Uranium in the Environment: A Characterization and Comparison of Uranium Mobility in Ancient and Modern Sediments

by

Laura L. Bergen

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Department of Geological Sciences University of Manitoba Winnipeg, Manitoba

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Abstract

The behavior of U in near surface sedimentary environments has changed throughout geologic time. There is a marked shift in U (IV) mineral stability and deposit style at approximately 2200 Ma due to changes in the concentration of O in the atmosphere. For example, prior to 2200 Ma, fluvial U deposits could form and U(IV) were stable in surface and near-surface environments. In modern, anthropogenic sedimentary systems such as U tailings, U (IV) minerals are not stable and readily oxidize to U (VI) minerals. In addition, U is much more mobile in modern sediments relative sediments that were deposited prior to 2200 Ma.

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Chapter 1. Introduction

Uranium (U), atomic number 92, is a member of the actinide series in Group IIIB of the periodic table of elements. The geochemistry of U in natural (uranium deposits) and engineered systems (tailing sites and potential waste repositories) has been extensively studied (e.g., Ewing and Macfarlane 2002; Gascoyne et al. 2002; Krupka and Serne 2002; Allard et al. 2007; Naamoun and Merkel 2008; Dong et al. 2011). Uranium transport in near surface environments is of particular interest because of the potential impact on ecological systems (e.g., Abdelouas 2006; Lottermoser 2007; Carvalho and Oliveria 2008;Torgoev et al. 2008). The geochemical behavior of U in near-surface environments is largely controlled by redox-reactions, which are mediated by a number of factors including: pH, adsorption and biogeochemical processes (Krupka and Serne 2002).

Uranium occurs in multiple oxidation states including: U(III), U(IV), U(V) and U(VI). Aqueous U(III) is readily oxidized to the more stable U(IV) in most reducing environments and U(V) easily disproportionates to U(IV) and U(VI); thus U(IV) and U(VI) are the most common and wide-spread species of U in natural environments (Krupka and Serne 2002). Under reducing (Eh <3) and neutral (pH ~7) conditions U(IV) is the prevalent species and forms insoluble minerals such as uraninite (UO₂). Uranium exists in the U(VI) species for all pH conditions in weakly reducing to oxidizing conditions (Eh >4) and is readily mobilized by neutral to alkaline fluids (Meunier et al. 1992; Krupka and Serne 2002; Abdelouas 2006; Lottermoser 2007). Sorption of U onto pre-existing minerals has been extensively studied and plays an important role in the immobilization of U(VI) (e.g., Wersin et al. 1994; Majdan et al. 2010; Shang et al. 2011; Tits et al. 2011); however, low pH fluids can easily decrease sorption efficiency (Abdelouas 2006).

Biogeochemical relationships in near surface sedimentary environments are complex and in different circumstances either bind (ie. reduce) U as U(IV) or liberate (ie. oxidize) U as U(VI). Microbial oxidation of iron, promoting acid generation in mine tailing sediments can indirectly increase U mobility whereas other biological activity will directly reduce U (i.e. Huhle et al. 2008; Mkandawire and Dudel 2008; Merroun and Selenska-Pobell 2008). The above-mentioned physiochemical parameters controlling the geochemical behavior of U in near surface environments are dynamic and have evolved through geologic time.

Uranium is a trace element in the crust (2.7 ppm in the upper crust and 1 to 1.7 ppm is the global crustal average) and mantle (~0.015 ppm) and is often found in accessory minerals such as zircon. However, high concentrations of U do occur on many continents throughout the world where U deposits can contain millions of kilograms of U (e.g., unconformity-type U deposits, Canada). Uranium deposits are important sources of energy for countries that rely heavily on nuclear power (e.g. France). These deposits have been used to model Earth's ancient climates (e.g., Holland 1984) and as natural analogues for the geologic disposal of radioactive waste (e.g., Gauthier-Lafaye et al. 1996).

Uranium minerals and deposits have evolved through geologic history; new U minerals formed as a result of global and atmospheric events and portions of the geologic time scale are marked by the prevalence of specific U deposit types (Hazen et al. 2009; Kyser and Cuney 2009). Table 1.1 illustrates the temporal distribution of various U deposit types. The rise of atmospheric oxygen is the subject of some controversy with two theories; one theory suggests the atmosphere has been oxygenated since the early Archean (~3800 Ma) (Grassineau 2006; Ishihara 2006; Law and Phillips 2006) whereas the alternate theory suggests a Great Oxidation

Event between 2300 and 2100 Ma (~2200 Ma) (Hazen et al. 2009; Miner 2006; Yamaguchi and

Ohmoto 2006).

Table 1.1. Table showing the various types of U deposits and their main ages and formational fluids (modified after Kyser and Cuney 2009).

Deposit Type	Main Age	Geology	Formative Fluids	
Surficial	Tertiary	Drainage basin	Groundwater	
Collapse breccia pipes	Tertiary	Intracratonic and extensional basins	Basinal brines	
Unconformity-related	1500-1900 Ma	Intracratonic and marginal basins	Basinal and basement brines	
Sandstone hosted	Phanerozoic - Tertiary	Extensional rift basins	Groundwater	
Phosphorite	Phanerozoic	Continental shelf/marine	Marine and brackish	
Vein deposits Proterozoic – Po Mesozoic ext		Post orogenic extensional basins	Metamorphic and hydrothermal	
Metasomatic	Proterozoic	Rift and back arc basins	Metamorphic and magmatic	
IOCG/breccia	Proterozoic	Arc and marginal basin	Magmatic and later hydrothermal	
Quartz-pebble conglomerate	>2200 Ma	Intracratonic and marginal basins	Groundwater and later hydrothermal	
Intrusive	All	Alkaline complexes	Magmatic and hydrothermal	
Volcanic associated	All	Rift and back arc basins	Basinal brines and hydrothermal	

Hazen et al (2009) suggests a four-phase model for the evolution of U mineralogy through geologic history. Phase I (4.5 - 3.5 Ga) was a period of U concentration in the earth's crust through magmatism and associated hydrothermal fluids. Phase II (3.5 - 2.2 Ga) was a period defined by detrital uraninite accumulation in fluvially deposited sediments, which had weathered

from the magmatic sources implaced during Phase I. Phase III is defined by the change in U mobility and concentration mechanisms with the Great Oxidation Event (2.2 Ga). Phase IV is defined by the rise of land plants and organically mediated U mineralization. The Great Oxidation Event that defines Phase III, marks an explosion of ~200 new U mineral species. Preservation of large amounts of detrital U mineral grains, such as uraninite, within the geologic rock record is a phenomenon restricted to ancient quartz-pebble conglomerate U deposits during Phase II (Hazen et al. 2009; Kyser and Cuney 2009). Detrital U deposits in fluvial sediments do not exist in younger successions; U hosted in sedimentary successions younger than 2200 Ma was implaced by post depositional fluids (Hazen et al. 2009; Kyser and Cuney 2009).

Ancient U deposits (> 2200 Ma) are generally hosted within quartz-pebble conglomerates, the most economic of which are Witwatersrand in South Africa and the Elliot Lake in Canada (Kyser and Cuney 2009). The origin of the U mineralogy within these deposits is the subject of some debate with three suggested genetic models including: hydrothermal, detrital/placer, and modified placer (e.g., Bergen and Fayek 2012; Ono and Fayek 2011; Minter 2006; Yamaguchi and Ohmoto 2006). Uraninite weathers rapidly in an oxygen-rich atmosphere, thus the presence of detrital uraninite in mature fluvial sediments strongly suggests an anoxic atmosphere at the time of deposition (Hazen et al. 2009). The correct classification of the U minerals within these deposits is an important step in understanding the geochemical behavior of U in ancient sedimentary environments.

Precambrian quartz-pebble conglomerate U deposits are the only examples of detrital U in the geologic record because they formed prior to the increase in oxygen in the atmosphere during the Great Oxidation Event (Kyser and Cuney 2009). The study of these deposits provides

an opportunity to characterize the conditions that preserved detrital uraninite and uranothorite in surface and near-surface sedimentary environments, and over large time-scales (billions of years).

The mining of uranium ore is an essential step in the preparation of nuclear fuel for civilian as well as military uses. In general, uranium is extracted from rocks containing uraniumbearing minerals (ore) using a variety of reagents. Mineral processing of hard rock metal ores (ie. U, Au, Ni, Zn) involves size reduction and separation of minerals. Crushing and grinding processes are used to significantly decrease the size of the ore feed. The ore feed is crushed to facilitate efficient chemical or physical separation of the desired ore material from the gangue minerals. All material that is not considered ore is discharged in tailing receiving areas (Lottermoser 2007). The U tailings receiving areas are usually low-lying areas, rivers or lakes adjacent to the mill. Presently, U tailings are used as underground backfill, or stored in tailings impoundment areas that are engineered to contain them (Hudson-Edwards et al. 2011). Tailings consist of both solid and liquid components and vary from site-to-site. The liquid component of the tailings comprises water along with any chemical reagent added during ore processing such as acids and organic chemicals (Lottermoser 2007; Hudson-Edwards et al. 2011; Jamieson 2011). All forms of mineral extraction results in the formation of some amount of waste or byproduct material, usually in the form of fine-grained mine tailings. Toxic substances including heavy metals can be introduced into the surrounding environment through oxidation of the metals in the tailings, which increases their solubility in meteoric water (Zhang et al. 2004).

Oxidizing conditions generally dominate the upper portions of tailings whereas at depth, where atmospheric oxygen cannot penetrate, the tailings are largely anaerobic (Fig. 1.1;

Wielinga et al. 1999). Therefore, both oxidizing and reducing reactions can occur within U mine tailings. These chemical reactions are generally complex, unidirectional and occur in multiple steps (Balci et al. 2007). Figure 1.1 shows a simplified schematic of a tailings impoundment, illustrating the oxidized and unoxidized or "fresh" tailings.



Figure 1.1. Simplified cross section of a tailings pond. The upper oxidized tailings is where aerobic reactions are dominant, and anaerobic reactions dominate the lower "fresh" tailings (modified after Wielinga et al. 1999).

Most environmental concerns associated with mill tailings are related to their tendency to readily react with the atmosphere and hydrosphere (Jamieson 2011). However, U tailings present a unique set of concerns, due to the presence of U and its associated decay products including radon and lead. Most U ore deposits contain some amount of sulfide minerals such as pyrite, galena or chalcopyrite. Oxidation of pyrite within tailings is the principle cause of Acid Mine Drainage (AMD) resulting in the formation of acidic run off from the tailings (Balci et al. 2007). Acid generation primarily occurs in the upper oxidized zone of tailings where they can readily and easily react with the atmosphere and hydrosphere, outlined in the following three reactions:

$$FeS_2 + 7/2O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+$$
 [1]

$$Fe^{2+} + 1/4O_2 + H^+ - Fe^{3+} + 1/2H_2O$$
 [2]

$$FeS_2 + 14Fe^{3+} + 8H_2O \rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+$$
 [3]

The oxidation of pyrite will liberate any trace impurities in the mineral, contributing to heavy metal mobility. Pore water acidification is a contributing factor in dissolution of U minerals, maintaining aqueous U(VI) and increasing U mobility (Abdelouas 2006; Balci et al. 2007; Diaby et al. 2007; Jamieson 2011). Effective milling processes can remove up to 90 % of the U, however, this results in at least 10 % making its way into the tailings. Once in the tailings area, the U may readily react with surface waters and the atmosphere, which increases the solubility and mobility of U, especially in historical tailing sites where no effective tailings containment is in place, (Mudd 2000; Abdelouas 2006; Lottermoser 2007; Jamieson 2011). Environmental contamination by U is of concern due to its radiotoxic and chemo-toxic properties (Schnug and Haneklaus 2008). Improper disposal of mill tailings during early decades of U mining (1940's to 1960's) has resulted in soil, surface water and groundwater contamination through wind erosion and aqueous transport (Abdelouas 2006; Lottermoser 2007).

The study of U minerals in sedimentary environments from modern tailings sites to Archean sediments, that are over 2 billion years old, provide an opportunity to understand the behavior of U in anaerobic and oxidizing near surface sedimentary environments. Knowing how U reacts in the both oxidizing and anaerobic conditions, and over large-time scales will allow researchers to minimize and potentially reverse contamination by this heavy metal. This information could potentially help scientists develop better methods for the disposal of highly radioactive nuclear waste (HRNW).

1.1 Objectives

Modern anthropogenic U mill tailings offer an opportunity to observe the behavior of U in near surface sedimentary oxidizing and anaerobic environments over short time-scales. The study of Precambrian quartz-pebble conglomerate U deposits provides an opportunity to study the uranium mineral preservation in anaerobic conditions over large time-scales. Therefore, my thesis involves the study of U in both ancient and modern sediments.

The objectives are:

- Assign a genetic model to the Pele Mountain Quartz-Pebble Conglomerate Uranium Deposit for U mineral deposition, to confirm presence of detrital U minerals (Chapter 2).
 - Identify and characterize the U mineralization.
 - Determine the age of U mineralization events.
 - Identify fluid events that have modified U mineralization.
- Characterize U mobility in the upper 1 meter of the Lorado Mill Historical Tailings Site, Uranium City, Saskatchewan, Canada (Chapter 3).
 - Characterize U concentrations both laterally and vertically.
 - Characterize the form of U (e.g., minerals, adsorbed U).
 - Develop a model for U mobility within the Lorado Mill tailings.
 - Provide suggestions for minimizing uranium mobility at the Lorado Historical Tailings.

1.2 References

- Abdelouas, A. (2006) Uranium mill tailings: Geochemistry, mineralogy, and environmental impact. Elements, 2, 335-341.
- Allard, T., Calas, G., Ildefonse, P. (2007) Reconstruction of past U migration in a sedimentary deposit (Coutras, France): Implications for a radwaste repository. Chemical Geology, 239, 50-63.
- Balci, N., Shanks III, W.C., Mayer, B. & Mandernack, K.W. (2007) Oxygen and sulfur isotope symantics of sulfate produced by bacterial and abiotic oxidation of pyrite. Geochimica et Cosmochimica Acta, **71**, 3796-3811.
- Bergen, L.L. and Fayek, M. (2012) Petrography and geochronology of the Pele Mountain quartzpebble conglomerate uranium deposit, Elliot Lake District, Canada. American Mineralogist, 97, 1274-1283.
- Carvalho, F.P. and Oliveria, J.M. (2008) Radioactivity in soils and horticulture products near uranium mining sites. Uranium, Mining and Hydrogeology, Springer-Verlag Berlin Heidelberg. 681-688.
- Diaby, N., Dold, B., Pfeifer, H., Holliger, C., Johnson, D.B. & Hallberg, K.B. (2007) Microbial communities in a porphyry copper tailings impoundment and their impact on the geochemical dynamics of the mine waste. Environmental Microbiology, **9**, 298-307.
- Dong, W., Tokunaga, T.K., Davis, J.A. and Wan, J. (2011) Uranium(VI) adsorption and surface complexation modeling onto background sediments from the F-Area Savannah River Site. Environmental Science and Technology, 46, 1565-1571.
- Ewing, R.C. and Macfarlane, A. (2002): Yucca Mountain. Science, 296, 659-660.
- Gascoyne, M., Miller, N.H., Neymark, L.A. (2002) Uranium-series disequilibrium in tuffs from Yucca Mountain, Nevada, as evidence of pore-fluid flow over the last million years. Applied Geochemistry, 17, 781-792.
- Gauthier-Lafaye, F., Holliger, P., Blanc, P.L. (1996) Natural fission reactors in the Franceville Basin, Gabon: a review of the conditions and results of a "critical event" in a geologic system. Geochimica et Cosmochimica Acta, 60, 4831-4852.
- Grassineau, N.V., Abell, P., Appel, P.W.U., Lowry, D. and Nisbet, E.G. (2006) Early life signatures in sulfur and carbon isotopes from Isua, Barberton, Wabigoon (Steep Rock), and Belingwe Greenstone Belts (3.8 to 2.7 Ga). In Evolution of Earth's Early Atmosphere, Hydrosphere, and Biosphere-Constraints from Ore Deposits. Geological Society of America Memoir, 198, 33-52.
- Hazen, R.M., Ewing, R.C. and Sverjensky, D.A. (2009) Evolution of uranium and thorium minerals. American Mineralogist, 94, 1293-1311.
- Holland, H.D. (1984) The chemical evolution of the atmosphere and oceans. Princeton University Press, New Jersey, 598.

