	Canyon Diablo, 100um, 95%, 20Hz	Canyon Diablo, 100um, 95%, 20Hz
V	b.d.	b.d.	b.d.	b.d.
Cr	7.2	9.2	5.7	7.4
Nb	b.d.	b.d.	b.d.	b.d.
Mo	6.3	6.3	6.3	6.3
Mo	6.6	6.6	5.8	6.6
Ta	b.d.	b.d.	b.d.	b.d.
W	1.6	0.86	1.4	1.1
W	1.5	0.89	1.4	1.2

Concentrations in ppm, Concentrations in boxes are assumed normalized concentrations

There are 2 uncertainties in the experiment: 1) counting statistics and 2) concentration of Niobium. The uncertainty in the counting statistics can be determined by taking 1/(square root of the # of counts).

Count Uncertainty

Meteorite	Counts/sec	Uncertainty
Nedagolla	1000	3.2%
Hoba	1000	3.2%
Canyon Diablo troilites	700	3.8%
Canyon Diablo troilites	1000	3.2%
Canyon Diablo troilites	2000	2.2%
Canyon Diablo troilites	14000	0.8%
Canyon Diablo metal	Below detection	N/A
Standards	1000	3.2%

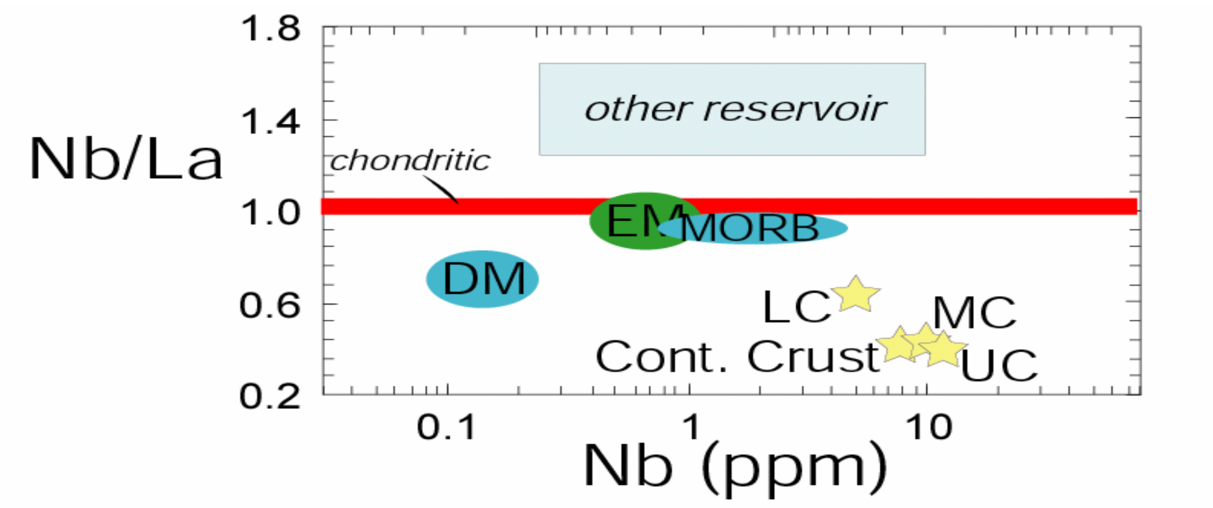
The uncertainty in Nb concentrations as measured by LA-ICP-MS has been determined by first finding the mean of the concentration of elements from the different trials. Then by subtracting the concentration mean of the trials by each of the concentrations of elements in each trial. Finally, by using the equation for standard deviation (s = square root ((trial concentration-mean concentration)^(2)/(# of trials-1))). This is assuming the meteorites are homogeneous samples.

Nb concentration Uncertainty

Trial	XNb (ppm)	Mean XNb	XNb-Mean XNb	(XNb-Mean XNb)^2	Uncertainty
Nedagolla 1	0.067	0.050	0.017	0.00029	0.02%
Nedagolla 2	0.032		-0.018	0.00032	
Hoba 1	0.143	0.136	0.0070	0.000049	0.01%
Hoba 2	0.128		-0.0080	0.000064	
Canyon Diablo troilite 1	0.62	0.60	0.02	0.00040	0.16%
Canyon Diablo troilite 2	0.81		0.21	0.044	
Canyon Diablo troilite 3	0.53		-0.070	0.0049	
Canyon Diablo troilite 4	0.42		-0.18	0.032	

Therefore the uncertainty in the measurements of the Nb concentration for Nedagolla is 0.050±0.02%, for Hoba is 0.136±0.01%, and for Canyon Diablo is 0.60±0.16%.

Also, I have created a model for the eclogitic reservoir by solving for the following equation:



$$\left(\frac{Nb}{La}\right)_{Earth} = \frac{(M_{CC} * \chi_{CC}^{Nb}) + (M_{DM} * \chi_{DM}^{Nb}) + (M_{other} * \chi_{other}^{Nb})}{(M_{CC} * \chi_{CC}^{La}) + (M_{DM} * \chi_{DM}^{La}) + (M_{other} * \chi_{other}^{La})}$$

M_j = Mass of reservoir j, χ_j^i = concentration of i in reservoir j

By solving for the equation, there were several uncertainties addressed:

1. the mass percentage of the depleted mantle
2. the mass percentage of the undepleted mantle
3. the mass percentage of the "other" reservoir
4. the constraints that Al2O3 percent is >10% and < 20%
5. the concentration of La needs to be < 5 ppm in the eclogite reservoir.

With these uncertainties taken into consideration, Nb and Ta concentrations were calculated for another reservoir (ex: eclogites) in the silicate Earth.

Discussion of Results

Nb concentration in the Meteorites

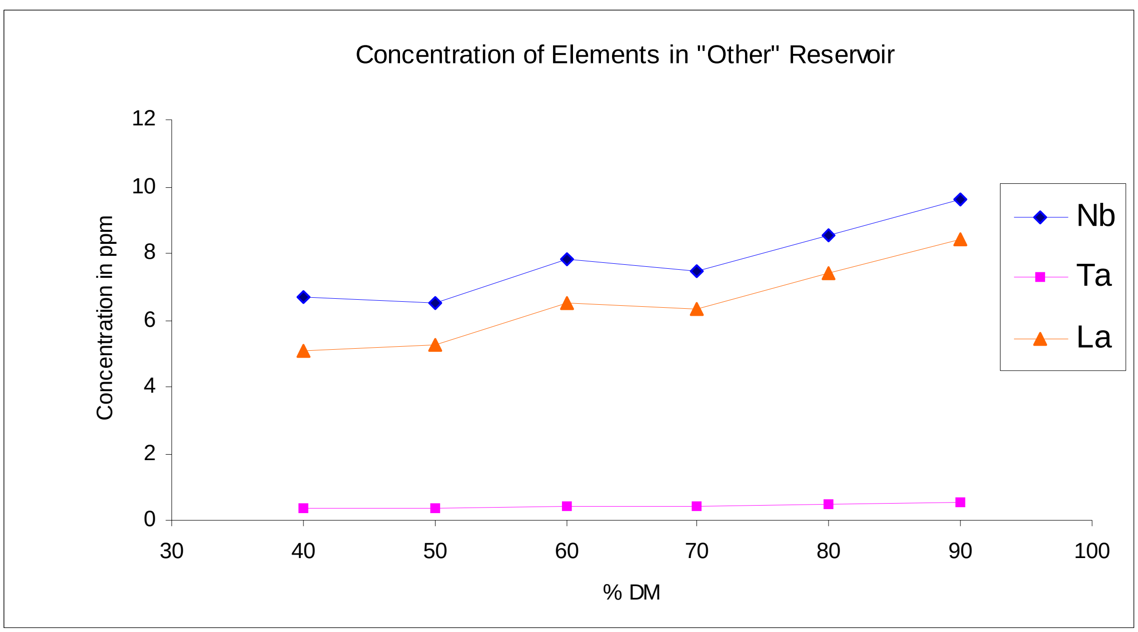
Meteorite	Nb concentration (ppm)
Nedagolla	0.067
Nedagolla	0.032
Hoba	0.143
Hoba	0.128
Canyon Diablo troilite	0.62
Canyon Diablo troilite	0.81
Canyon Diablo troilite	0.53
Canyon Diablo troilite	0.42

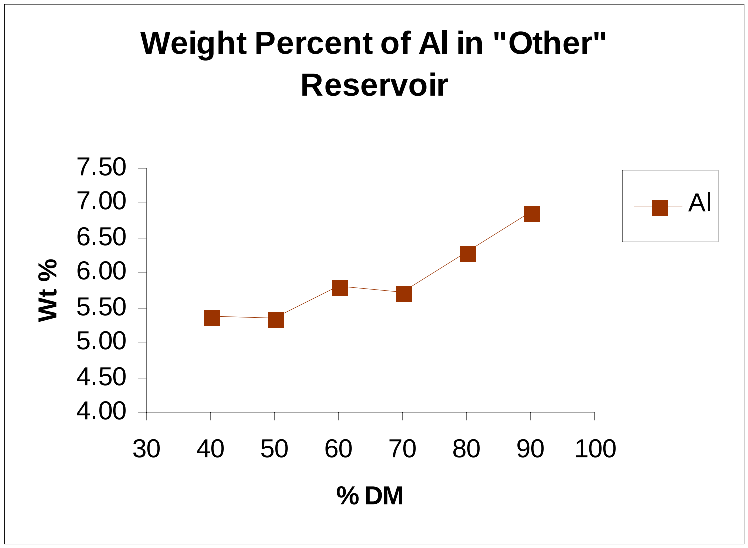
The results of the laser ablation measurements show that Nb is hosted in the Canyon Diablo troilites[13] (an iron sulfide ($Fe^{+2}S$) found as nodules of meteorites and in serpentinites and in layered ultramafic intrusives) and less so in taenites from Nedagolla and Hoba. Canyon Diablo troilites have an average Nb concentration of 0.60ppm (600ppb) while Nedagolla+Hoba have an average Nb concentration of 0.093ppm (93ppb). Since the metal phases of the other meteorites, including Canyon Diablo, did not yield significant amounts of Nb, it can be assumed that the high concentrations of Nb found is in the sulfide phase. According to McDonough (2003), the Earth's core has a sulfur content of approximately 3%. So, assuming 100% of Nb went into the sulfide phase, then approximately 4 ppb of Nb is actually in the core. For there to be chondritic proportions of Nb in the Earth, approximately 60 ppb should be found in the core. Therefore, though Nb does behave as chalcophile in the troilites, not enough of it is sequestered in those troilites to say that the Earth's core is a Nb-rich reservoir.