- Hudson-Edwards, K.A., Jamieson, H.E. and Lottermoser, B.G. (2011) Mine wastes: past, present, future. Elements, 7, 375-380.
- Huhle, B., Heilmeier, H. and Merkel, B. (2008) Potential of Brassica juncea and Helianthus annuus in phytoremediation for uranium. Uranium, Mining and Hydrogeology, Springer-Verlag Berlin Heidelberg. 307-318.
- Ishihara, S., Ohmoto, H., Anhaeusser, C.R., Imai, A. and Robb, L.J. (2006) Discovery of the oldest oxidized granitoids in the Kaapvaal Craton and its implications for the redox evolution of early Earth. In Evolution of Earth's Early Atmosphere, Hydrosphere, and Biosphere-Constraints from Ore Deposits. Geological Society of America Memoir, 198, 67-80.
- Jamieson, H. (2011) Geochemistry and mineralogy of solid mine waste: Essential knowledge for predicting environmental impact. Elements, 7, 381-386.
- Krupka, K.M. and Serne, R.J. (2002) Geochemical factors affecting the behavior of antimony, cobalt, europium, technetium, and uranium in vadose sediments. Prepared for CH2M HILL Hanford Group, Inc., and the U.S. Department of Energy, under Contract DE-AC06-76RL01830. December 2002.
- Kyser, K. and Cuney, M. (2009) Recent and not-so-recent developments in uranium deposits and implications for exploration. Mineralogical Association of Canada Short Course, 39.
- Law, J. and Phillips, N. (2006) Witwatersrand gold-pyrite-uraninite deposits do not support a reducing Archean atmosphere. In Evolution of Earth's Early Atmosphere, Hydrosphere, and Biosphere-Constraints from Ore Deposits. Geological Society of America Memoir, 198, 121-142.
- Lottermoser, B. G. (2007) Mine wastes characterization, treatment and environmental impacts. Springer-Berlin Heidelberg New York. 304 pages.
- Majdan, M., Pikus, S., Gajowiak, A., Gladysz-Plaska, A., Krzyzanowska, H., Zuk, J. and Bujacka, M. (2010) Characterization of uranium(VI) sorption by organobentonite. Applied Surface Science, 256, 5416-5421.
- Merroun, M.L. and Selenska-Pobell, S. (2008) Bacterial interactions with uranium: an environmental perspective. Journal of Contaminant Hydrology. 102, 285-295.
- Meunier, J.D., Bruhlet, J. and Pagel, M. (1992) Uranium mobility in the sediment-hosted uranium deposit of Courtas, France. Applied Geochemistry, 7, 111-121.
- Minter, W.E.L. (2006) The sedimentary setting of Witwatersrand placer mineral deposits in an Archean atmosphere. In Evolution of Earth's Early Atmosphere, Hydrosphere, and Biosphere-Constraints from Ore Deposits. Geological Society of America Memoir, 198, 105-119.
- Mkandawire, M. and Dudel, E.G. (2008) Natural occurring uranium nanoparticles and the implication in bioremediation of surface mine waters. Uranium, Mining and Hydrogeology, Springer-Verlag Berlin Heidelberg. 487-496.

- Mudd, G.M. (2000) Critical review of acid in situ leach uranium mining. Environmental Geology, 41, 390-403.
- Naamoun, T. and Merkel, B. (2008) Chemical behaviour of uranium in the tailings material of Schneckenstein (Germany). Uranium, Mining and Hydrogeology, Springer-Verlag Berlin Heidelberg. 271-283.
- Ono, S. and Fayek, M. (2011) Decoupling of O and Pb isotope systems of uraninite in the early Proterozoic conglomerates in the Elliot Lake district. Chemical Geology, 288, 1-13.
- Schnug, E. and Haneklaus, S. (2008) Dispersion of uranium in the environment by fertilization. Uranium, Mining and Hydrogeology, Springer-Verlag Berlin Heidelberg. 45-52.
- Shang, J., Liu, C., Wamg, Z. and Zachara, J.M. (2011) Effect of grain size on uranium(VI) surface complexation kinetics and adsorption additivity. Environmental Science & Technology, 45, 6025-6031.
- Tits, J., Geipel, G., Mace, N., Eilzer, M. and Wieland, E. (2011) Determination of uranium(VI) sorbed species in calcium silicate hydrate phases: a laser-induced luminescence spectroscopy and batch sorption study. Journal of Colloid and Interface Science, 359, 248-256.
- Torgoev, I., Aleshin, Y., Ashirov, G. (2008) Impacts of uranium mining on environment of Gergana Valley in Central Asia. Uranium, Mining and Hydrogeology, Springer-Verlag Berlin Heidelberg. 285-294.
- Wersin, P., Hochella, M.F., Persson, P., Redden, G., Leckie, J.O. and Harris, D.W. (1994) Interaction between aqueous uranium (VI) and sulfide minerals: spectroscopic evidence for sorption and reduction. Geochimica et Cosmochimica Acta, 58, 2829-2843.
- Wielinga, B., Lucy, J.K., Moore, J.N., Seastone, O.F. & Gannon, J.E. (1999) Microbial and geochemical characterization of fluvially deposited sulfidic mine tailings. Applied and Environmental Microbiology, 65, 1548-1555.
- Yamaguchi, K.E., and Ohmoto, H. (2006) Evidence from sulfur isotope and trace elements in pyrites for their multiple post-depositional processes in uranium ores at the Stanleigh Mine, Elliot Lake, Ontario, Canada. In Evolution of Earth's Early Atmosphere, Hydrosphere, and Biosphere-Constraints from Ore Deposits. Geological Society of America Memoir, 198, 143-156.
- Zhang, G., Liu, C., Yang, Y. & Wu, P. (2004) Characterization of heavy metals and sulphur isotope in water and sediments of a mine-tailings area rich in carbonate. Water, Air and Soil Pollution, **155**, 51-62.

Chapter 2. Petrography and Geochronology of the Pele Mountain Quartz-Pebble Conglomerate Uranium Deposit, Elliot Lake District, Canada

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2.1 Abstract

Uranium deposits older than about 2200 Ma are generally hosted within quartz-pebble conglomerates and are a source of economic uranium. The genesis of these deposits is controversial and genetic models include hydrothermal, detrital/placer, and modified placer. Petrography of the uranium mineralogy from the Pele Mountain quartz-pebble conglomerate uranium deposit of the Elliot Lake district, Canada, shows that the dominant uranium minerals are thorite [(Th,U)SiO₄] and brannerite [(U,Ca,Ce)(Ti,Fe)₂O₆]. Uranium-lead (U-Pb) and leadlead (Pb-Pb) isotopic analyses of thorite, brannerite, and galena were obtained using secondary ion mass spectrometry. Thorite has U-Pb ages of 2489 ± 24 in the quartzose conglomerate and 280 ± 67 Ma in the quartz arenite. Brannerite has a U-Pb age of 2403 ± 120 Ma. Thorite Pb-Pb ages range from 521 ± 19 to 248 ± 8 Ma in the arenite and from 2453 ± 12 to 935 ± 27 Ma in the conglomerate, whereas brannerite Pb-Pb ages are between 1335 ± 0.11 and 848 ± 13 Ma. Galena has a Pb-Pb age of 2659 ± 8 Ma, which likely represents the age of the source formation that produced detrital galena. The rounded texture and U-Pb age of the conglomerate thorite corresponds to the depositional age of the host conglomerate bed of the Matinenda Formation, suggesting a detrital origin. The young U-Pb age of the thorite in the arenite represents the age of a resetting event. The brannerite, which replaces rutile, has a U-Pb consistent with fluid events associated with the Blezardian or Penokean Orogenic events, and is likely of hydrothermal origin. Therefore, based on the textures and variable ages of the uranium and sulfide minerals,

the Pele Mountain quartz-pebble conglomerate uranium deposit is interpreted to be a modified placer-type deposit.

2.2 Introduction

There are over 360 000 tonnes of uranium ore hosted within quartz-pebble conglomerate (paleo-placer) deposits in Canada and South Africa, with individual deposits ranging from 5000 to 160 000 tonnes (Kyser and Cuney 2009; Dahlkamp 2009). The origin and formation of uranium minerals within quartz-pebble conglomerate deposits is controversial. Three genetic models of formation include: detrital/placer, hydrothermal, and hydrothermally modified placer (Little 1975). Proponents of the placer model use textural evidence such as the size, shape, and roundness of uraninite, brannerite, and pyrite grains along with the high-Th and variable uraninite content to suggest a detrital mode of uranium mineralization (Little 1975; Robertson 1975; Meddaugh et al. 1982; Minter 2006; Cuney 2009; Duhamel and Cuney 2009). Rundle and Snelling (1977) reported a uraninite age from the Witwatersrand deposit between 3086 and 3074 Ma, which is older than the host units (~2970 Ma), indicating a detrital origin. Studies that support the hydrothermal model used sulfur isotopes of pyrite along with U-Pb geochronology to suggest that uranium minerals precipitated from hydrothermal fluids (e.g., Yamaguchi and Ohmoto 2006). Some researchers have acknowledged that, although the majority of the uranium mineralization was detrital in origin, hydrothermal fluids later affected these deposits and some uranium minerals were precipitated from later hydrothermal fluids (e.g., Cuney 2009; Ono and Fayek 2011).

The objective of this study is to report U-Pb and Pb-Pb ages for the galena and uranium minerals from the Pele Mountain quartz-pebble conglomerate. These ages, in conjunction with

textural evidence, are used to determine the appropriate genetic model for the Pele Mountain quartz-pebble conglomerate uranium deposit.

2.3 Geologic Setting

Elliot Lake is located north of Lake Huron and is approximately 160 km west of Sudbury, Ontario, Canada. It resides within the boundary zone between the Archean Superior and Proterozoic Southern Geological Provinces of the Canadian Shield (Smethurst 2009). The geology of the area can be divided into two main parts: Archean basement rocks, sedimentary, and volcanic rocks of the Huronian Supergroup and post Huronain intrusive rocks (Fig. 2.1; Robertson 1975).



Figure 2.1. Simplified Geologic map of southern Ontario showing the distribution of Archean basement rocks and the Huronian Supergroup. Elliot Lake is denoted with a star (modified after Young et al. 2001).

The Archean basement in the area consists of Keewatin-type meta-volcanics and

Algoman granites with minor mafic intrusions (Frarey 1977). The Keewatin-type rocks include

massive and pillow lavas, pyroclastic, and sedimentary rocks. Granitic Algoman rocks (~2500 Ma) extend throughout the region and are characterized by medium- to coarse-grained gneissic to massive granodiorite and massive red quartz monzonite (Robertson 1975). The red quartz monzonite has been characterized as slightly radioactive, containing between 5 and 10 ppm U, and is therefore considered as a possible source for uranium in the Elliot Lake area (Darnley and Grasty 1971; Robertson 1975; Ruzicka 1975).

The Huronian Supergroup unconformably overlies the Archean basement, and consists predominantly of early Proterozoic siliciclastic rocks (Fig. 2.2; Roscoe 1975; Robinson and Spooner 1984). The Supergroup was deposited along an Archean cratonic margin during a period of Paleoproterozoic crustal extension. Crustal stretching created a basin for sediment deposition and avenues for volcanic activity (Rousell et al. 2002). Facies distribution within the basin was influenced by a supply of clastic detritus from short-headed river systems and their associated braided-deltas (Long 2004). The uranium-bearing Matinenda Formation was deposited within a high-energy, braided fluvial system as interpreted from trough cross-stratification and ripple laminations in interbedded quartzites (Robinson and Spooner 1984).

	Group	Formation	Member		
		Bar River			
	C 1 1	Gordon Lake			
	Cobait	Lorrain			
d		Gowganda			
rou Ia)		Serpent			
uronian Supergi (2,450 – 2,217 M	Quirke	Espanola			
	Lake	Bruce			
	Hough	Mississagi			
	Lake	Ramsey Lake			
		McKim			
H			Keelor		
	Flliot	Matinenda Manfred (2,450-2,350 Ma) Stinson			
	Lake				
			Ryan **		
		Livingstone Creek			

Figure 2.2. Generalized stratigraphic section of the Huronian Supergroup, with the U bearing Ryan Member indicated by ** (modified after Rousell et al. 2002).

The Elliot Lake Group, which hosts the Matinenda Formation, forms the base of the Huronian Supergroup and the upper part of the unconformity between the basement and the Supergroup (Fig. 2.2; Rousell et al. 2002). Deposition of the Huronian Supergroup occurred between ~2450 and ~2217 Ma based on relationships between the underlying Thessalon Formation (~2450 Ma) and the cross-cutting Nipissing intrusions (~2217 Ma) (Bekker and Kaufman 2007). The Matinenda Formation is located at the base of the Huronian Supergroup and, therefore, is likely closer in age to the Thessalon Formation than the Nipissing intrusions. Others have interpreted the Matinenda Formation to be coeval with the Copper Cliff Rhyolite

(between 2350 and 2450 Ma) based on an intercalated relationship observed south of Sudbury (Hattori et al. 1983; Krogh et al. 1984; Sutton and Maynard 1993; Murakami et al. 2011). Thus, for the purpose of this chapter, the authors have used the age of the Copper Cliff Rhyolite as the age of the Matinenda Formation as this is the best-constrained age for the formation available. The Matinenda Formation was deposited as a series of regressive sequences resulting in layers of pyritic and uraniferous quartz-pebble conglomerate interbedded with arkose sandstone (Kyser and Cuney 2009). From oldest to youngest, the formation is subdivided into four members; Ryan Member, Stinson Member, Manfred Member, and Keelor Member (Fig. 2.2). The Ryan Member is of particular interest as it hosts the bulk of the uranium mineralization for the Pele Mountain quartz-pebble conglomerate uranium deposit in what is referred to as the Main Conglomerate Bed (MCB) (Smethurst 2009).

Following the conclusion of Huronian sedimentation, the area was subjected to a long period of structural deformation, igneous activity including the emplacement of the Nipissing dikes (~2217 Ma) and regional metamorphism during the Penokean Orogeny (1900–1700 Ma; Riller et al. 1999; Robertson 1975).

2.4 Methodology

2.4.1 Petrography

Nine samples from diamond drill core were selected from the Pele Mountain quartzpebble conglomerate uranium deposit. Three samples were collected from each of the following boreholes on the Pele Mountain property: PM 84, PM 89, and PM 168 ranging between 123 to 240 m depth. Polished thin sections of all nine samples were made for petrographic

characterization. Mineralogical and textural relationships within the samples were characterized using both optical and scanning electron microscopy (SEM). All polished thin sections were examined in transmitted and reflected light using a Nikon Eclipse 50i polarizing microscope. Images of polished thin sections were taken using NIS Elements F 3.0 software. Thin sections were carbon coated, to create a conductive surface, prior to analysis using a Cambridge Stereoscan 120 scanning electron microscope (SEM) at the University of Manitoba. The SEM is equipped with a backscattered electron detector as well as an energy-dispersive X-ray spectroscopy detector with digital imaging capabilities. The SEM was used to further characterize the textures present within the samples and provide high-magnification images. Energy-dispersive spectroscopy was used to obtain qualitative characterization of the minerals in thin section.

2.4.2 Electron Microprobe Analysis

Based on petrographic results, three samples were chosen for quantitative chemical analysis by the electron microprobe (EMP). Analyses of the different uranium minerals and galena within the samples were obtained using the Cameca SX100 electron microprobe (EMP) with a PGT energy-dispersive spectrometer equipped with 5 wavelength-dispersive spectrometers at the University of Manitoba. For these analyses, the EMP was operated at an acceleration voltage of 15 keV with a 20 nA current with a beam size of 5 µm. Diopside, UO₂, sphene, fayalite, PbTe, andalusite, ThO₂, pyrite, albite, orthoclase, VP207, and apatite were used as standards to analyze the following elements: Si, Ca, U, Ti, Fe, Pb, Al, Th, S, Na, K, V, and P with detection limits of ~0.1 wt%.

Secondary Ion Mass Spectrometry

Based on petrographic and quantitative EMP results three samples were chosen for secondary ion mass spectrometry (SIMS) analysis, one from the quartz arenite and two from the quartzose conglomerate. Areas of textural and mineralogical interest indicated by petrography and EMPA were cut from the polished thin sections and placed into a phenyl ring 25 mm in diameter. The ring was filled with epoxy and left to set overnight. Prior to analysis, the phenyl ring mount was thoroughly cleaned then gold coated to create a conductive surface on the sample.