The fact that Nb behaves in a chalcophile manner is an interesting find. Especially since its "chemical twin" Ta does not have significant concentrations in the Canyon Diablo troilites (average Ta concentration = 0.011). However, both Ta and Nb have similar concentrations in the taenites of Nedagolla and Hoba (Hoba+Nedagolla, Nb average concentration=0.093ppm, Ta average concentration=0.066ppm) and have concentrations below detection in the Canyon Diablo metal. This indictates that though both behave in a lithophile manner, Nb has an unknown chemical tendency to be weakly chalcophile as well.

Concentrations of Elements in "Other" Reservoir

%DM	Nb (ppm)	La (ppm)	Ta (ppm)	Al (wt %)	% "other" reservoir
40	6.69	5.07	0.34	5.38	3.0
50	6.53	5.26	0.34	5.35	4.0
60	7.8	6.48	0.41	5.82	4.0
70	7.45	6.35	0.4	5.71	5.0
80	8.53	7.39	0.46	6.29	5.0
90	9.6	8.42	0.52	6.88	5.0





The results for the modeling of the "other" reservoir when figuring in that La must be < 5ppm, the only model that works is 40% mass DM with a 3.0% mass "other" reservoir. So, the amount expected to be in the 3.0% mass "other" reservoir is ~60ppb. This is what should also be found in the core if the core was a Nb-rich reservoir.

Suggestions for Future Work

One idea for future work should encapsulate using more magmatic iron meteorites to get a better sense of what the Earth's core is like as well as analyzing numerous samples from each meteorite. More LA-ICP-MS analyses as well as ICP-MS solution analyses of magmatic iron meteorites will help solidify the possibility that there are no significant Nb concentrations in the core and that the silicate Earth contains the "missing" Nb-rich reservoir.

Another idea for future work should investigate why Nb does behave as a weakly chalcophile element while its "chemical twin" Ta does not. By doing LA-ICP-MS of the sulfides in several different kinds of meteorites and the sulfides in continental crust rock samples, perhaps that will give a better scope on why Nb behaves as a weakly chalcophile element.

Conclusions

In conclusion, when the Earth formed, it is assumed the Earth started out with chondritic proportions of Nb. Several LA-ICP-MS analyses on iron meteorites were conducted to determine if there were significant amounts (~ 60ppb in the core) of Nb within them. The modeling done also suggests if the core is not the Nb-rich reservoir, then the "other" reservoir in the silicate Earth should have ~ 60ppb of Nb. The analyses determined Nb behaves as a weakly chalcophile element since high concentrations (an average of 600ppb) were found in the troilites (iron sulfides) of the Canyon Diablo meteorite. These results are similar to Humayun and Campbell (2002) who also observed that Nb also behaves as a weakly chalcophile element. The metal analyses of the Hoba and Nedagolla iron meteorites did not yield significant concentrations of Nb (an average of 93ppb). The metal analyses of the Canyon Diablo iron meteorite had concentrations below detection of Nb. However, the sulfide concentrations (~ 4ppb in the core) were not abundant enough to say the Earth's core is an Nb-rich reservoir. Therefore Nb is most likely in the silicate Earth as a lithophile in rutile-bearing refractory eclogites as Rudnick et. al. (2000) predicted or perhaps there is another Nb-rich reservoir in the silicate Earth that has yet to be discovered.

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Honor Pledge: “I pledge on my honor that I have not given or received any unauthorized assistant on this assignment.” – Chalbeth Reynolds

Model for "Other" Reservoir

40% Depleted Mantle

	BSE	CC	DM	undepleted	other	Sum	normalized to MORB	Al2O3 %
Nb (ppm)	0.658	8.6	0.12	0.658	18.8	0.658	8.1	
Ta (ppm)	0.037	0.7	0.007	0.037	1.0	0.037	7.2	
La (ppm)	0.648	18	0.13	0.648	13.9	0.648	5.6	
Al (wt %)	2.355	8.363	2.064	2.355	11.4	2.355	1.4	21.6
mass (kg)	4.04E+24	1.74E+22	1.62E+24	2.37E+24	4.04E+22			
La/Nb	0.98	2.09	1.08	0.98	0.74	0.98	Al2O3 = 10<x<20	
Nb/Ta	17.8	12.3	17.1	17.8	19.7	17.8	La < 5 ppm	
% mass	100%	0.43%	40%	59%	1.0%	100%		

	BSE	CC	DM	undepleted	other	Sum	normalized to MORB	Al2O3 %
Nb (ppm)	0.658	8.6	0.12	0.658	9.71	0.658	4.2	
Ta (ppm)	0.037	0.7	0.007	0.037	0.49	0.037	3.7	
La (ppm)	0.648	18	0.13	0.648	7.28	0.648	2.9	
Al (wt %)	2.355	8.363	2.064	2.355	6.89	2.355	0.9	13.0
mass (kg)	4.04E+24	1.74E+22	1.62E+24	2.33E+24	8.08E+22			
La/Nb	0.98	2.09	1.08	0.98	0.75	0.98		
Nb/Ta	17.8	12.3	17.1	17.8	19.6	17.8		
% mass	100%	0.43%	40%	58%	2.0%	100%		

	BSE	CC	DM	undepleted	other	Sum	normalized to MORB	Al2O3 %
Nb (ppm)	0.658	8.6	0.12	0.658	6.69	0.658	2.9	
Ta (ppm)	0.037	0.7	0.007	0.037	0.34	0.037	2.6	
La (ppm)	0.648	18	0.13	0.648	5.07	0.648	2.0	
Al (wt %)	2.355	8.363	2.064	2.355	5.38	2.355	0.7	10.2
mass (kg)	4.04E+24	1.74E+22	1.62E+24	2.29E+24	1.21E+23			
La/Nb	0.98	2.09	1.08	0.98	0.76	0.98		
Nb/Ta	17.8	12.3	17.1	17.8	19.6	17.8		
% mass	100%	0.43%	40%	57%	3.0%	100%		

	BSE	CC	DM	undepleted	other	Sum	normalized to MORB	Al2O3 %
Nb (ppm)	0.658	8.6	0.12	0.658	5.18	0.658	2.2	
Ta (ppm)	0.037	0.7	0.007	0.037	0.27	0.037	2.0	
La (ppm)	0.648	18	0.13	0.648	3.96	0.648	1.6	
Al (wt %)	2.355	8.363	2.064	2.355	4.62	2.355	0.6	8.7
mass (kg)	4.04E+24	1.74E+22	1.62E+24	2.25E+24	1.62E+23			
La/Nb	0.98	2.09	1.08	0.98	0.76	0.98		
Nb/Ta	17.8	12.3	17.1	17.8	19.5	17.8		
% mass	100%	0.43%	40%	56%	4.0%	100%		

	BSE	CC	DM	undepleted	other	Sum	normalized to MORB	Al2O3 %
Nb (ppm)	0.658	8.6	0.12	0.658	4.28	0.658	1.8	
Ta (ppm)	0.037	0.7	0.007	0.037	0.22	0.037	1.7	
La (ppm)	0.648	18	0.13	0.648	3.30	0.648	1.3	
Al (wt %)	2.355	8.363	2.064	2.355	4.17	2.355	0.5	7.9
mass (kg)	4.04E+24	1.74E+22	1.62E+24	2.20463E+24	2.02E+23			
La/Nb	0.98	2.09	1.08	0.98	0.77	0.98		
Nb/Ta	17.8	12.3	17.1	17.8	19.5	17.8		
% mass	100%	0.43%	40%	55%	5.0%	100%		

<u>50% Depleted Mantle</u>

	BSE	CC	DM	undepleted	other	Sum	normalized to MORB	Al2O3 %
Nb (ppm)	0.658	8.6	0.12	0.658	24.1	0.658	10.4	
Ta (ppm)	0.037	0.7	0.007	0.037	1.3	0.037	9.5	
La (ppm)	0.648	18	0.13	0.648	19.1	0.648	7.6	
Al (wt %)	2.355	8.363	2.064	2.355	14.3	2.355	1.8	27.1
mass (kg)	4.04E+24	1.74E+22	2.02E+24	1.96E+24	4.04E+22			
La/Nb	0.98	2.09	1.08	0.98	0.79	0.98	Al2O3 = 10<x<20	
Nb/Ta	17.8	12.3	17.1	17.8	19.3	17.8	La < 5 ppm	
% mass	100%	0.43%	50%	49%	1.0%	100%		