The analytical protocol for U-Pb and Pb-Pb isotopic measurements in uranium minerals using the CAMECA 7f ion microprobe at the University of Manitoba is similar to that used by Sharpe and Fayek (2011). Data obtained from standards and samples during the three analytical sessions are summarized in Tables 2.1 and 2.2. During SIMS analysis, an intrinsic mass-dependant bias is commonly introduced to the measurements; this is referred to as instrumental mass fractionation (IMF). Accurate SIMS analysis requires that the IMF be corrected by standardization with mineral standards chemically similar to the unknowns. Lead isotopes measured by SIMS exhibit negligible instrumental fractionation during sputtering (Fayek et al. 2002a, 2002b; Evans et al. 2001; Meddaugh 1983), therefore, uncertainties on 206 Pb/²⁰⁷Pb ratios are small (±0.05%), which result in errors in calculated 206 Pb/²⁰⁷Pb ages to be between ±1 and ±56 Ma (Tables 2.1 and 2.2). However, there is fractionation among U, Pb, and the isotopes of U (Fayek et al. 2002b). Although mass bias effects are minimal, a standard was used to correct the measurements obtained by SIMS analysis. Although we did not have a thorite or brannerite standard, unlike analysis of zircons or monazites by SIMS, which have trace concentrations of U and Pb, mass fractionation during SIMS analysis of uranium minerals is largely affected by Pb content, rather than crystal structure or other elements such as Th and Ti (Fayek et al. 2002a, 2002b; Ono and Fayek 2011). In addition, we found that by applying both medium mass resolution (DM/M 1400) and a voltage offset of -50 V, the matrix effects are minimized for uranium minerals with a range of Pb contents, therefore, a natural crystal of pegmatite-hosted uraninite (LAMNH) from the Scotty mine, Oxford County, Maine, was used to standardize the U-Pb isotopic analyses from all three analytical sessions. The LAMNH standard was used for this study because it has comparable Pb content to our samples (Evans et al. 2001). The measured values of the LAMNH standard by SIMS during an analytical session are compared to the accepted isotopic composition, shown in Table 2.3 (Evans et al. 2001), to calculate a correction factor (α) using Equation 1:

$$\alpha_{\text{SIMS}} = R_{\text{SIMS}} / R_{\text{TRUE}}$$
 [1]

where R_{SIMS} is the isotopic ratio measured directly by SIMS and R_{TRUE} is the accepted or true ratio measured by thermal ionization mass spectrometry (TIMS). The correction factor is then applied to the measurements of the unknown samples obtained during the same analytical session using Equation 2 (Fayek et al. 2002b):

$$R_{cor} = (R_{SIMS}/\alpha)$$
[2]

where R_{cor} is the corrected isotopic ratio for the samples and R_{SIMS} is the measured ratio for the samples. The uncorrected SIMS data is presented in Appendix 2.A.

The U-Pb isotopic ratios (²⁰⁷Pb/²³⁵U and ²⁰⁷Pb/²³⁵U) were used to estimate ages for thorite and brannerite using ISOPLOT (Ludwig 1993). Data points plotting together were averaged.

The Pb isotopic ratios (207 Pb/ 206 Pb) were used to determine the age of thorite, brannerite, and galena using Equation 3 and decay constants defined in Jaffey et al. (1971).

 $(^{207}\text{Pb}/^{206}\text{Pb}) = (1/137.88)[(e^{\lambda_2 t_{-1}})/(e^{\lambda_1 t_{-1}})]$ [3]

Sample	Sample Name	²⁰⁶ Pb/ ²⁰⁴ Pb	²⁰⁷ Pb/ ²⁰⁶ Pb	²³⁵ U/ ²³⁸ U	²⁰⁷ Pb/ ²³⁵ U	²⁰⁶ Pb/ ²³⁸ U	Analysis Date
Standard	LAMNH	1.030E+04	5.447E-02	7.485E-03	5.362E-01	7.359E-02	November 26, 2009
Standard	LAMNH	8.279E+03	5.576E-02	7.505E-03	5.588E-01	7.459E-02	November 26, 2009
Standard	LAMNH	1.050E+04	5.284E-02	7.500E-03	5.278E-01	7.431E-02	November 26, 2009
Standard	LAMNH	N/A	5.350E-02	7.459E-03	5.186E-01	7.224E-02	November 26, 2009
Average		9.691E+03	5.414E-02	7.487E-03	5.354E-01	7.368E-02	
Standard	Deviation	1.227E+03	1.272E-03	2.021E-05	1.722E-02	1.052E-03	
% Error	(1σ)	1.30E+01	2.00E+00	3.00E-01	3.00E+00	1.00E+00	
FF (a)		1.938E-01	1.007E+00	1.032E+00	1.303E+00	1.316E+00	
Standard	LAMNH	2.488E+02	5.401E-02	7.561E-03	4.810E-01	6.688E-02	January 25, 2010
Standard	LAMNH	2.489E+02	5.400E-02	7.546E-03	4.810E-01	6.675E-02	January 25, 2010
Standard	LAMNH	2.452E+03	5.429E-02	7.481E-03	5.108E-01	7.068E-02	January 25, 2010
Average		9.833E+02	5.410E-02	7.529E-03	4.909E-01	6.810E-02	
Standard	Deviation	1.272E+02	1.631E-04	4.252E-05	1.721E-02	2.232E-3	
% Error	(1σ)	1.29E+02	3.00E-01	1.00E+00	4.00E+00	3.00E+00	
FF (α)		1.967E-02	1.006E+00	1.038E+00	1.195E+00	1.216E+00	
Standard	LAMNH	NA	5.36E-02	7.43E-03	1.90E-01	2.67E-02	April 12, 2011
Standard	LAMNH	NA	5.33E-02	7.53E-03	1.46E-01	2.05E-02	April 12, 2011
Standard	LAMNH	NA	5.50E-02	7.34E-03	1.54E-01	2.05E-02	April 12, 2011
Average		NA	5.39E-02	7.43E-03	1.63E-1	2.25E-02	
Standard	Deviation	NA	8.90E-04	9.34E-05	2.38E-02	3.56E-03	
% Error	(1σ)	NA	1.65E+00	1.26E+00	1.46E+01	1.58E+01	
FF (a)		NA	1.00E+00	1.02E+00	3.97E-01	4.03E-01	

Table 2.1. Secondary ion mass spectrometer analyses of the LAMNH uraninite standard.

Mineralogy	²⁰⁶ Pb/ ²⁰⁴ Pb	Poisson%	²⁰⁷ Pb/ ²⁰⁶ Pb	Poisson%	²³⁵ U/ ²³⁸ U	Poisson%	²⁰⁷ Pb/ ²³⁵ U	Poisson%	²⁰⁶ Pb/ ²³⁸ U	Poisson%	
Thorite (conglomerate)	3.98E+03	1.09E+01	1.32E-01	1.23E+00	7.29E-03	1.29E+00	7.61E-01	1.60E+00	4.30E-02	4.55E-01	November 26, 2009
Thorite (conglomerate)	2.46E+03	3.75E+00	1.60E-01	4.75E-01	7.26E-03	1.21E+00	6.03E+00	1.29E+00	2.72E-01	2.10E-01	November 26, 2009
Thorite (conglomerate)	3.84E+03	1.06E+01	1.32E-01	1.24E+00	7.19E-03	1.13E+00	7.17E-01	1.60E+00	3.95E-02	4.39E-01	November 26, 2009
Thorite (conglomerate)	2.11E+03	2.19E+01	8.80E-02	2.46E+00	7.21E-03	1.32E+00	2.39E-01	2.68E+00	1.98E-02	7.30E-01	November 26, 2009
Thorite (conglomerate)	2.48E+03	1.40E+01	1.18E-01	1.82E+00	7.26E-03	1.33E+00	4.61E-01	2.17E+00	2.85E-02	6.09E-01	November 26, 2009
Thorite (conglomerate)	2.37E+03	3.54E+01	7.02E-02	2.91E+00	7.13E-03	1.30E+00	1.57E-01	3.09E+00	1.62E-02	7.80E-01	November 26, 2009
Thorite (conglomerate)	2.14E+03	1.56E+01	1.09E-01	2.22E+00	7.27E-03	1.40E+00	3.39E-01	2.49E+00	2.28E-02	7.12E-01	November 26, 2009
Thorite (conglomerate)	NA	1.57E+01	1.07E-01	1.76E+00	7.17E-03	7.73E-01	5.40E-01	1.86E+00	3.64E-02	5.44E-01	April 12, 2011
Thorite (conglomerate)	NA	2.06E+01	1.10E-01	1.81E+00	7.28E-03	7.19E-01	4.54E-01	1.84E+00	2.97E-02	5.66E-01	April 12, 2011
Thorite (conglomerate)	NA	2.37E+01	9.41E-02	2.23E+00	7.15E-03	7.77E-01	3.21E-01	2.30E+00	2.47E-02	6.54E-01	April 12, 2011
Thorite (conglomerate)	NA	3.36E+01	1.02E-01	2.77E+00	7.20E-03	8.31E-01	2.54E-01	2.77E+00	1.83E-02	8.32E-01	April 12, 2011
Thorite (conglomerate)	NA	1.90E+01	1.24E-01	1.90E+00	7.20E-03	9.57E-01	2.20E+00	2.02E+00	4.24E-02	6.40E-01	April 12, 2011
Thorite (conglomerate)	NA	3.80E+01	1.12E-01	3.06E+00	7.19E-03	1.07E+00	3.65E-01	3.02E+00	2.35E-02	9.60E-01	April 12, 2011
Thorite (arenite)	NA	4.50E+01	5.35E-02	3.50E+00	7.16E-03	1.20E+00	3.25E-01	3.59E-01	4.43E-02	7.50E-01	April 12, 2011
Thorite (arenite)	NA	NA	5.12E-02	3.37E+00	7.26E-03	1.00E+00	2.33E-01	3.48E+00	3.32E-02	7.60E-01	April 12, 2011
Thorite (arenite)	NA	5.04E+01	5.55E-02	2.87E+00	7.23E-03	9.12E-01	2.60E-01	3.04E+00	3.45E-02	6.65E-01	April 12, 2011

Table 2.2. Secondary ion mass spectrometer analyses, corrected using LAMNH, with poisson % errors.

Thorite	NA	5.80E+00	5.78E-02	3.66E+00	7.22E-01	1.00E+00	1.91E-01	3.60E+00	2.43E-02	8.60E-01	April 12,
Thorite (arenite)	NA	5.05E+01	5.15E-02	3.78E+00	7.15E-03	1.11E+00	2.32E-01	3.80E+00	3.19E-02	8.46E-01	April 12, 2011
Thorite (arenite)	NA	4.11E+01	5.23E-02	3.30E+00	7.12E-03	1.71E+00	6.88E-01	3.75E+00	9.68E-02	7.65E-01	April 12, 2011
Thorite (arenite)	NA	5.04E+01	5.91E-02	3.14E+00	7.21E-03	1.72E+00	7.74E-01	3.56E+00	9.57E-02	7.59E-01	April 12, 2011
Thorite (arenite)	NA	5.07E+01	7.66E-02	7.38E+00	7.08E-03	2.64E+00	3.50E-01	7.56E+00	3.20E-02	1.97E+00	April 12, 2011
Brannerite	7.14E+03	1.60E+01	7.57E-02	1.40E+00	7.42E-03	1.13E+00	5.09E-01	1.13E+00	5.03E-02	3.90E-01	November 26, 2009
Brannerite	6.85E+03	1.14E+01	8.49E-02	1.24E+00	7.30E-03	1.07E+00	6.42E-01	1.07E+00	5.56E-02	3.61E-01	November 26, 2009
Brannerite	5.48E+03	1.58E+01	7.38E-02	1.59E+00	7.34E-03	1.12E+00	4.15E-01	1.12E+00	4.13E-02	4.34E-01	November 26, 2009
Brannerite	8.49E+03	4.08E+01	6.73E-02	1.53E+00	7.34E-03	1.08E+00	4.17E-01	1.08E+00	4.55E-02	4.00E-01	November 26, 2009
Brannerite	5.21E+04	1.31E+01	7.50E-02	1.53E+00	7.27E-03	1.19E+00	5.10E-01	1.88E+00	5.03E-02	4.10E-01	January 25, 2010
Brannerite	5.06+04	1.16E+01	8.59E-02	1.33E+00	7.15E-03	1.17E+00	6.72E-01	1.71E+00	5.68E-02	3.92E-01	January 25, 2010
Galena	1.78E+03	2.23E+00	1.81E-01	3.13E-01	N/A	N/A	N/A	N/A	N/A	N/A	November 26, 2009

* Measurements taken on April 12, 2011 were calibrated taking into account the 15% error in the standard ²⁰⁶Pb/²³⁸U measurement

	TIMS sample	206/204	207/206	208/206	207/235	206/238
LAMNH	MF-1a	4200	0.05388	0.00254	0.409	0.055
	MF-3	>50000	0.05377	0.00264	0.411	0.055
	MF-3a	>50000	0.05377	0.00264	0.411	0.056

Table 2.3. Isotopic composition of LAMNH standard measured by TIMS (Evans et al. 2001).

2.5 Results

2.5.1 Petrography

Three of the nine samples examined are medium grained, medium to dark gray-green quartz arenite. The quartz arenite samples comprise 80–90% quartz, \leq 5% feldspar, and 5–15% sulfides, primarily pyrite with minor chalcopyrite, minor amounts of monazite and thorite, and trace zircon.

The six remaining samples are medium to dark gray-green, predominantly clast supported quartzose conglomerate. The quartzose conglomerate samples comprise 50–90% quartz, \leq 5% feldspar, \leq 5% mica, 5–40% sulfides, primarily pyrite with chalcopyrite, pyrrhotite, and galena, \leq 5% uranium minerals, minor amounts of monazite and rutile, and trace zircon. The samples contain 60–90% framework grains and 10–40% matrix material. Framework grains have an average diameter of 5–10 mm, and are a mixture of mono- and polycrystalline quartz pebbles that are equant to oblate and sub-rounded to rounded. The interstitial matrix consists of fine to medium sand-sized grains that are equant to oblate, or sub-rounded. Sample descriptions are presented in Appendix 2.B.

2.5.2 Sulfide and Oxide Minerals

Sulfide minerals comprise 5–20% of the samples; they average about 50 μ m and have various morphologies. Electron microprobe analysis and EDS indicate the primary sulfide mineralogy is pyrite (FeS₂) with chalcopyrite (CuFeS₂) and minor amounts of pyrrhotite (Fe_{1–x}S) and galena (PbS) (Fig. 2.3). Based on morphology and textural relationships pyrite is both detrital (Py1) and authigenic (Py2); sample Py1 is anhedral and sub-rounded to rounded; Py2 is typically subhedral to euhedral and in some cases encompasses Py1 and other detrital minerals (Fig. 2.3). Chalcopyrite and pyrrhotite are purely authigenic and formed around earlier minerals including Py2 (Fig. 2.3).



Figure 2.3. Reflected light photomicrograph showing textural relationship between various sulfide minerals within the quartzose conglomerate including two generations of pyrite (Py1 and Py2), chalcopyrite, pyrrhotite and detrital galena.

There appears to be two generations of galena. Detrital galena (Gn1) has an average size of about 50 μ m and is subhedral and sub-rounded (Figs. 2.3 and 2.4a), whereas small (up to 10 μ m) blebs of galena (Gn2) occur within thorite and brannerite grains (Figs. 2.4b and 2.4c).

Oxide minerals comprise 1–5% of the samples. Electron microprobe analysis and EDS indicate the silicate and oxide mineralogy within the samples is thorite $[(Th,U)SiO_4]$ and brannerite $[(U,Ca,Ce)(Ti,Fe)_2O_6]$ with trace rutile (TiO₂). Thorite can be identified by its relatively high ThO₂ concentrations (40–63 wt% ThO₂) and relatively low UO₂ concentrations (2–17 wt% UO₂), with SiO₂ and PbO concentrations ranging between 7–23 wt% SiO₂ and ≤9 wt% PbO. Brannerite is identified by a higher UO₂ concentration than thorite (22–34 wt% UO₂) with lower ThO₂ concentrations (≤ 4 wt% ThO₂); brannerite has SiO₂ and PbO concentrations ranging between 4–11 wt% SiO₂ and ≤ 3 wt% PbO. The most defining chemical characteristic of brannerite is the notable high concentration of TiO₂ (23–34 wt% TiO₂). The chemical composition of thorite and brannerite grains analyzed is presented in Appendix 2.C.

Thorite (Th1) grains are equant to elongate and sub-rounded to rounded (Figs. 2.4a, 2.4b, and 2.4d). Thorite within the quartz arenite has an average grain size of 0.1 mm (Figs. 2.4a and 2.4d) and an average grain size of 1 mm in the quartzose conglomerate (Fig. 2.4b). The smaller thorite grains within the arenite are fractured and infilled by pyrite (Py2) (Fig. 2.4a). Thorite grains are occasionally encapsulated by sulfide minerals, typically pyrite (Py2) (Fig. 2.4a). A trace amount of thorite (Th2) forms as exsolution lamellae in monazite grains (Fig. 2.4e). Most thorite (Th1) grains appear heterogeneous, with blebs of exsolved galena (Gn2) scattered throughout the grain indicating Pb loss (Fig. 2.4b).