	BSE	CC	DM	undepleted	other	Sum	normalized to MORB	Al2O3 %
Nb (ppm)	0.658	8.6	0.12	0.658	12.4	0.658	5.3	
Ta (ppm)	0.037	0.7	0.007	0.037	0.6	0.037	4.9	
La (ppm)	0.648	18	0.13	0.648	9.9	0.648	3.9	
Al (wt %)	2.355	8.363	2.064	2.355	8.3	2.355	1.0	15.8
mass (kg)	4.04E+24	1.74E+22	2.02E+24	1.92E+24	8.08E+22			
La/Nb	0.98	2.09	1.08	0.98	0.80	0.98		
Nb/Ta	17.8	12.3	17.1	17.8	19.2	17.8		
% mass	100%	0.43%	50%	48%	2.0%	100%		

	BSE	CC	DM	undepleted	other	Sum	normalized to MORB	Al2O3 %
Nb (ppm)	0.658	8.6	0.12	0.658	8.49	0.658	3.6	
Ta (ppm)	0.037	0.7	0.007	0.037	0.44	0.037	3.3	
La (ppm)	0.648	18	0.13	0.648	6.79	0.648	2.7	
Al (wt %)	2.355	8.363	2.064	2.355	6.35	2.355	0.8	12.0
mass (kg)	4.04E+24	1.74E+22	2.02E+24	1.88E+24	1.21E+23			
La/Nb	0.98	2.09	1.08	0.98	0.80	0.98		
Nb/Ta	17.8	12.3	17.1	17.8	19.2	17.8		
% mass	100%	0.43%	50%	47%	3.0%	100%		

	BSE	CC	DM	undepleted	other	Sum	normalized to MORB	Al2O3 %
Nb (ppm)	0.658	8.6	0.12	0.658	6.53	0.658	2.8	
Ta (ppm)	0.037	0.7	0.007	0.037	0.34	0.037	2.6	
La (ppm)	0.648	18	0.13	0.648	5.26	0.648	2.1	
Al (wt %)	2.355	8.363	2.064	2.355	5.35	2.355	0.7	10.1
mass (kg)	4.04E+24	1.74E+22	2.02E+24	1.84E+24	1.62E+23			
La/Nb	0.98	2.09	1.08	0.98	0.81	0.98		
Nb/Ta	17.8	12.3	17.1	17.8	19.2	17.8		
% mass	100%	0.43%	50%	46%	4.0%	100%		

	BSE	CC	DM	undepleted	other	Sum	normalized to MORB	Al2O3 %
Nb (ppm)	0.658	8.6	0.12	0.658	5.35	0.658	2.3	
Ta (ppm)	0.037	0.7	0.007	0.037	0.28	0.037	2.1	
La (ppm)	0.648	18	0.13	0.648	4.34	0.648	1.7	
Al (wt %)	2.355	8.363	2.064	2.355	4.75	2.355	0.6	9.0
mass (kg)	4.04E+24	1.74E+22	2.02E+24	1.80063E+24	2.02E+23			
La/Nb	0.98	2.09	1.08	0.98	0.81	0.98		
Nb/Ta	17.8	12.3	17.1	17.8	19.1	17.8		
% mass	100%	0.43%	50%	45%	5.0%	100%		

60% Depleted Mantle

	BSE	CC	DM	undepleted	other	Sum	normalized to MORB	Al2O3 %
Nb (ppm)	0.658	8.6	0.12	0.658	29.23	0.658	12.5	
Ta (ppm)	0.037	0.7	0.007	0.037	1.54	0.037	11.6	
La (ppm)	0.648	18	0.13	0.648	23.98	0.648	9.6	
Al (wt %)	2.355	8.363	2.064	2.355	16.22	2.355	2.0	30.6
mass (kg)	4.04E+24	1.74E+22	2.42E+24	1.58E+24	4.04E+22			
La/Nb	0.98	2.09	1.08	0.98	0.82	0.98		
Nb/Ta	17.78	12.29	17.14	17.78	19.0	17.8		
% mass	100%	0.4%	60%	39%	1%	100%		

	BSE	CC	DM	undepleted	other	Sum	normalized to MORB	Al2O3 %
Nb (ppm)	0.658	8.6	0.12	0.658	14.95	0.658	6.4	
Ta (ppm)	0.037	0.7	0.007	0.037	0.79	0.037	6.0	
La (ppm)	0.648	18	0.13	0.648	12.31	0.531	4.9	
Al (wt %)	2.355	8.363	2.064	2.355	9.29	2.355	1.2	17.5
mass (kg)	4.04E+24	1.74E+22	2.42E+24	1.54E+24	8.08E+22			
La/Nb	0.98	2.09	1.08	0.98	0.82	0.81		
Nb/Ta	17.78	12.29	17.14	17.78	19.0	17.8		
% mass	100%	0.4%	60%	38%	2%	100%		