Brannerite (Br) grains have an average grain size of $50-100 \mu m$, elongate, with a needlelike internal structure and a sub-rounded external texture (Fig. 2.4f). Brannerite is pseudomorphous after rutile (Figs. 2.4c and 2.4f) and is commonly associated with sulfides (Figs. 2.4c and 2.4f). Brannerite grains are observed to be heterogeneous with exsolved galena (Fig. 2.4c).



Figure 2.4. Backscattered electron images of sulfide and oxide minerals: A) Fractured thorite in quartz arenite encompassed by pyrite (Py2). B) Thorite (Th1) with exsolved galena (Gn2) in quartzose conglomerate. C) Brannerite with exsolved galena (Gn2) in quartzose conglomerate. D) Rounded thorite grains with associated pyrite in quartz arenite. E) Monazite with lamellae of exsolved thorite (Th2) and detrital galena (Gn1) in quartzose conglomerate. F) Brannerite (Br) with needle-like internal texture and associated pyrite (Py1) in quartzose conglomerate.

2.5.3 Mineral Paragenesis

The mineral paragenesis based on textural observations from the Elliot Lake quartzpebble conglomerate and arenite is summarized in Figure 2.5 and can be divided into detrital and hydrothermal minerals. Quartz (Q1), feldspar (Fsp), monazite (Mnz), zircon, pyrite (Py1), thorite (Th1), galena (Gn1), and rutile all occur as detrital mineral grains. Microcrystalline and recrystallized quartz (Q2) is associated with secondary pyrite (Py2) and iron-rich muscovite (Fems) in veins through the arenite. Chalcopyrite (Ccp) and pyrrhotite (Po) are observed to rim pyrite (Py2) among other minerals (Fig. 2.3) and are paragenetically late. Brannerite (Br) is pseudomorphous after rutile, suggesting brannerite has a later hydrothermal origin. There are two generations of galena including detrital grains (Gn1) and galena blebs (Gn2) exsolved from both thorite and brannerite (Gn2) (Figs. 2.4b and 2.4c).


Figure 2.5. Diagram showing the mineral paragenesis from the Pele Mountain quartz-pebble conglomerate uranium deposit. Uranium minerals are highlighted in red.

2.5.4 U-Pb and Pb-Pb Geochronology

U-Pb ages were obtained for thorite grains from both the quartzose conglomerate and quartz arenite along with brannerite from the quartzose conglomerate. Thorite in the quartzose conglomerate is highly discordant with an upper intercept age of 2489 ± 24 Ma with a lower intercept age of 83 ± 10 Ma (Fig. 2.6a). The age given by the lower intercept does not appear to correlate with any regional event rather suggests Pb diffusion was an ongoing process over an extended period of time. Conversely, thorite grains in the quartz arenite are only slightly discordant with an upper intercept age of 280 ± 67 Ma (Fig. 2.6b).

The brannerite grains, like thorite in the conglomerate, are highly discordant with an upper intercept age of 2403 ± 120 Ma and a lower intercept age of 252 ± 8 Ma (Fig. 2.6c). The age given by the lower intercept correlates to, and may be influenced by Pangean tectonism (320–185 Ma), prior to the initial break up of Pangea at about 185 Ma (Veevers 2004).



Figure 2.6. Concordia plots for the uranium minerals from the Pele Mountain quartz-pebble conglomerate uranium deposit. A) Thorite from the quartzose conglomerate unit with an upper intercept age of 2489 ± 24 Ma and a lower intercept of 83 ± 10 Ma. B) thorite from the quartz arenite unit with an upper intercept age of 280 ± 67 Ma, and C) brannerite with an upper intercept age of 2403 ± 120 Ma and a lower intercept of 252 ± 8 Ma.

The Pb isotope ratios obtained by SIMS analysis were used to calculate Pb-Pb isotopic ages of thorite, brannerite, and galena (Table 2.4). Thorite from the quartzose conglomerate has a wide range of Pb-Pb ages between 2453 ± 12 and 935 ± 27 Ma; thorite from the quartz arenite has Pb-Pb ages between 521 ± 19 and 248 ± 8 Ma. The Pb-Pb ages for brannerite are between 1335 ± 0.11 and 848 ± 13 Ma. Galena has an Archean age of 2659 ± 8 Ma.

	²⁰⁷ Pb/ ²⁰⁶ Pb Age (Ma)	Error (Ma)
Thorite		
Quartzose Conglomerate		
	1748	31
	1799	33
	1510	34
	1653	46
	1840	56
	2120	26
	2453	12
	2131	26
	1383	34
	1927	35
	935	27
	1780	40
Quartz Arenite		
	349	12
	248	8
	431	12
	521	19
	263	10
Brannerite	1078	8
	1314	16
	1335	1
	848	13
Galena	2659	8

Table 2.4. Calculated ²⁰⁷Pb/²⁰⁶Pb ages of thorite, brannerite and galena.

2.6 Discussion

Quartz-pebble conglomerate uranium deposits were economically significant, and therefore have been extensively studied for decades (e.g., Robertson 1975; Roscoe 1975; Frarey 1977; Cochrane et al. 2007; Smethurst 2009). In addition, U⁴⁺-mineralization (e.g., uraninite, thorite) in these deposits generally occurs as disseminated grains in fluvial sediments older than about 2300 Ma (Kyser and Cuney 2009). Despite numerous studies, the processes associated with the formation of these deposits and the age of uranium mineralization has remained controversial. The study of U⁴⁺-rich minerals such as uraninite is complicated by the susceptibility of this phase to alteration in oxic surface environments (Janeczek and Ewing 1995; Kotzer and Kyser 1995; Fayek and Kyser 1997, 1999). The association of uraninite with fluvially deposited sediments prompted most early researchers to suggest the uranium minerals associated with quartz-pebble conglomerate deposits were detrital in origin (e.g., Ruzicka 1975; Robertson 1975; Little 1975).

Numerous studies have used textures, mineral chemistry, and the ages of uranium and other minerals to argue for the detrital, hydrothermal, or mixed origin of uranium minerals within quartz-pebble conglomerate deposits (e.g., Ruzicka 1975; Little 1975; Robinson and Spooner 1982; Meddaugh et al. 1982; Frimmel 2005; Minter 2006; Yamaguchi and Ohmoto 2006; Duhamel and Cuney 2009). The sulfur isotopic composition of pyrite from the Elliot Lake deposit was studied by Yamaguchi and Ohmoto (2006). They divided pyrite grains by morphology into "younger" and "older" groups. The pyrite that appears detrital in origin based on petrography (rounded and anhedral) is classified as "older" pyrite and has δ^{34} S values that range between –3.1 to ~+4.0‰ and the "younger" (subhedral and euhedral) pyrite δ^{34} S ranges

between –9 and +5.5‰. Although these values are similar to the δ^{34} S values of mantle-derived sulfides, which range between –3 to +2‰, Yamaguchi and Ohmoto (2006) suggested the pyrite grains within the Matinenda Formation are hydrothermal in origin. However, hydrothermal pyrite grains generally have δ^{34} S values that are >5‰ (Ohmoto 1986). Based on the morphology and textures observed in this study, two generations of pyrite were identified: (1) detrital pyrite (Py1), and (2) late hydrothermal pyrite (Py2) (Fig. 2.3). Therefore, the data from Yamaguchi and Ohmoto (2006) along with petrography from our study suggests that "older" pyrite (Py1) in the Matinenda Formation is detrital in origin as the grains are rounded and anhedral, with δ^{34} S values similar to magmatic sulfide values. "Younger" pyrite (Py2) is likely hydrothermal or diagenetic in origin because Py2 occurs as overgrowths on other mineral grains such as thorite and Py1 and a wider range of δ^{34} S values.

Previous geochronology studies on the Elliot Lake deposit reported U-Pb and Pb-Pb isotopic ages for uranium minerals and galena, respectively (Meddaugh et al. 1982; Meddaugh 1983; Ono and Fayek 2011). Meddaugh et al. (1982) reported Pb-Pb ages for galena from the Elliot Lake quartz-pebble conglomerate that were interpreted to be the age of Pb loss events at 2150 and 1700 Ma, under the assumption that all the Pb in the galena was radiogenic and the uraninite had to be older than 2150 Ma. Meddaugh (1983) used U-Pb isotopes to date uraninite from Elliot Lake and reported ages from 2210 ± 430 to 2575 ± 180 Ma. Within error, these ages are older than the deposition of the Matinenda Formation and suggest a detrital origin. Ono and Fayek (2011) used U-Pb isotopes to date uranothorite, uraninite, and brannerite from the Elliot Lake area. All the uranium minerals are highly discordant. Uranothorite consists of exsolved galena inclusions and gives an upper intercept age of 2348 ± 121 Ma, whereas uraninite from

discordia lines giving upper intercept ages between 1780 and 1880 Ma (Ono and Fayek 2011). The age of the uranothorite is older than the Matinenda Formation, whereas the ages of the uraninite match the age of the Penokean Orogeny when the Huronian Supergroup experienced maximum metamorphism. This event likely reset the U-Pb isotope system in the uraninite. However, the high Th content (>4 wt%) of the uraninite grains suggest that uraninite formed at high temperatures (e.g., magmatic) and were likely derived from a magmatic source (Cuney 2009). Brannerite has an upper intercept age of 1448 ± 435 Ma (Ono and Fayek 2011). Textural relationships and morphology of brannerite within the deposits suggest secondary replacement of rutile by hydrothermal fluids (Saager and Stupp 1983; Robinson and Spooner 1984), whereas Ruzicka (1975) argues a detrital origin for brannerite based on rounded shape of the grains. Therefore, Ono and Fayek (2011) concluded that the uraninite and uranothorite minerals were detrital in origin, and the brannerite formed from hydrothermal fluids that also affected the U-Pb system in uraninite.

The samples from the Pele Mountain quartz-pebble conglomerate uranium deposit of the Elliot Lake district, Canada, from this study contain thorite and brannerite and are devoid of uraninite. The U-Pb age of thorite grains are similar to the uraninite ages from other deposits in the Elliot Lake district. Thorite grains within the quartzose conglomerate have a U-Pb age of 2489 \pm 24 Ma, which is within the range of uraninite and uranothorite ages from previous studies of 2210 \pm 430 to 2575 \pm 180 Ma (Meddaugh 1983; Ono and Fayek 2011). Thorite grains from the quartz arenite have a U-Pb age of 280 \pm 67 Ma, this age is significantly younger than uraninite ages from previous studies. Thorite from the quartz arenite (280 \pm 67 Ma) is significantly younger than the Matinenda Formation and these grains are fractured and

significantly smaller than thorite grains from the conglomerate (0.1 μ m in the arenite vs. 1 μ m in the conglomerate). The smaller grains in the arenite are fractured and these fractures are infilled with late pyrite (Py2). This late pyrite indicates that a fluid interacted with these grains along fractures, which could have facilitated Pb loss. Therefore, the small and fractured thorite grains experienced nearly complete Pb loss during regional tectonic events. The U-Pb age of thorite in the quartz arenite correlates with Appalachian tectonics (760–250 Ma) encompassing failed rifting, opening of the Iapetus, Taconic Orogeny, Acadian Orogeny, and Alleghanian Orogeny (Park et al. 2010). Because these gains are small (~100 μ m), rounded, fractured, and only slightly discordant, they may indeed be detrital but hydrothermal fluids related to regional tectonics have reset the grains imparting a false young age.

Brannerite from the Pele Mountain quartz-pebble conglomerate uranium deposit gives a U-Pb age of 2403 ± 120 Ma, which is older than the brannerite described in Ono and Fayek (2011), but similar in age to the uranium minerals in the study by Meddaugh (1983). Galena (2659 \pm 8 Ma) and thorite from the quartzose conglomerate (2490 ± 29 Ma) are both older than the Matinenda Formation (2450-2350 Ma) and the uranothorite reported in Ono and Fayek (2011). Their rounded and relatively unaltered textures suggest that these grains are detrital. The different ages for these two minerals indicate multiple sources of detritus for the Matinenda Formation (2450-2350 Ma) and is observed to psuedomorphically replace rounded grains of rutile, which would have been part of the detritus. Because the age of brannerite is within the range of ages reported for the Matinenda Formation, it is likely these grains were not deposited in the Ryan Member at the base of the formation, but formed after deposition of the

member. Based on textural evidence and geochronology, the formation of brannerite is most likely related to circulating hydrothermal fluids generated by tectonic events such as Blezardian tectonics between 2400–2200 Ma (Riller et al. 1999).

The Pb-Pb ages of thorite and brannerite from the conglomerate are significantly younger and have a wider range than their U-Pb ages; whereas thorite grains from the quartz arenite have similar Pb-Pb and U-Pb ages (Fig. 2.7). Figure 2.7 shows a group of Pb-Pb ages of thorite from the conglomerate that range between 1600 and 1900 Ma. These ages correlate with the ages obtained by Ono and Fayek (2011), which are attributed to Pb loss events. Petrography of these samples shows Pb exsolution in both thorite and brannerite (Figs. 2.4b and 2.4c), indicating these minerals experienced significant Pb loss. Physical evidence of Pb loss (i.e., exsolved galena) in addition to a high degree of discordance indicate that the Pb-Pb ages do not reflect formational ages but ages of Pb loss events. Because thorite from the quartz arenite is only slightly discordant, the Pb-Pb ages closely mirror the U-Pb age and represent the age of the resetting event. The Pb-Pb isotopic ages for the uranium minerals (Table 2.4) coincide with numerous regional tectonic events including: deposition of the Huronian Supergroup (2450-2217 Ma), Blezardian Orogen (2400–2200 Ma), Penokean Orogen (1900–1700 Ma), the Grenville Orogen (1300–950 Ma), and Appalachian tectonics (760–250 Ma) (Fig. 2.7; Hattori et al. 1983; Bennett et al. 1991; Riller et al. 1999; Rousell et al. 2002; Park et al. 2010). For example, Pb-Pb post depositional ages of thorite from the quartzose conglomerate suggests that the grains were affected by the Blezardian, Penokean, and Grenvillian Orogenic events, whereas the Pb-Pb ages of brannerite are consistent with Grenvillian tectonics. U-Pb and Pb-Pb ages for quartz arenite thorite indicate resetting was associated with Appalachian tectonics (Fig. 2.7).



Figure 2.7. Schematic showing the approximate U-Pb and Pb-Pb ages of thorite, brannerite and galena from this study in comparison to the approximate ages of various orogenic and depositional events.

Petrography and geochronology of uranium minerals in the Pele Mountain quartz-pebble conglomerate uranium deposit suggest that this deposit has had a protracted history of Pb loss and U remobilization. Based on grain morphology and ages that are older than the host Matinenda Formation, thorite and galena are detrital minerals, whereas brannerite is a pseudomorphic replacement of rutile related to circulating hydrothermal fluids. The U-Pb ages of the uranium minerals within the Pele Mountain quartz-pebble conglomerate are both detrital (thorite) and hydrothermal (brannerite) in origin. The presence of both detrital and hydrothermal uranium minerals suggests that the Pele Mountain quartz-pebble conglomerate deposit is a modified paleoplacer-type uranium deposit.

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2.8 References

- Bekker, A. and Kaufman, A.J. (2007) Oxidative forcing of global climate change: a biogeochemical record across the oldest Paleoproterozoic ice age in North America. Earth and Planetary Science Letters, 258, 486-499.
- Bennett, G., Dresser, B.O. and Robertson, J.A. (1991) The Huronian Supergroup and associated intrusive rocks. In Geology of Ontario. Edited by Thurston, P.C. et al., Ontario Geological Survey Special Paper, 4, 549-591.
- Cochrane, L.B., Hwozdyk, L.R. and Hayden, A.S. (2007) Preliminary assessment on the Elliot Lake project, Ontario, Canada: Prepared for Pele Mountain Resourses Inc. Technical Report.
- Cuney, M. (2009) The extreme diversity of uranium deposits. Mineral Deposita, 44, 3-9.
- Dahlkamp, F.J. (2009) Uranium deposits of the world. Springer, Berlin, Heidelberg.
- Darnley, A.G. and Grasty, R.L. (1971) Airborne radiometric survey of the Elliot Lake area. Canadian Geological Survey, Open File Report no. 75.
- Duhamel, I. and Cuney, M. (2009) Geochemistry of uraninite from the Elliot Lake and Wits basins: New insights on the source of uranium. Goldschmidt Conference Abstract Page A312.

- Evans, L.Z., Sunde, T., Schöberg, H. and Fayek, M. (2001) U and Pb isotope calibration of uraninite and galena standards for SIMS. SKB Technical Report TR-01-35.
- Faure, G. (1977) Principles of Isotope Geology. John Wiley and Sons, New York, USA.
- Fayek, M. and Kyser, K.T. (1997) Characterization of multiple fluid events and rare-earthelement mobility associated with formation of unconformity-type uranium deposits in the Athabasca Basin, Saskatchewan. Canadian Mineralogist, 35, 627-658.
- Fayek, M. and Kyser, K.T. (1999) Stable isotope geochemistry of uranium deposits. Reviews in Mineralogy, 38, 181-220.
- Fayek, M., Harrison, M.T., Ewing, R.C., Grove, M. and Coath, C.D. (2002a) O and Pb isotopic analyses of uranium minerals by ion microprobe and U-Pb ages from the Cigar Lake deposit. Chemical Geology, 185, 205-225.
- Fayek, M., Kyser, K.T. and Riciputi, L.R. (2002b) U and Pb isotope analysis of uranium minerals by ion microprobe and the geochronology of the McArthur River and Sue Zone uranium deposits, Saskatchewan, Canada. Canadian Mineralogist, 40, 1553-1569.
- Frarey, M.J. (1977) Geology of the Huronian Belt between Sault Ste. Marie and Blind River, Ontario. Geologic Survey of Canada; Energy Minerals and Resources Canadian Memoirs, 383, 87 pages.
- Frimmel, H.E. (2005) Archean atmospheric evolution: evidence from the Witwatersrand gold fields, South Africa. Earth Science Reviews, 70, 1-46.
- Hattori, K., Campbell, F.A. and Krouse, H.R. (1983) Sulfur isotope abundances in Aphebian clastic rocks: the implications for the coeval atmosphere. Nature, 302, 323-326.
- Jaffey A.H., Flynn, K.F., Glenndenian, L.E., Bentley, W.C. and Essling, A.M. (1971) Precision measurements of the half-lives and specific activities of ²³⁵U and ²³⁸U. Physics Review, 4, 1889-1906.
- Janeczek, J. and Ewing, R.C. (1995) Mechanisms of lead release from uraninite in the natural fission reactors in Gabon. Geochimica Acta., 59, 1917-1931.
- Kotzer, T.G. and Kyser, K.T. (1995) Petrogenesis of the Proterozoic Athabasca Basin, northern Saskatchewan, Canada, and its relation to diagenesis, hydrothermal uranium mineralization and paleohydrogeology. Chemical Geology, 120, 45-89.
- Krogh, T.E., Davis, D.W. and Corfu, F. (1984) Precise U-Pb zircon and baddeleyite ages for the Sudbury Structure. Edited by Pye, E.G. Ontario Geological Survey, Special Volume 1, 431-446.
- Kyser, K. and Cuney, M. (2009) Recent and not-so-recent developments in uranium deposits and implications for exploration. Mineralogical Association of Canada Short Course, 39.
- Little, H.W. (1975) Genesis of Canadian uraniferous quartz-pebble conglomerate ores. Genesis of uranium- and gold- bearing Precambrian quartz-pebble conglomerates. Geological Survey Professional Paper 1161-A-BB.

- Long, D.G.F. (2004) The tectonostatigraphic evolution of the Huronian basement and the subsequent basin fill: Geological constraints on impact models of the Sudbury event. Precambrian Research, 129, 203-223.
- Ludwig, K.R. (1993) ISOPLOT: A plotting and regression program for radiogenic-isotope data. U.S. Geological Survey, Open File Report 91-445.
- Meddaugh, W.S. (1983) Age and origin of uraninite in the Elliot Lake, Ontario uranium ores. Ph.D. Thesis; Harvard University, Camridge, Massachusetts.
- Meddaugh, W.S., Holland, H.D. and Shimizu, N. (1982) The isotopic composition of lead in galena's in the uranium ores at Elliot Lake, Ontario, Canada. Ore genesis; the state of the art, 25-37.
- Minter, W.E.L. (2006) The sedimentary setting of Witwatersrand placer mineral deposits in an Archean atmosphere. In Evolution of Earth's Early Atmosphere, Hydrosphere, and Biosphere-Constraints from Ore Deposits. Geological Society of America Memoir, 198, 105-119.
- Murakami, T., Kasama, T. and Utsunomiya, S. (2011) Early Proterozoic weathering under low O₂ conditions reconstructed from a 2.45 Ga paleosol in Pronto, Canada. American Mineralogist, 96, 1613-1623.
- Ohmoto, H. (1986) Stable isotope geochemistry of ore deposits. Stable Isotopes in High Temperature Geological Processes. Reviews in Mineralogy, 16, 491-560.
- Ono, S. and Fayek, M. (2011) Decoupling of O and Pb isotope systems of uraninite in the early Proterozoic conglomerates in the Elliot Lake district. Chemical Geology, 288, 1-13.
- Park, H., Barbeau, D.L., Rickenbaker, A., Bachmann-Krug, D. and Gehrels, G. (2010) Application of foreland basin detrital-zircon geochronology to the reconstruction of the southern and central Appalachian orogen. Journal of Geology, 118, 23-44.
- Riller, U., Schwerdtner, W.M., Halls, H.C. and Card, K.D. (1999) Transpressive tectonism in the eastern Penokean orogen, Canada cosequences for Proterozoic crustal kinematics and continental fragmentation. Precambrian Research, 93, 51-70.
- Robertson, J.A. (1975) The Blind River uranium deposits: the ores and their settings. Genesis of uranium- and gold- bearing Precambrian quartz-pebble conglomerates. Geological Survey Professional Paper 1161-A-BB.
- Robinson, A. and Spooner, E.T.C. (1982) Source of the detrital components of uraniferous conglomerates, Quirke ore zone, Elliot Lake, Ontario, Canada. Nature 299, 622-624.
- Robinson, A. and Spooner, E.T.C. (1984) Postdepositional modification of uraninite-bearing quartz-pebble conglomerates from the Quirke Ore Zone, Elliot Lake, Ontario. Economic Geology, 79, 297-321.
- Roscoe, S.M. (1975) Temporal and other factors affecting deposition of uraniferous conglomerates. Genesis of uranium-and gold-bearing Precambrian quartz-pebble conglomerates. Geological Survey Professional Paper 1161-A-BB.

- Rousell, D.H., Meyer, W. and Prevec, S.A. (2002) Bedrock geology and mineral deposits. Special Volume Ontario Geological Survey, 5, 21-55.
- Rundle, C.C. and Snelling, N.J. (1977) The geochronology of uraniferous minerals in the Witwatersrand triad: an interpretation of new and existing U-Pb data on rocks and minerals from the Dominion Reef, Witwatersrand and Ventersdorp Supergroups. Philosophical Transactions of The Royal Society of South Africa, 286, 567-583.
- Ruzicka, V. (1975) Some metallogenic features of the Huronian and post-Huronian uraniferous conglomerates. Genesis of uranium- and gold- bearing Precambrian quartz-pebble conglomerates. Geological Survey Professional Paper 1161-A-BB.
- Saager, R. and Stupp, H.D. (1983) U-Ti phases from Precambrian quartz-pebble conglomerates of the Elliot Lake area, Canada, and the Pongola Basin, South Africa. Tschermaks Mineralogische und Petrographische Mitteiungen, 32, 83-102.
- Sharpe, R. and Fayek, M. (2011) The world's oldest observed primary uraninite. The Canadian Mineralogist, 49, 1199-1210.
- Smethurst, M.T. (2009) Assessment and activities report: Pele Mountain Resources INC. Drilling Campaign, Elliot Lake, June 4, 2008 to February 23, 2009. Technical Report.
- Sutton, S.J. and Maynard, J.B. (1993) Petrology, mineralogy, and geochemistry of sandstones of the lower Huronian Matinenda Formation: Resemblance to underlying basement rocks. Canadian Journal of Earth Sciences, 30, 1209-1223.
- Veevers, J.J. (2004) Gondwanaland from 650-500 Ma assembly through 320 Ma merger in Pangea to 185-100 Ma breakup: supercontinental tectonics via stratigraphy and radiometric dating. Earth and Science Reviews, 68, 1-132.
- Yamaguchi, K.E., and Ohmoto, H. (2006) Evidence from sulfur isotope and trace elements in pyrites for their multiple post-depositional processes in uranium ores at the Stanleigh Mine, Elliot Lake, Ontario, Canada. In Evolution of Earth's Early Atmosphere, Hydrosphere, and Biosphere-Constraints from Ore Deposits. Geological Society of America Memoir, 198, 143-156.
- Young, G.M., Long, D.G.F., Fedo, C.M. and Nesbitt, H.W. (2001) Paleoproterozoic Huronian basin: Product of a Wilson cycle punctuated by glaciations and a meteorite impact. Sedimentary Geology, 141-142. 233-254.

Chapter 3. Characterization of Uranium Mineralogy and Geochemistry of the Lorado Mill Historical Tailings Site, Uranium City, Saskatchewan, Canada

3.1 Abstract

The characterization of uranium (U) in mine tailings is important in developing a better understanding of uranium transport and its potential impact on the environment. The main objective of this research is to characterize the U mineralogy, geochemistry and transport within the top meter of the Lorado Mill historical tailings site in northern Saskatchewan. The heterogeneous tailings, broadly consisting of a sand horizon overlying a silty horizon, were characterized both laterally and vertically. Uranium concentration increases with depth and is elevated within the silty horizons; however U is especially concentrated within surface sulfate salts. Synchrotron characterization of the U speciation and associated elements, indicate local variability not identified by previous site assessments. Mineralogical and chemical characterization of the U in the Lorado tailings suggests U is being oxidized and is transported upwards by water through evaporation and is concentrated in surface evaporite minerals. The sulfates are soluble and represent a significant means for U introduction into the environment.

3.2 Introduction

Uranium exploration in northern Saskatchewan began in 1944, when federal government geologists started investigating radioactive veins identified during previous gold exploration (Beck 1986; Smith 1986). A ban on exploring for and producing U, due to the metal's military significance, was lifted after World War II, resulting in Canada's first U boom. As a result of this boom approximately 16 producing deposits and the settlement known as Uranium City were established along the north shore of Lake Athabasca (Beck 1986). Three mills operated out of the Uranium City Region including Lorado (1957-1960), Gunnar (1955-1964) and Eldorado (1953-1982). Lorado processed 425,474 tons of ore, yielding 1,009,282 kilograms of recovered U_3O_8 (Smith 1986). Mines and mills shut down due to depleted ore bodies, decreased global markets and the discovery of large U reserves in the Athabasca Basin in the late 1960's and 1970's, resulting in the decline of Uranium City (Beck 1986; Cameco 2012).

The Lorado Mill is located within the Beaverlodge mineral district of the Precambrian Shield, north of Lake Athabasca approximately 10 km southwest of Uranium City (Fig. 3.1). The mill treated ore from a number of mines including its namesake the Lorado Mine as well as the Cayzor, Rix Leonard and Cinch Lake mines (SRC 2009). These deposits are characterized as having a simple mineralogy mineral assemblage containing uraninite, quartz, carbonates, chlorite, hematite, pyrite, chalcopyrite, galena with occasional brannerite and coffinite. These deposits are hosted by a package of metamorphosed sedimentary and volcanic rocks referred to as the Tazin Group (Amendolagine 1956; Beck 1986). Upon arrival at the mill, ore was crushed and ground to 60% minus the 200 mesh fraction, the ground material was then leached with sulfuric acid to dissolve U minerals. The U loaded solution passed through ion exchange columns where U was deposited onto resin. Dilute hydrochloric acid was used to rinse the resin; magnesium oxide (MgO) was used to precipitate out the U. The tailings, which were discharged into an adjacent topographic depression eventually overflowed into Nero Lake; with a total estimated tailings volume of 227,000 m³ (Golder 2008; Edwards 2012).



Figure 3.1. A series of simplified maps illustrating the location of the study area within the province of Saskatchewan relative to Uranium City. A) Is a simplified map of Saskatchewan showing the generalized location of the study area, B) shows the location of the Lorado Mill Tailings site with respect to Uranium City. C) Is a simplified map of the Lorado Mill Tailings site showing the sampling area along A-A', core locations along A-A' are indicated with circles.

In early periods of the U mining industry (1940's-1960's), there was little thought towards protecting the environment or creating legislation to protect the environment. When many mining activities shut down during the 1960's, they were simply abandoned; many of these sites have ongoing environmental issues related to radiation and contamination due to seepage from tailings and waste rock piles (Waggitt 2008). Improper disposal of mill tailings during early U mining has resulted in substantial soil, surface water and groundwater contamination. Most environmental concerns associated with mill tailings are related to their tendency to readily react with air and water (Jamieson 2011). However, U tailings present a unique set of concerns, due to the presence of U and its associated decay products. Effective milling processes can remove only up to 90% of the U, allowing at least 10% to make its way into the tailings. Once in the tailings area, the U may readily react with surface water and atmosphere potentially mobilizing it into the local environment especially in situations where no effective tailings containment is in place (Mudd 2000; Abdelouas 2006; Lottermoser 2007; Jamieson 2011). Environmental contamination by U is of concern due to its radiotoxic and chemo-toxic properties; the main toxic effect U has on organisms is DNA damage, which can result in mutations (Schnug and Haneklaus 2008). In order to take steps to remediate a U mill tailings site to avoid U contamination in the environment, it is important to understand the character of U within tailings.

A single previous detailed site assessment of the Lorado Tailings (Golder 2008) looked at the site in a very broad manner and carried out extensive bulk analyses. This offers important information about the tailings but does not reveal the small-scale complexities existing within the tailings that drive metal mobility. To accurately predict the U transport processes and mobility

within tailings, it is important to understand the following: location of U on a macro and micro scale, the form of U present and where the U is bound. Thus, the objective of this study is to carry out a detailed analysis of the top meter of the Lorado Tailings to characterize the U and its movement.

3.3 Sampling and Analytical Methods

3.3.1 Sampling Strategies

In June 2010 preliminary site investigation and sampling including a single 1 m core was carried out. A more extensive and detailed sampling program took place in June of 2011 where 11 core samples were collected; including a single 1 m core and ten 0.5 m cores. Site conditions and sampling methods documented in Appendix 3.A. A southwest northeast transect through the tailings, marked A-A' on figure 3.1, from the road to Nero Lake was defined by five cores including the 1 m core located closest to the road and former mill site. The other six 0.5 m cores were collected from various locations throughout the tailings. For the purpose of this study only results from the five cores collected along A-A' (Fig. 3.1) will be discussed in detail as the remaining cores agree with results from these five cores.

Core samples were collected using 2" diameter central vacuum tubing cut into 0.5 m sections. The section of pipe was hammered into the ground till flush with tailings surface, the tube was then capped with a central vacuum pipe end cap to avoid contaminating debris. The pipe was dug out and capped; the resulting pit was then filled in to avoid creating potential safety hazards. Once the pipe was recovered they were secured with duct tape and up direction and location was labeled on each core for identification.

The cores were vacuum-sealed in FoodSaver® 8"x20' Heat-seal rolls using a FoodSaver® V2060 Vacuum Sealer for transport and storage. The cores were kept in a cool dry place until they could be frozen upright for approximately 4 weeks 5 days after collection. Once frozen solid, the cores were split lengthwise twice producing a single ½ section and two ¼ sections for each core, using a non-lubricated diamond blade on a table saw. The ½ section was left to ambient conditions to air dry before continuous 2" segments were collected for bulk chemical and XRD analysis. One of the ¼ sections from selected cores was cut into consecutive sections correlating with segments sent for bulk chemical characterization, for polished thin sectioning. Polished thin sections were prepared by Vancouver Petrographics in Langley, British Columbia in the absence of water to prevent the possible dissolution of soluble phases.

Extensive salt crusts not present in 2010 were observed in 2011 covered large areas of the tailings with a range in colour from brown to white to orange. Twenty salt samples were collected to obtain a representative collection of the various colours, ranging from brown, to white to orange. The salts were sampled and characterized separately from the tailings mass. The salt samples were stored and transported in dry plastic containers.

Polished salt mounts were prepared for a small number of salt samples allowing for more detailed analyses. To avoid dissolution of the salt components mounts were prepared in two steps, where water could be used in the first step to clean the mount allowing for a solvent free second step. A 5 mm layer of epoxy was poured into 25 mm diameter phenyl rings using a glass slide and grease as a bottom seal. Once hardened the phenyl ring and epoxy mount was thoroughly cleaned and dried. Selected pieces of salt were placed in the phenyl ring on the

epoxy base and more epoxy was poured around the salt piece. Once the epoxy cured the mounts were polished using a series of sand papers creating a smooth, flat polished surface on the salt. *3.3.2 Powder X-ray Diffraction*

Powder x-ray diffraction (XRD) using a Siemens Diffraktometer D5000 at the University of Manitoba was used to determine bulk mineral composition of the tailings and salt samples. Mounts were prepared without the use of solvents to avoid partial sample dissolution. The samples were analyzed using a zero background quartz plate and resulting spectra were compared to MDI Jade 7.5 XRD software for mineral identification.