	BSE	CC	DM	undepleted	other	Sum	normalized to MORB	Al2O3 %
Nb (ppm)	0.658	8.6	0.12	0.658	10.18	0.658	4.4	
Ta (ppm)	0.037	0.7	0.007	0.037	0.54	0.037	4.1	
La (ppm)	0.648	18	0.13	0.648	8.42	0.648	3.4	
Al (wt %)	2.355	8.363	2.064	2.355	6.98	2.355	0.9	13.2
mass (kg)	4.04E+24	1.74E+22	2.42E+24	1.49E+24	1.21E+23			
La/Nb	0.98	2.09	1.08	0.98	0.83	0.98		
Nb/Ta	17.78	12.29	17.14	17.78	19.0	17.8		
% mass	100%	0.4%	60%	37%	3%	100%		

	BSE	CC	DM	undepleted	other	Sum	normalized to MORB	Al2O3 %
Nb (ppm)	0.658	8.6	0.12	0.658	7.80	0.658	3.3	
Ta (ppm)	0.037	0.7	0.007	0.037	0.41	0.037	3.1	
La (ppm)	0.648	18	0.13	0.648	6.48	0.648	2.6	
Al (wt %)	2.355	8.363	2.064	2.355	5.82	2.355	0.7	11.0
mass (kg)	4.04E+24	1.74E+22	2.42E+24	1.45E+24	1.62E+23			
La/Nb	0.98	2.09	1.08	0.98	0.83	0.98		
Nb/Ta	17.78	12.29	17.14	17.78	19.0	17.8		
% mass	100%	0.4%	60%	36%	4%	100%		

	BSE	CC	DM	undepleted	other	Sum	normalized to MORB	Al2O3 %
Nb (ppm)	0.658	8.6	0.12	0.658	6.37	0.658	2.7	
Ta (ppm)	0.037	0.7	0.007	0.037	0.34	0.037	2.6	
La (ppm)	0.648	18	0.13	0.648	5.31	0.648	2.1	
Al (wt %)	2.355	8.363	2.064	2.355	5.13	2.355	0.6	9.7
mass (kg)	4.04E+24	1.74E+22	2.42E+24	1.41E+24	2.02E+23			
La/Nb	0.98	2.09	1.08	0.98	0.83	0.98		
Nb/Ta	17.78	12.29	17.14	17.78	18.9	17.8		
% mass	100%	0.4%	60%	35%	5%	100%		

70% Depleted Mantle

	BSE	CC	DM	undepleted	other	Sum	normalized to MORB	Al2O3 %
Nb (ppm)	0.658	8.6	0.12	0.658	34.61	0.658	14.9	
Ta (ppm)	0.037	0.7	0.007	0.037	1.84	0.037	13.9	
La (ppm)	0.648	18	0.13	0.648	29.16	0.648	11.7	
Al (wt %)	2.355	8.363	2.064	2.355	19.13	2.355	2.4	36.1
mass (kg)	4.04E+24	1.74E+22	2.83E+24	1.17E+24	4.04E+22			
La/Nb	0.984802	2.093023	1.083333	0.98	0.84	0.98		
Nb/Ta	17.78378	12.28571	17.14286	17.8	18.9	17.8		
% mass	100%	0.43%	70%	29%	1.0%	100%		

	BSE	CC	DM	undepleted	other	Sum	normalized to MORB	Al2O3 %
Nb (ppm)	0.658	8.6	0.12	0.658	17.64	0.658	7.6	
Ta (ppm)	0.037	0.7	0.007	0.037	0.94	0.037	7.1	
La (ppm)	0.648	18	0.13	0.648	14.90	0.648	6.0	
Al (wt %)	2.355	8.363	2.064	2.355	10.74	2.355	1.3	20.3
mass (kg)	4.04E+24	1.74E+22	2.83E+24	1.13E+24	1.13E+24			
La/Nb	0.984802	2.093023	1.083333	0.98	0.84	0.98		
Nb/Ta	17.78378	12.28571	17.14286	17.8	18.8	17.8		
% mass	100%	0.43%	70%	28%	2.0%	100%		

	BSE	CC	DM	undepleted	other	Sum	normalized to MORB	Al2O3 %
Nb (ppm)	0.658	8.6	0.12	0.658	11.98	0.658	5.1	
Ta (ppm)	0.037	0.7	0.007	0.037	0.64	0.037	4.8	
La (ppm)	0.648	18	0.13	0.648	10.15	0.648	4.1	
Al (wt %)	2.355	8.363	2.064	2.355	7.95	2.355	1.0	15.0
mass (kg)	4.04E+24	1.74E+22	2.83E+24	1.09E+24	1.09E+24			
La/Nb	0.984802	2.093023	1.083333	0.98	0.85	0.98		
Nb/Ta	17.78378	12.28571	17.14286	17.8	18.8	17.8		
% mass	100%	0.43%	70%	27%	3.0%	100%		