3.3.3 Ultra-Trace Metal Analysis

Bulk trace metal analysis of 51 metals for 120 solid tailings samples and 15 solid salt samples was determined using an aqua regia digestion of a 0.5 g aliquot followed by inductively coupled plasma-mass spectroscopy (ICP-MS) and inductively coupled plasma-atomic emission spectroscopy (ICP-AES) analyses at ALS laboratories (package ME-MS41).

3.3.4 Scanning Electron Microscopy

Sample mineralogy was further characterized, including identification of U grains, using the energy-dispersive spectrometer (EDS) capabilities of the Cambridge Stereoscan 120 scanning electron microscope (SEM) at the University of Manitoba. Images were collected using a backscattered electron detector for atomic number contrast. The SEM was used to help with mineral identification as well as locating uranium mineral grains present within the samples and obtain high magnification images. Energy dispersive spectroscopy was used to obtain qualitative characterization of the minerals in carbon coated thin sections.

3.3.5 Electron Microprobe

A Cameca SX100 electron microprobe (EMP) with a PGT EDS equipped with 5 wavelength-dispersive spectrometers at the University of Manitoba was used to characterize the chemistry of the U grains identified by SEM and the salt samples. The EMP operated at an acceleration voltage of 15 keV with a 20 nA current with a beam size of 5 µm. Diopside, UO₂, sphene, fayalite, PbTe, andalusite, ThO₂, pyrite, albite, orthoclase, VP207 and apatite were used at standards to analyze the following elements: Si, Ca, U, Ti, Fe, Pb, Al, Th, S, Na, K, V and P with detection limits of ~0.1 wt %. Images were collected using a backscattered electron detector for atomic number contrast. Qualitative x-ray element maps were used to guide the quantitative mirco-analysis of the salt mounts. Targets from thin sections were chosen based on previous SEM characterization.

3.3.6 Synchrotron Analysis

Synchrotron analysis, including XANES, has become an important analytical method for environmentally relevant elements in sediments such as tailings. XANES has the ability to provide molecular-scale information on element speciation environment (O'Day et al, 2004). The application of synchrotron techniques to environmental problems related to mine waste is increasing in popularity due to its element specificity, minimal sample preparation and the ability to make both spatially resolved and bulk measurements. Bulk U speciation from two tailings samples and one salt sample were characterized by XANES analysis using the HXMA (Hard X-ray MicroAnalysis) beamline at the CLS. Micro U speciation from two salt sample mounts and one tailings thin section was characterized using the bending magnet VESPERS (Very Sensitive Elemental and Structural Probe Employing Radiation from a Synchrotron)

beamline at the Canadian Light Source (CLS). The VESPERS techniques included micro-X-ray Fluorescence (μ-XRF) mapping and micro-X-ray Absorption Near Edge Structure (μ-XANES). EXAFS (extended x-ray absorption fine structure) could not be acquired based on low count rates. The XANES data collected at both the HXMA and VESPERS beamlines at the CLS was compared to a set of standards analyzed during the same analytical session under the same analytical conditions. The ATHENA version 0.8.56 software was used to identify absorption edge energies of both the standard materials of known oxidation and samples of unknown oxidation. The absorption energies of the unknowns were compared to those of the standards to obtain oxidation states for the unknown samples.

3.3.6.1 Hard X-Ray MicroAnalysis

The super-conducting wiggler sourced HXMA (Hard X-ray MicroAnalysis) beamline at the CLS was used to obtain XANES spectra of two bulk tailings samples, a single bulk salt sample as well as standard materials. Samples were ground into a fine-grained powder and pressed into an aluminum window sealed with kapton tape creating a flat surface. The standard compounds were diluted with boron nitride, thus creating a unified edge jump for XANES. The straight ion chamber detectors were used in the transmission mode experiment for model compounds, whereas a 32 element Ge detector was used in the fluorescence mode data collection for tailing samples. A Si (111) monochromator crystal and Rh mirrors (collimating and focusing mirrors) were used during data collection. The sizes of scan steps for the pre-edge, XANES, and EXAFS regions were 10 eV/step, 0.25 eV/step, and 0.5 Å⁻¹/step, respectively. Each XANES spectra was internally calibrated using a zirconium foil.

3.3.6.2 Very Sensitive Elemental and Structural Probe Employing Radiation from a Synchrotron

The bending magnet sourced VESPERS beamline at the CLS was used to obtain µ-XRF spectra of two salt mounts and tailings thin section. The µ-XRF maps were used to define targets for μ -XANES analysis. μ -XRF spectra were collected for the following elements: U L α , Fe K α , Ca Ka, Ti Ka, Cr Ka, Ni Ka, V Ka, Cu Ka, Zn Ka, Co Ka, Se Ka, Hg Ka, Pb La, Pb Lβ, As Kβ and Th L β . Contoured element maps were created from the μ -XRF spectra using SigmaPlot version 12.2 software to characterize element distribution for the preselected elements of interest. During XRF mapping a 3 µm pink beam was rastered over areas approximately 200 µm x 200 μm in size. A 7 μm mono beam was utilized to obtain XANES analyses. An average of at least 3-4 XANES spectra were collected for each analytical point. U L₃ and Fe Ka XANES spectra were collected at room temperature from targets defined by XRF maps. The incident x-ray pink beam was monochromatized to the mono beam using a double-crystal Si (111) monochromator. The Vortex Silicon Drift detector was set at a distance of 40 mm. Samples were analyzed at room temperature oriented at a 45° angle to the detector. The U L₃ μ -XANES spectra were obtained by scanning through the U L₃-edge in three segments: -200 eV to -50 eV in 10 eV steps for 1 second per step then -50 eV to 50 eV in 0.5 eV steps for 2 seconds per step and 50 eV to 8 k in 0.05 k steps for 10 seconds per step. The Fe K α μ -XANES spectra were obtained by scanning through the Fe k-edge in three segments: -100 eV to -50 eV in 1 eV steps for 1 second per step then -50 eV to 50 eV in 0.5 eV steps for 5 seconds per step and 50 eV to 8 k in 0.05 k steps for 10 seconds per step.

3.4 Results and Discussion

Previous assessments of the Lorado Mill tailings by Golder (2008) and SRC (2009) have determined the Lorado Mill tailings are up to 4 m thick in some areas, consisting of silt tailings overlain by sandy tailings. There is an estimated total of 227,000 m³ of tailings with 177,000 m³ on land and the remaining 50,000 m³ in Nero Lake. The Lorado Mill tailings cover an estimated area of approximately 14 hectares including the subaqueous tailings (Golder 2008; SRC 2009).

Based on core collected during this study the tailings consist of an orange-brown sand horizon overlying a purple-grey silty horizon. The sand unit ranges up to 0.5 m thick, the silty unit was encountered straddling the water table and has discontinuous purple-red layers between 3 - 150 mm thick. Photographs of the cores are presented in Appendix 3.B. Previous characterization of the tailings identified oxidized tailings and unoxidized tailings, based on their description the oxidized tailings correlate with the sandy horizon from this study and the unoxidized tailings correlate with the silty horizon (Golder 2008). The stratigraphic extent of the horizons is illustrated in Appendix 3.C, the sand unit is thickest near the former mill site and thins towards Nero Lake. A discontinuous salt crust covering the tailings surface preferentially forms on elevated areas on the tailings including: raised dry sandy areas and some deadfall (Golder 2008). The salts preferentially form on western facing surfaces suggesting evaporative processes drive their formation. The salt exhibits an array of colors including: brown, grey, white, yellow, green and orange; images illustrating the various salt colors can be found in Appendix 3.D.

3.4.1 Mineralogical and Chemical Characterization of the Salts and Tailings

In 2008, Golder Associates carried out a bulk mineralogical and chemical study on samples of the salt curst. Their study focused on the white colored sulfate samples. Mineralogical and chemical characterization of their samples identified epsomite [MgSO₄7H₂O] and pickingerite [MgAl₂(SO₄)₄22H₂O] with an unidentified Al-Fe-Mg sulfate with relatively low U concentrations (102 ppm). This is consistent with the some of the minerals that we have identified. In our study, multiple salt samples were collected and characterized covering the variability in salt colour that was not characterized in the previous study. Powder XRD and chemical analyses from this study show a mineralogical and chemical variation between salt colours: brown-grey, white, yellow- multi-coloured and orange salts.

The white salts are primarily magnesium (Mg) and aluminum (Al) sulfates, including epsomite, hexahydrite [MgSO₄6H₂O], millosevichite [Al₂(SO₄)₃] and pickeringite, with a relatively low U concentration (510-561 ppm). Mixed colored salts, including yellow, are primarily Mg, Al and calcium (Ca) sulfates with the appearance of minor iron (Fe) sulfates including bilinite [Fe²⁺Fe³⁺₂(SO₄)₄22H₂O]. These salts have elevated U concentrations (366-1995 ppm). The orange salts are composed of the same Mg, Al and Ca sulfates with more Fe sulfates including romerite [Fe²⁺Fe³⁺₂(SO₄)₄14H₂O] and halotrichite [Fe²⁺Al₂(SO₄)₄22H₂O], and increased U concentrations (2150-3230 ppm). The brown-grey salt is thinner than the other colors and comprises gypsum [CaSO₄2H₂O] and epsomite with quartz [SiO₂] and albite [NaAlSi₃O₈]. This salt has increased iron (Fe), nickel (Ni) and lead (Pb) and decreased U (74-344 ppm) concentrations with respect to other salt colors, however, it has similar elemental concentrations to the tailings. The presence of silicates along with similar chemical patterns to the tailings suggests a significant incorporation of tailings material in the brown-grey salt. Representative XRD spectra from each salt color and more detailed bulk chemistry data is in Appendicies 3.E and 3.F. Qualitative and quantitative EMP analyses were performed on two high U concentration salt samples (3230 ppm and 1195 ppm; Appendix 3.G). Chemical maps showing relative element distributions were used to define areas of higher U concentration in order to locate areas for quantitative EMP analysis. Quantitative spot analyses revealed low U concentrations in the salts (less than 5 wt%). Uranium sulfates exist, including uranopilite $[(UO_2)_6(SO_4)O_2(OH)_63H_2O]$, johannite $[Cu(UO_2)_2(SO_4)_2(OH)_28H_2O]$ and zippeite [K₃(UO₂)₄(SO₄)₂O₃(OH)₃H₂O], these minerals have large U contents (48–68 wt% U). Low U values of the sulfate crusts indicate an absence of U sulfates. Figure 3.2 illustrates a solid solution between Fe and Al within the salts and identifies a limited solid solution whereby U substitutes in low concentrations into the Fe and Al sulfates. Golder (2008) concluded there was no evidence suggesting metal substitution into the identified sulfate mineral phases indicating minimal risk to the environment as a result of salt dissolution in runoff water. However, results of our study suggest that U is incorporated into the sulfate minerals, and the salts are chemically heterogenous and have a complex mineralogy.



Figure 3.2. Ternery diagram illustrating the chemical relationship between Fe, Al and U within the sulfate salt samples. There is a solid solution between Al and Fe and only a partial solid solution between Al and U.

Bulk mineralogy of the Lorado tailings consist of a coarser orange-brown sand horizon overlying a finer grey silty horizon that contains discontinuous purple-red layers or laminations. The three cores closest to the former mill site consist of about 0.5 m of the sand horizon, whereas the two cores closest to Nero Lake are predominantly the silty horizon. These horizons were characterized using XRD (Appendix 3.H.). The orange-brown sand horizon contains quartz, albite, gypsum and muscovite [KAl₂(Si₃Al)O₁₀(OH,F)₂]. The silty horizon consists of quartz,

albite, gypsum, muscovite and clinochlore $[(Mg,Fe)_5Al(Si_3Al)O_{10}(OH)_8]$ whereas the purple-red layers contain quartz, hematite $[Fe_2O_3]$ and a magnesium nickel iron oxide $[Ni_{0.4}Mg_{0.6}Fe_2O_4]$.

In addition to U, a suite of elements were analyzed from core samples correlated with depth along A-A' (Figure 3.1) to determine chemical changes with depth and mineralogy (Appendix 3.I.). There is a significant difference in metal concentration between the sand horizon and the silt horizon; this difference is magnified with depth as well. The sand horizon tends to have relatively depleted metal concentrations whereas the silty horizon is more enriched in metals such as As, Co, Cu, Fe, Ni, Pb, Zn and U. Concentration of As, Pb, U and Zn are mediated by both the silty horizon and depth with the highest concentration samples collected between 35-50 cm depth within the silty horizon. The concentrations of As, Pb, U and Zn are as follows for the sand and silty horizons respectively: As (6.5-30.8 ppm and 20.5-41 ppm), Pb (115.5-282 ppm and 45.9-631 ppm), U (15-40 ppm and 40-141 ppm) and Zn (13-39 ppm and 45-107 ppm. Metals such as Co, Cu, Fe and Ni are largely concentrated within the purple-red layers and laminations throughout the silty horizon. The concentrations of Co, Cu, Fe and Ni in both the sand and silty horizons are: Co (1.7-15.2 ppm and 13.8-103 ppm), Cu (28.5-100 ppm and 69.6-448 ppm), Fe (2.04-4.34 % and 3.75-29.2 %) and Ni (7-38.9 ppm and 41-352 ppm). This is concurrent with the mineralogical shift between the sand and silty horizons; the silty horizon including the red layers or laminations contain higher abundances of metal bearing minerals such as clinochlore and hematite.

Elevated U concentrations are associated with the silty unit and with depth, which is similar to the results from previous studies (Golder 2008; Naamoun and Merkel 2008). The U concentration in the sand horizon is 15-40 ppm whereas the silty horizon has an elevated relative

concentration of 40-141 ppm. The top 0-5 cm of some cores contain elevated U ranging between 27-202 ppm, this has been attributed to formation of sulfate salt near the surface as visually identified during sampling. These values represent the interface between the tailings and the surface salt formations. Previous studies (Golder, 2008) have shown that the sandy horizon contains 34.4–121 ppm U and the silty tailings contain 19-312 ppm U. This range in U concentrations is higher than our results for both the sand and silt horizons, however if surficial (0-5 cm) samples are removed from Golder's data the salt contamination is effectively removed yielding U concentrations analogous to our study. As previously discussed U concentration increases with depth, thus the wide range in the silty horizon or unoxidized tailings concentrations can be attributed to the greater depth at which samples were collected (up to 670 cm deep) for the Golder (2008) study.

Depth correlated polished thin sections were characterized using the scanning electron microscope and electron microprobe to identify and characterize U mineralogy. A number of thin sections were analyzed with the SEM identifying the presence and distribution of U-rich grains. Uranium grains are uncommon, small ($<20 \mu$ m) and commonly encapsulated by quartz and feldspar grains (Appendix 3.J.). Quantitative EMP analysis of these grains identified high U content (40-76 wt%) with slightly elevated Pb (up to 3 wt%; Appendix 3.K.). Based on EMP results these grains have been identified as uraninite (UO₂) grains. The slightly elevated Pb within these grains suggests the uraninite is relatively old because Pb is the final decay product of U (Faure 1977). Therefore, based on the chemical composition (e.g. elevated Pb content) and textures (association with quartz and feldspar) we interpret the U-rich grains as residual uraninite ore that survived the milling process.

Scanning electron microscopy and EMP analyses show no visual difference in abundance or distribution of the uraninite grains between samples from the sand and silt units or between samples with the lowest and highest U concentrations (i.e., 15 ppm and 141 ppm, respectively). Therefore, the difference in U concentration between samples suggests that excess U is possibly adsorbed onto mineral surfaces or incorporated into secondary mineral phases.

3.4.2 Synchrotron Analysis

In recent years, increasing government interest in the environmental impact of U mine tailings has resulted in a number of synchrotron studies including XANES analyses of U contaminated sediments and mine tailings. These studies focused on a variety of elements including: As, Fe and Mo, with only a small number of studies characterizing the U in the tailings (Dreesen et al. 1982; Bertsch et al. 1994; Moldovan et al. 2003; O'Day et al. 2004; Arai et al. 2007; Essilfie-Dughan et al. 2011). In our study, we focused on U and Fe in both salt and tailing samples. First-derivative XANES spectra are presented in order to emphasise the absorption edge position of the standards and samples. We used both bulk XANES and microsynchrotron techniques to link the oxidation state of U and Fe with the mineralogy of the samples and determine whether U is adsorbed onto or incorporated in minerals, which would affect its relative mobility in the environment.

3.4.3 Bulk-Synchrotron Analysis

Bulk XANES analysis on two tailings samples and one salt sample were analyzed to characterize the oxidation-state of U. In order to achieve count rates for reasonable analysis times, only tailings samples with elevated U concentrations were analyzed (141.5 ppm and 91.7

ppm) both of which are from the silty unit. The salt sample with the highest U concentration was also analyzed (3230 ppm). XANES spectra from the single salt sample indicate the U is oxidized ($U^{+5.4\pm0.2}$) based on comparison of the absorption edge energy to those of standard materials (Fig. 3.3). Uranium XANES spectra from both the 141.5 ppm and 91.7 ppm tailings samples indicate that the U is also relatively oxidized ($U^{5.5\pm0.2}$ and $U^{4.9\pm0.1}$) (Fig. 3.4).



Figure 3.3. Uranium bulk-XANES first-derivative spectra of a salt sample (3230 ppm U) showing the presence of oxidized uranium. The absorption edge of the salt sample, highlighted by the pink line, was compared to those of the different standard materials $UO_2 (U^{4+})$, $U_3O_8 (U^{5.3+})$ and $UO_3 (U^{6+})$.



Figure 3.4. Uranium bulk-XANES first-derivative spectra of 2 tailings samples (141 and 91.7 ppm U) showing the presence of relatively oxidized uranium. The absorption edges of the tailings samples, highlighted by the pink line, were compared to those of the different standard materials UO_2 (U⁴⁺), U₃O₈ (U^{5.3+}) and UO₃ (U⁶⁺).

3.4.4 Micro-Synchrotron Analysis

XRF spectra maps were collected to define targets for U and Fe μ -XANES analyses. Additional XRF contour maps are located in the Appendix 3.A (Appendix 3.L.). The XRF data from the 3230 ppm orange salt sample show no relationship between Fe and U (Fig. 3.5); whereas Fe and U in the 1195 ppm U yellow salt do correlate (Fig. 3.5). μ -XANES spectra from two locations on the orange sample identified in figure 3.4 indicate U is oxidized (U^{+5.5±0.2} and U^{+5.3±0.2}) (Fig. 3.6). Uranium μ -XANES spectra from two locations from the yellow sample indicate U is reduced relative to the orange sample (U^{+4.7±0.1} for both spots) (Fig. 3.5 and Fig. 3.6). Iron μ -XANES spectra from two locations from the yellow sample, chosen based on U-Fe spatial relationship indicate Fe is oxidized (Fig. 3.5 and Fig. 3.7). Therefore, U locally associated with Fe in the sulfate minerals is relatively reduced compared to U that does not correlate with Fe. The range of U oxidation states identified in the salt samples with μ -XANES analysis, U^{+4.7}-U^{+5.5} indicate that overall, the salts consist of predominantly oxidized U, which can be mobilized through dissolution of the salts by meteoric water.



Figure 3.5. X-ray fluorescence (XRF) element maps of two salt samples, one orange sample (3230 ppm U) and one yellow sample (1195 ppm U). The maps show the distribution of U and Fe from areas indicated on sample mount photo. Locations of spot μ -XANES analyses are indicated with an X on the XRF maps.



Figure 3.6. Uranium μ -XANES analyses from salt samples (3230 and 1195 ppm U) as indicated in figure 4 showing a range of uranium speciation. The absorption edges for the 1195 ppm U salt 1 and 2 as well as 3230 ppm U salt 1 are highlighted by the pink line whereas the 3230 ppm U salt 2 sample is highlighted by the blue line were all compared to those of the different standard materials UO₂ (U⁴⁺), U₃O₈ (U^{5.3+}) and UO₃ (U⁶⁺).


Figure 3.7. Iron μ -XANES first-derivative spectra from salt sample (1195 ppm U) as indicated in figure 4 suggesting the iron is highly oxidized. The absorption edges highlighted by the pink line were compared to those of the different standard materials pyrite (Fe²⁺), magnetite (Fe²⁺) and hematite (Fe³⁺).

XRF maps were obtained from preselected areas in a thin section of the tailing sample with 141 ppm U. Additional XRF maps can be found in Appendix 3.L. Figure 3.8 shows that there is no correlation between Fe and U. Uranium μ -XANES spectra for a U-rich grain suspected to be uraninite, indicates U(IV) is the dominant form (U^{+4.3 ± 0.1}) based on comparison

of the absorption edges to those of the measured standards (Fig. 3.9). Uraninite is the most common reduced U(IV) mineral species and is the main ore in the U deposits processed through at the Lorado Mill. Therefore, μ -XANES data supports our interpretation that the U-rich grains associated with quartz and feldspar are uraninite ore that survived the milling process.



Figure 3.8. X-ray fluorescence (XRF) element maps from tailings thin section sample illustrating the distribution of U and Fe from areas indicated on sample mount photo. Location of spot μ -XANES analysis indicated with an X on the uranium XRF map.



Figure 3.9. Uranium μ -XANES analysis from a previously identified uranium grain from the silty horizon of the tailings indicated in figure 5 showing reduced uranium speciation. The absorption edge highlighted by the pink line was compared to those of the different standard materials UO₂ (U⁴⁺), U₃O₈ (U^{5.3+}) and UO₃ (U⁶⁺).

Bulk XANES analysis of the tailings indicated oxidized U, however spatially resolved μ -XANES analysis identified variability in the U speciation with the presence of reduced U within uraninite grains. As previously discussed there is minimal visual difference in U grain abundance and distribution between high and low U concentration tailings samples. There is an excess of U that is visually unaccounted for within the higher concentration samples. Arai et al. (2007) suggests adsorbed U species are significant in bulk-scale analyses over-printing any variability present thus bulk scale XANES analyses may primarily represent the adsorbed U fraction (Bertsch et al. 1994). Multiple studies have looked at characterizing the sorption of U to other mineral surfaces, (such as: His and Langmuir 1985; Waite et al. 1994; Wazne et al. 2003; Davis et al. 2004; Arai et al. 2007; Hyun et al. 2009; Dong et al. 2011; Shang et al. 2011; Wang et al. 2011) however, adsorption was not characterized during this study. It is difficult to fully characterize U adsorption in complex open systems, however, in these studies a variety of factors have been found to greatly impact U adsorption including: mineralogy, grain size and water chemistry. Positively charged uranium may adsorb to the surfaces of negatively charged minerals such as sulfides, clays, quartz and Fe, Mg and Al oxyhydroxides (Lottermoser 2007; Davis et al. 2004). Grain size defines the abundance of reactive surface area for U to adsorb to; smaller grain size fractions will experience higher adsorption than larger grain sizes (Lottermoser et al. 2005; Shang et al. 2011). Based on these factors, the excess U observed chemically but not visually in the silty horizon of the tailings is likely adsorbed onto mineral surfaces within this horizon. The smaller grain size of the silty horizon along with the introduction of more Fe and Mg rich minerals such as clinochlore, hematite and Mg,Ni,Fe oxide likely control U adsorption in the Lorado Mill tailings.

3.4.5 Implications: Uranium Transport Through the Lorado Mill Tailings

Based on field observations and core stratigraphy from this and previous studies, the Lorado tailings are vertically stratified and laterally variable (Golder 2008; SRC, 2009; Appendix 3.C.). Uranium distribution is largely stratigraphically mediated with the lowest

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concentration associated with the sandy horizon overlying the silty horizon with slightly elevated U concentrations. The salt crust on the tailings surface, especially in regions where the sand horizon is present, contains the highest U concentration. These are a result of evaporative processes wicking pore water upwards through the tailings precipitating sulfate salts on the tailings surface (Golder 2008 and Nordstrom 2011). The U in the salts is generally in the form of U(VI) with minor local variability including a slight reduction when spatially associated with Fe. The high concentration of U and the predominantly oxidized form of U in the salt minerals can be attributed to the presence of highly soluble U(VI) in the upper portion of the tailings, which is mobilized by pore water that is drawn upwards by evaporation through the sandy horizon (Abdelouas 2006 and Mkandawire and Dudel 2008). The sulfate salts are highly soluble accounting for roughly 80% of the mass loading into Nero Lake from the tailings, indicating the dissolution of the salts in surface runoff is the predominant mechanism for U introduction into the environment (Golder 2008). The U in the silty horizon is predominantly oxidized with localized reduced U in residual uraninite ore. As suggested by Arai et al. (2007) the bulk XANES measurement may represent the speciation of the adsorbed U, which is generally oxidized and is readily soluble and mobilized (Mkandawire and Dudel 2008). The silty horizon has lower porosity than the sand horizon thus trapping the oxidized adsorbed U and effectively decreasing its mobility, this is likely the cause of the excess U observed in the silty horizon versus the sandy horizon. Although adsorbed U in the sandy horizon is readily mobilized due to increased porosity and permeability, the majority of the U remaining in the sand horizon is likely less mobile as it occurs as U(IV) in residual uraninite grains that are encapsulated in guartz and feldspar grains. The majority of U in the Lorado Mill tailings is in the form of U(VI) and can be

transported by pore water via upward capillary action driven by evaporation or directly into Nero Lake when the amount of infiltrating water exceeds the evaporation rate.

Historically tailings were simply discharged to a convenient location with no additional precautions to avoid migration of contaminants into the surrounding environment. Modern tailings facilities utilize tailings damns and various forms of surface cover including water, soil, sand or rock and basal liners (Landa 2004; Abdelouas 2006; Lottermoser 2007; Hudson-Edwards et al. 2011). Recently geochemical barriers have been utilized to line the bottom of tailings impoundment facilities. The liners function by removing contaminants from water passing through by adsorption onto liner material. A variety of low-cost solid sorbants have been proposed for use in these liners including fly ash, sawdust, coal, zeolites and ferric oxides (Landa 2004 and Lottermoser 2007). As illustrated by this study the primary direction of U migration is upwards, resulting in the formation of U-rich evaporative sulfate salts on the tailings surface. The sulfate salts are readily dissolved, facilitating the transport of U into the surrounding aquatic environment through runoff. Based on these observations a barrier that reduces the upward U migration could effectively reduce the amount of contamination to the surrounding environment. Further research into effective surface barriers is required, specifically the applicability of the basal liner materials to serve as surface covers on U tailings facilities.

3.6 References

- Abdelouas, A. (2006): Uranium mill tailings: Geochemistry, mineralogy, and environmental impact. Elements, 2, 335-341.
- Amandolagine, E. (1956) Uranium mineralization and mapping of Cayzor Athabasca Mines Ltd. Uranium City, Saskatchewan, Canada. Masters Thesis Columbia University. 15 pages.

- Arai, Y., Marcus, M.A., Tamura, N., Davis, J.A. and Zachara, J.M. (2007): Spectroscopic evidence for uranium bearing precipitates in vadose zone sediments at the Hanford 300-Area Site. Environmental Science and Technology, 41, 4633-4639.
- Beck, L.S. (1986) General geology and uranium deposits of the Beaverlodge district, Special Volume: Canadian Institute of Mining and Metallurgy, 33, 85-94.
- Bertsch, P.M., Hunter, D.B., Sutton, S.R., Bajt, S. and Rivers, M.L. (1994): In situ chemical speciation of uranium in soils and sediments by micro x-ray absorption spectroscopy. Environmental Science and Technology: Communications, 28, 980-984.
- Cameco Corp. (2012) Q1 Operational Update, History/Innovations. Updated May 2012.
- Davis, J.A., Meece, D.E., Kohler, M. and Curtis, G.P. (2004) Approaches to surface complexation modeling of uranium (VI) adsorption on aquifer sediments. Geochimica et Cosmochimica Acta, 18, 3621-3641.
- Dong, W., Tokunaga, T.K., Davis, J.A. and Wan, J. (2011) Uranium(VI) adsorption and surface complexation modeling onto background sediments from the F-Area Savannah River Site. Environmental Science and Technology, 46, 1565-1571.
- Dreesen, D.R., Williams, J.M., Marple, M.L., Gladney, E.S. and Perrin, D.R. (1982): Mobility and bioavailability of uranium mill tailings contaminants. Environmental Science and Technology, 16, 702-709.
- Edwards, C. (2012) Uranium milling in northern Saskatchewan's Athabasca Basin: Past, present and future. CIM Journal: Uranium issue, 3, 69-94.
- Essilfie-Dughan, J., Pickering, I.J., Hendry, M.J., George, G.N. and Kotzer, T. (2011): Molybdenum speciation in uranium mine tailings using x-ray absorption spectroscopy. Environmental Science and Technology, 45, 455-460.
- Faure, G. (1977) Principles of Isotope Geology. John Wiley and Sons, New York, USA.
- Golder Associates (2008) Technical Information Document for the Inactive Lorado Uranium Tailings Site. Submitted to EnCana Corporation, April 2008.
- His, C.D., Langmuir, D. (1985): Adsorption of uranyl onto ferric oxyhydroxides: application of the surface complexation site bonding model. Geochimica et Cosmochimica Acta, 49, 1931-1941.
- Hudson-Edwards, K.A., Jamieson, H.E. and Lottermoser, B.G. (2011) Mine wastes: past, present, future. Elements, 7, 375-380.
- Hyun, S.P., Fox, P.M., Davis, J.A., Campbell, K.M., Hayes, K.F. and Long, P.E. (2009) Surface complexation modeling of U(VI) adsorption by aquifer sediments from a former mill tailings site at Rifle, Colorado. Environmental Science and Technology, 43, 9368-9373.
- Jamieson, H. (2011) Geochemistry and mineralogy of solid mine waste: Essential knowledge for predicting environmental impact. Elements, 7, 381-386.

- Landa, E.R. (2004) Uranum mill tailings: nuclear waste and natural laboratory for geochemical and radioecological investigations. Journal of Environmental Radioactivity, 77, 1-27.
- Lottermoser, B.G. (2007): Mine wastes characterization, treatment and environmental impacts. Springer-Berlin Heidelberg New York. 304 pages.
- Lottermoser, B.G., Ashley, P.M. and Costelloe, M.T. (2005) Contaminant dispersion at the rehabilitated Mary Kathleen uranium mine, Australia. Environmental Geology, 48, 748-671.
- Mkandawire, M. and Dudel, E.G. (2008): Natural occurring uranium nanoparticles and the implication in bioremediation of surface mine waters. Uranium, Mining and Hydrogeology, Springer-Verlag Berlin Heidelberg. 487-496.
- Moldovan, B.J., Jiang, D.T. and Hendry, M.J. (2003): Mineralogical characterization of arsenic in uranium mine tailings precipitated from iron-rich hydrometallurgical solutions. Environmental Science and Technology, 37, 873-879.
- Mudd, G.M. (2001): Critical review of acid in situ leach uranium mining. Environmental Geology, 41, 390-403.
- Naamoun, T. and Merkel, B. (2008) Chemical behaviour of uranium in the tailings material of Schneckenstein (Germany). Uranium, Mining and Hydrogeology, Springer-Verlag Berlin Heidelberg. 271-283.
- Nordstrom, D.K. (2011) Mine waters: acidic to circumneutral. Elements, 7, 393-398.
- O'Day, P.A., Rivera, N., Root, R. and Carroll, S.A. (2004): X-ray absorption spectroscopic study of Fe reference compounds for the analysis of natural sediments. American Mineralogist, 89, 572-585.
- Schnug, E. and Haneklaus, S. (2008) Dispersion of uranium in the environment by fertilization. Uranium, Mining and Hydrogeology, Springer-Verlag Berlin Heidelberg. 45-52.
- Shang, J., Liu, C., Wamg, Z. and Zachara, J.M. (2011): Effect of grain size on uranium(VI) surface complexation kinetics and adsorption additivity. Environmental Science & Technology, 45, 6025-6031.
- Smith, E.E.N. (1986) Geology of the Beaverlodge operation, Eldorado Nuclear Limited, Special Volume: Canadian Institute of Mining and Metallurgy, 33, 95-109.
- SRC (2009) Former Lorado uranium mill site rehabilitation project description. Saskatchewan Research Council, Environment and Forestry Division, SRC publication No. 12578-1E09, 196 pages.
- Waggitt, P. (2008) Uranium mining legacies remediation and renaissance development: an international overview. Uranium, Mining and Hydrogeology, Springer-Verlag Berlin Heidelberg. 11-18.
- Waite, T.D., Davis, J.A., Payne, T.E. Waychunas, G.A. and Xu, N. (1994): Uranium (VI) adsorption to ferrihydrite: application of a surface complexation model. Geochim. Cosmochim. Acta, 58, 5465-5478.

- Wang, Z., Zachara, J.M., Boily, J., Xia, Y., Resch, T.C., Moore, D.A. and Liu, C. (2011) Determining individual mineral contributions to U(VI) adsorption in a contaminated aquifer sediment: a fluorescence spectroscopic study. Geochimica et Cosmochimica Acta, 75, 2965-2979.
- Wazne, M., Korfiatis, G.P. and Meng, X.G. (2003): Carbonate effects on hexavelent uranium adsorption by iron oxyhydroxide. Environmental Science and Technology, 37, 3619-3624.