	BSE	CC	DM	undepleted	other	Sum	normalized to MORB	Al2O3 %
Nb (ppm)	0.658	8.6	0.12	0.658	9.15	0.658	3.9	
Ta (ppm)	0.037	0.7	0.007	0.037	0.49	0.037	3.7	
La (ppm)	0.648	18	0.13	0.648	7.77	0.648	3.1	
Al (wt %)	2.355	8.363	2.064	2.355	6.55	2.355	0.8	12.4
mass (kg)	4.04E+24	1.74E+22	2.83E+24	1.05E+24	1.05E+24			
La/Nb	0.984802	2.093023	1.083333	0.98	0.85	0.98		
Nb/Ta	17.78378	12.28571	17.14286	17.8	18.8	17.8		
% mass	100%	0.43%	70%	26%	4.0%	100%		

	BSE	CC	DM	undepleted	other	Sum	normalized to MORB	Al2O3 %
Nb (ppm)	0.658	8.6	0.12	0.658	7.45	0.658	3.2	
Ta (ppm)	0.037	0.7	0.007	0.037	0.40	0.037	3.0	
La (ppm)	0.648	18	0.13	0.648	6.35	0.648	2.5	
Al (wt %)	2.355	8.363	2.064	2.355	5.71	2.355	0.7	10.8
mass (kg)	4.04E+24	1.74E+22	2.83E+24	1.01E+24	1.01E+24			
La/Nb	0.984802	2.093023	1.083333	0.98	0.85	0.98		
Nb/Ta	17.78378	12.28571	17.14286	17.8	18.8	17.8		
% mass	100%	0.43%	70%	25%	5.0%	100%		

<u>80% Depleted Mantle</u>

	BSE	CC	DM	undepleted	other	Sum	normalized to MORB	Al2O3 %
Nb (ppm)	0.658	8.6	0.12	0.658	39.99	0.658	17.2	
Ta (ppm)	0.037	0.7	0.007	0.037	2.14	0.037	16.2	
La (ppm)	0.648	18	0.13	0.648	34.34	0.648	13.7	
Al (wt %)	2.355	8.363	2.064	2.355	22.04	2.355	2.8	41.6
mass (kg)	4.04E+24	1.74E+22	3.23E+24	7.68E+23	4.04E+22			
La/Nb	0.984802	2.093023	1.083333	0.98	0.86	0.98		
Nb/Ta	17.78378	12.28571	17.14286	17.8	18.7	17.8		
% mass	100%	0.43%	80%	19%	1.0%	100%		

	BSE	CC	DM	undepleted	other	Sum	normalized to MORB	Al2O3 %
Nb (ppm)	0.658	8.6	0.12	0.658	20.33	0.658	8.7	
Ta (ppm)	0.037	0.7	0.007	0.037	1.09	0.037	8.2	
La (ppm)	0.648	18	0.13	0.648	17.49	0.648	7.0	
Al (wt %)	2.355	8.363	2.064	2.355	12.20	2.355	1.5	23.0
mass (kg)	4.04E+24	1.74E+22	3.23E+24	7.27E+23	8.08E+22			
La/Nb	0.984802	2.093023	1.083333	0.98	0.86	0.98		
Nb/Ta	17.78378	12.28571	17.14286	17.8	18.7	17.8		
% mass	100%	0.43%	80%	18%	2.0%	100%		

	BSE	CC	DM	undepleted	other	Sum	normalized to MORB	Al2O3 %
Nb (ppm)	0.658	8.6	0.12	0.658	13.77	0.658	5.9	
Ta (ppm)	0.037	0.7	0.007	0.037	0.74	0.037	5.6	
La (ppm)	0.648	18	0.13	0.648	11.88	0.648	4.8	
Al (wt %)	2.355	8.363	2.064	2.355	8.92	2.355	1.1	16.8
mass (kg)	4.04E+24	1.74E+22	3.23E+24	6.87E+23	1.21E+23			
La/Nb	0.984802	2.093023	1.083333	0.98	0.86	0.98		
Nb/Ta	17.78378	12.28571	17.14286	17.8	18.7	17.8		
% mass	100%	0.43%	80%	17%	3.0%	100%		

	BSE	CC	DM	undepleted	other	Sum	normalized to MORB	Al2O3 %
Nb (ppm)	0.658	8.6	0.12	0.658	10.49	0.658	4.5	
Ta (ppm)	0.037	0.7	0.007	0.037	0.56	0.037	4.3	
La (ppm)	0.648	18	0.13	0.648	9.07	0.648	3.6	
Al (wt %)	2.355	8.363	2.064	2.355	7.28	2.355	0.9	13.7
mass (kg)	4.04E+24	1.74E+22	3.23E+24	6.46E+23	1.62E+23			
La/Nb	0.984802	2.093023	1.083333	0.98	0.86	0.98		
Nb/Ta	17.78378	12.28571	17.14286	17.8	18.7	17.8		
% mass	100%	0.43%	80%	16%	4.0%	100%		

	BSE	CC	DM	undepleted	other	Sum	normalized to MORB	Al2O3 %
Nb (ppm)	0.658	8.6	0.12	0.658	8.53	0.658	3.7	
Ta (ppm)	0.037	0.7	0.007	0.037	0.46	0.037	3.5	
La (ppm)	0.648	18	0.13	0.648	7.39	0.648	3.0	
Al (wt %)	2.355	8.363	2.064	2.355	6.29	2.355	0.8	11.9
mass (kg)	4.04E+24	1.74E+22	3.23E+24	6.06E+23	2.02E+23			
La/Nb	0.984802	2.093023	1.083333	0.98	0.87	0.98		
Nb/Ta	17.78378	12.28571	17.14286	17.8	18.7	17.8		
% mass	100%	0.43%	80%	15%	5.0%	100%		

<u>90 % Depleted Mantle</u>

	BSE	CC	DM	undepleted	other	Sum	normalized to MORB	Al2O3 %
Nb (ppm)	0.658	8.6	0.12	0.658	45.37	0.658	19.5	
Ta (ppm)	0.037	0.7	0.007	0.037	2.44	0.037	18.5	
La (ppm)	0.648	18	0.13	0.648	39.52	0.648	15.8	
Al (wt %)	2.355	8.363	2.064	2.355	24.95	2.355	3.1	47.1
mass (kg)	4.04E+24	1.74E+22	3.64E+24	3.64E+23	4.04E+22			
La/Nb	0.98	2.09	1.08	0.98	0.87	0.98		
Nb/Ta	17.8	12.3	17.1	17.8	18.6	17.8		
% mass	100%	0.43%	90%	9.0%	1.0%	100%		

	BSE	CC	DM	undepleted	other	Sum	normalized to MORB	Al2O3 %
Nb (ppm)	0.658	8.6	0.12	0.658	23.02	0.658	9.9	
Ta (ppm)	0.037	0.7	0.007	0.037	1.24	0.037	9.4	
La (ppm)	0.648	18	0.13	0.648	20.08	0.648	8.0	
Al (wt %)	2.355	8.363	2.064	2.355	13.65	2.355	1.7	25.8
mass (kg)	4.04E+24	1.74E+22	3.64E+24	3.23E+23	8.08E+22			
La/Nb	0.98	2.09	1.08	0.98	0.87	0.98		
Nb/Ta	17.8	12.3	17.1	17.8	18.6	17.8		
% mass	100%	0.43%	90%	8.0%	2.0%	100%		

	BSE	CC	DM	undepleted	other	Sum	normalized to MORB	Al2O3 %
Nb (ppm)	0.658	8.6	0.12	0.658	15.56	0.658	6.7	
Ta (ppm)	0.037	0.7	0.007	0.037	0.84	0.037	6.3	
La (ppm)	0.648	18	0.13	0.648	13.60	0.648	5.4	
Al (wt %)	2.355	8.363	2.064	2.355	9.89	2.355	1.2	18.7
mass (kg)	4.04E+24	1.74E+22	3.64E+24	2.83E+23	1.21E+23			
La/Nb	0.98	2.09	1.08	0.98	0.87	0.98		
Nb/Ta	17.8	12.3	17.1	17.8	18.6	17.8		
% mass	100%	0.43%	90%	7.0%	3.0%	100%		

	BSE	CC	DM	undepleted	other	Sum	normalized to MORB	Al2O3 %
Nb (ppm)	0.658	8.6	0.12	0.658	11.84	0.658	5.1	
Ta (ppm)	0.037	0.7	0.007	0.037	0.64	0.037	4.8	
La (ppm)	0.648	18	0.13	0.648	10.36	0.648	4.1	
Al (wt %)	2.355	8.363	2.064	2.355	8.01	2.355	1.0	15.1
mass (kg)	4.04E+24	1.74E+22	3.64E+24	2.42E+23	1.62E+23			
La/Nb	0.98	2.09	1.08	0.98	0.88	0.98		
Nb/Ta	17.8	12.3	17.1	17.8	18.6	17.8		
% mass	100%	0.43%	90%	6.0%	4.0%	100%		

	BSE	CC	DM	undepleted	other	Sum	normalized to MORB	Al2O3 %
Nb (ppm)	0.658	8.6	0.12	0.658	9.60	0.658	4.1	
Ta (ppm)	0.037	0.7	0.007	0.037	0.52	0.037	3.9	
La (ppm)	0.648	18	0.13	0.648	8.42	0.648	3.4	
Al (wt %)	2.355	8.363	2.064	2.355	6.88	2.355	0.9	13.0
mass (kg)	4.04E+24	1.74E+22	3.64E+24	2.02E+23	2.02E+23			
La/Nb	0.98	2.09	1.08	0.98	0.88	0.98		
Nb/Ta	17.8	12.3	17.1	17.8	18.6	17.8		
% mass	100%	0.43%	90%	5.0%	5.0%	100%		