Chapter 4. Conclusion

The purpose of this study was to understand the behavior of U in both oxidizing and anaerobic near surface environments over various time-scales. Chapter 2 is the study detrital U minerals from a Precambrian quart-pebble conglomerate U deposit. Based on this study the following observations can be made:

- Two horizons where studied; sandstone and conglomerate.
- The U mineralalogy from both horizons consists of thorite [(Th,U)SiO₄] and brannerite [(U,Ca,Ce)(Ti,Fe)₂O₆]
- U-Pb ages of the U mineralogy are:
 - Thorite in the sandstone is 280 ± 67 Ma
 - Thorite in the conglomerate is 2489 ± 24 Ma
 - Brannerite is 2403 ± 120 Ma
- Based on textural information and the ages of the U minerals, thorite is interpreted to be detrital in origin, whereas brannerite is a post depositional hydrothermal mineral.
- The Pele Mountain quartz-pebble conglomerate uranium deposit is, therefore, a modified placer-type uranium deposit and U minerals can survive over long time-scales under anaerobic near-surface conditions.

Chapter 3 is the study of U mineralogy and geochemistry from the Lorado Mill historical tailings site. Based on this study the following conclusions can be made:

• The Lorado Mill tailings are heterogeneous and there is vertical stratification as well as a lateral variability in horizon thicknesses.

- Two horizons were characterized in detail; top sandy unit and a lower silty unit.
- U concentration is stratigraphically controlled. Generally the concentration of U increases with depth, however the highest concentrations are associated with the surficial sulfate salt crusts. Therefore, U generally moves upwards through the sandy horizon.
- Both relatively reduced and oxidized U, exist within the sulfate salt crusts
 - Relatively reduced U is spatially associated with Fe(III)
 - Oxidized U is not spatially associated with Fe(III) and is the dominant U phase within the salts
- Both reduced and oxidized U are observed within the tailings.
 - Reduced U is associated with the residual uraninite ore throughout the tailings.
 - Oxidized, adsorbed U comprises the bulk of the U.

Uranium mobility in near-surface sedimentary environments is controlled by redox reactions. In historical tailings, these redox reactions are facilitated by milling processes increasing reactive surface area and exposing the material to both the atmosphere and hydrosphere (Abdelouas 2006; Balci et al. 2007; Diaby et al. 2007; Jamieson 2011). Detailed characterization of the U species within the tailings and sulfate crust identified a large degree of water-facilitated transport of pervasively oxidized U. Limited redox reactions were observed in the ancient quartz-pebble conglomerate uranium deposits (e.g., formation of brannerite). Although, these fluvially deposited sediments would have likely experienced mechanical weathering and extensive exposure to both atmosphere and hydrosphere during transport and deposition, U (IV) minerals were preserved due to the lower levels of oxygen in the atmosphere prior to 2200 Ma. Based on observations from the Lorado Mill Historical Tailings Site, where so much U has been liberated by oxidation over short time-scales (51 years), under modern conditions the transport and deposition of U(IV)-mineral grains would have resulted in oxidation, facilitating aqueous transport of U.

Ancient quartz-pebble conglomerate U deposits have the potential to provide insight into Archean paleo-atmospheric conditions. The stability of different U minerals (e.g. uraninite vs. thorite) may affect the applicability of U deposits to infer atmospheric conditions. For example, thorite gives the age of sediment deposition because it is minimally affected by post-depositional hydrothermal fluids, but is less sensitive to changes in oxygen levels in the atmosphere relative to uraninite. Thus using multiple U minerals including uraninite to interpret Archean atmospheric conditions is essential.

One of the few ways to investigate the behavior of U minerals under near-surface anaerobic conditions is to study the Archean placer deposits that are over 2 billion years old. Modern anthropogenic U tailings sites offer a unique opportunity to study the behavior of U minerals under aerobic conditions. Understanding U mobility in nearsurface sedimentary environments, under both anaerobic and aerobic conditions, can provide important information regarding U containment in tailings sites and highly radioactive nuclear waste (HRNW) disposal in sub-surface repositories.

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4.1 References

- Abdelouas, A. (2006) Uranium mill tailings: Geochemistry, mineralogy, and environmental impact. Elements, 2, 335-341.
- Balci, N., Shanks III, W.C., Mayer, B. & Mandernack, K.W. (2007) Oxygen and sulfur isotope symantics of sulfate produced by bacterial and abiotic oxidation of pyrite. *Geochimica et Cosmochimica Acta*, **71**, 3796-3811.
- Diaby, N., Dold, B., Pfeifer, H., Holliger, C., Johnson, D.B. & Hallberg, K.B. (2007) Microbial communities in a porphyry copper tailings impoundment and their impact on the geochemical dynamics of the mine waste. *Environmental Microbiology*, 9, 298-307.
- Jamieson, H. (2011) Geochemistry and mineralogy of solid mine waste: Essential knowledge for predicting environmental impact. Elements, 7, 381-386.

Appendix 2.A

Secondary Ion Mass Spectrometer Data

Mineralogy	²⁰⁶ Pb/ ²⁰⁴ Pb	Poisson %	²⁰⁷ Pb/ ²⁰⁶ Pb	Poisson %	²³⁵ U/ ²³⁸ U	Poisson %	²⁰⁷ Pb/ ²³⁵ U	Poisson %	²⁰⁶ Pb/ ²³⁸ U	Poisson %
Thorite (Conglomerate)	7.722E+02	1.09E+01	1.326E-01	1.23E+00	7.527E-03	1.29E+00	9.908E-01	1.60E+00	5.659E-02	4.55E-01
Thorite (Conglomerate)	4.764E+02	3.75E+00	1.609E-01	4.75E-01	7.490E-03	1.21E+00	7.857E+00	1.29E+00	3.578E-01	2.10E-01
Thorite (Conglomerate)	7.451E+02	1.06E+01	1.334E-01	1.24E+00	7.426E-03	1.13E+00	9.344E-01	1.60E+00	5.202E-02	4.39E-01
Thorite (Conglomerate)	4.088E+02	2.19E+01	8.862E-02	2.46E+00	7.438E-03	1.32E+00	3.110E-01	2.68E+00	2.599E-02	7.30E-01
Thorite (Conglomerate)	4.806E+02	1.40E+01	1.189E-01	1.82E+00	7.496E-03	1.33E+00	6.010E-01	2.17E+00	3.754E-02	6.09E-01
Thorite (Conglomerate)	4.591E+02	3.54E+01	7.072E-02	2.91E+00	7.360E-03	1.30E+00	2.048E-01	3.09E+00	2.132E-02	7.80E-01
(Conglomerate)	4.152E+02	1.56E+01	1.096E-01	2.22E+00	7.507E-03	1.40E+00	4.418E-01	2.49E+00	3.006E-02	7.12E-01
Brannerite	1.384E+03	1.60E+01	7.625E-02	1.40E+00	7.662E-03	1.13E+00	6.633E-01	1.76E+00	6.620E-02	3.90E-01
Brannerite	1.327E+03	1.14E+01	8.550E-02	1.24E+00	7.540E-03	1.07E+00	8.357E-01	1.59E+00	7.317E-02	3.61E-01
Brannerite	1.063E+03	1.58E+01	7.430E-02	1.59E+00	7.581E-03	1.12E+00	5.400E-01	1.95E+00	5.428E-02	4.34E-01
Brannerite	1.646E+03	4.08E+01	6.781E-02	1.53E+00	7.577E-03	1.08E+00	5.428E-01	1.82E+00	5.986E-02	4.00E-01
Galena	3.455E+02	2.23E+00	3.455E+02	3.13E-01	N/A	N/A	N/A	N/A	N/A	N/A

Table 2.A.1 Secondary ion mass spectrometer analyses of LB04219, from the quartzose conglomerate, Raw uncorrected data, November 26, 2009 analytical session.

Table 2.A.2 Secondary ion mass spectrometer analyses of LB04219, from the quartzose conglomerate, Raw uncorrected data, January 25, 2010 analytical session.

Mineralogy	²⁰⁶ Pb/ ²⁰⁴ Pb	Poisson %	²⁰⁷ Pb/ ²⁰⁶ Pb	Poisson %	²³⁵ U/ ²³⁸ U	Poisson %	²⁰⁷ Pb/ ²³⁵ U	Poisson %	²⁰⁶ Pb/ ²³⁸ U	Poisson %
Brannerite	1.024E+03	1.31E+01	1.024E+03	1.53E+00	7.548E-03	1.19E+00	6.091E-01	1.88E+00	6.091E-01	4.10E-01
Brannerite	9.948E+02	1.16E+01	9.948E+02	1.33E+00	7.424E-03	1.17E+00	8.023E-01	1.71E+00	8.023E-01	3.92E-01

Mineralogy	²⁰⁶ Pb/ ²⁰⁴ Pb	Poisson %	²⁰⁷ Pb/ ²⁰⁶ Pb	Poisson %	²³⁵ U/ ²³⁸ U	Poisson %	²⁰⁷ Pb/ ²³⁵ U	Poisson %	²⁰⁶ Pb/ ²³⁸ U	Poisson %
Thorite (Arenite)	4.00E+02	4.50E+01	5.36E-02	3.50E+00	7.34E-03	1.20E+00	1.29E-01	3.59E-01	1.78E-02	7.50E-01
Thorite (Arenite)	NA	NA	5.13E-02	3.37E+00	7.44E-03	1.00E+00	9.26E-02	3.48E+00	1.34E-02	7.60E-01
Thorite (Arenite)	4.68E+02	5.04E+01	5.57E-02	2.87E+00	7.41E-03	9.12E-01	1.03E-01	3.04E+00	1.39E-02	6.65E-01
Thorite (Arenite)	2.79E+02	5.80E+00	5.79E-02	3.66E+00	7.40E-01	1.00E+00	7.60E-02	3.60E+00	9.79E-03	8.60E-01
Thorite (Arenite)	3.02E+02	5.05E+01	5.17E-02	3.78E+00	7.33E-03	1.11E+00	9.21E-02	3.80E+00	1.28E-02	8.46E-01
Thorite (Arenite)	3.80E+02	4.11E+01	5.25E-02	3.30E+00	7.29E-03	1.71E+00	2.73E-01	3.75E+00	3.90E-02	7.65E-01
Thorite (Arenite)	3.85E+02	5.04E+01	5.93E-02	3.14E+00	7.39E-03	1.72E+00	3.08E-01	3.56E+00	3.85E-02	7.59E-01
Thorite (Arenite)	6.25E+01	5.07E+01	7.68E-02	7.38E+00	7.25E-03	2.64E+00	1.39E-01	7.56E+00	1.29E-02	1.97E+00
Thorite (Conglomerate)	5.56E+02	1.57E+01	1.07E-01	1.76E+00	7.35E-03	7.73E-01	2.15E-01	1.86E+00	1.47E-02	5.44E-01
Thorite (Conglomerate)	6.10E+02	2.06E+01	1.10E-01	1.81E+00	7.46E-03	7.19E-01	1.80E-01	1.84E+00	1.20E-02	5.66E-01
Thorite (Conglomerate)	4.47E+02	2.37E+01	9.44E-02	2.23E+00	7.32E-03	7.77E-01	1.28E-01	2.30E+00	9.94E-03	6.54E-01
Thorite (Conglomerate)	3.04E+02	3.36E+01	1.02E-01	2.77E+00	7.38E-03	8.31E-01	1.01E-01	2.77E+00	7.38E-03	8.32E-01
Thorite (Conglomerate)	4.75E+02	1.90E+01	1.24E-01	1.90E+00	7.38E-03	9.57E-01	2.83E-01	2.02E+00	1.71E-02	6.40E-01
Thorite (Conglomerate)	2.36E+02	3.80E+01	1.13E-01	3.06E+00	7.37E-03	1.07E+00	1.45E-01	3.02E+00	9.46E-03	9.60E-01

Table 2.A.3 Secondary ion mass spectrometer analyses of Thorite from LB04217 and LB04220, from the quartz arenite quartzose conglomerate respectively, Raw uncorrected data, April 12, 2011 analytical session.

Appendix 2.B

Sample Descriptions



Figure 2.B.1. Photographs of diamond drill core for three samples classified as quartz arenite; a) LB04215, b) LB04216 and c) LB04217. Banding is observed in all three samples defined by high concentration of sulfides and oxides.

	Quartz	K-Feldspar	Matrix	Sulfides	Uranium Minerals
	• 85 - 90%	 ≥5% 	• ~5%	Concentrated in bands	Trace thorite
	• 0.05 - 2mm	• 0.05-1.5mm	• Very fine grained	• \geq 5% Pyrite	• 0.25-0.5mm
,	• Equant - oblate	• Equant – elongate	• Infilling interstitial	Trace chalcopyrite	• Equant – elongate
1	 Sub-rounded – rounded 	• Sub-rounded- rounded	spaces and fractures	• 0.05 – 0.75mm	• Sub-rounded-
	• Straight, sutured contacts	• Straight, sutured	• Fe-muscovite	• Equant	rounded
1	 Monocrystalline– 	contacts	Trace zircon	• Sub-rounded- angular	
	polycrystalline	Albite twinning	Trace monazite	• Euhedral – anhedral	
	 Undulatory extinction 				
	Polygonal texture from recrystallization				
	reerystamzation				

Table 2.B.1. Thin section description, LB04215 -Quartz Arenite

- Sulfide-rich bands ~1.5mm thick along bedding
 Some pyrite appears to be detrital
 Some pyrite appears to cross cut detrital grains

- Chalcopyrite encompasses quartz, feldspar and pyrite grains

	Quartz		K-Feldspar		Matrix		Sulfides		Uranium Minerals
•	80-85%	•	≥5%	•	~5%	•	Concentrated in band	•	Trace thorite
•	0.05 - 2mm Equant oblate	•	0.05-1.5mm Equant elongate	•	Very fine grained	•	≥15% Pyrite	•	0.25-0.5mm Equant elongate
•	Sub-rounded – rounded	•	Sub-rounded- rounded		spaces and fractures	•	0.05 - 0.75mm	•	Sub-rounded-
•	Straight, sutured contacts Monocrystalline–	•	Straight, sutured contacts	•	Fe-muscovite Trace zircon	•	Equant Sub-rounded- angular	•	rounded Trace brannerite
•	polycrystalline Undulatory extinction	•	Albite twinning	•	Trace monazite	•	Euhedral – anhedral	•	0.25-0.5mm Elongate
•	Polygonal texture from							•	Sub-rounded
	recrystallization							•	Needle-like internal structure
									Succure

Table 2.B.2. Thin section description, LB04216 – Quartz Arenite

- Sulfide-rich bands up to 7.5mm thick along bedding Some pyrite appears to be detrital •
- ٠
- Some pyrite appears to cross cut detrital grains
- Chalcopyrite encompasses quartz, feldspar and pyrite grains
- Quartz within the thick sulfide-rich band appears highly recrystallized ٠

	Quartz		K-Feldspar		Matrix		Sulfides		Uranium Minerals
•	85-90%	•	≥5%	٠	~5%	•	Concentrated in band	•	Trace thorite
•	0.05 - 2mm	•	0.05-1.5mm	•	Very fine grained	•	≥5% Pyrite	•	0.25-0.5mm
•	Equant - oblate	•	Equant – elongate	•	Infilling interstitial	•	Trace chalcopyrite	•	Equant – elongate
•	Sub-rounded – rounded	•	Sub-rounded- rounded		spaces and fractures	•	0.05 - 0.75mm	•	Sub-rounded-
•	Straight, sutured contacts	•	Straight, sutured	•	Fe-muscovite	•	Equant		rounded
•	Monocrystalline-		contacts	•	Trace zircon	•	Sub-rounded- angular	•	Trace brannerite
	polycrystalline	•	Albite twinning	•	Trace monazite	•	Euhedral – anhedral	•	0.25-0.5mm
•	Undulatory extinction							•	Elongate
•	Polygonal texture from							•	Sub-rounded
	recrystallization							•	Needle-like internal
									structure

Table 2.B.3. Thin section description, LB04217 – Quartz Arenite

- Sulfide rich bands up to ~1.5mm along bedding
 Some pyrite appears to be detrital
 Some pyrite appears to cross cut detrital grains
- Chalcopyrite encompasses quartz, feldspar and pyrite grains



Figure 2.B.2. Photograph of diamond drill core for the six samples classified as quartzose conglomerate; a) LB04218, b) LB04219 and c) LB04220, d) LB04221, e) LB04222 and f) LB04223.

Framework (80%)			Matrix (20%)		
Quartz	Quartz	K-Feldspar	Sulfides	Uranium Minerals	Other
 100% 5-20mm Equant-oblate Sub-rounded- rounded Straight contacts Monocrystalline – polycrystalline 	 ~80% 0.05 - 2mm Equant - oblate Sub-rounded – rounded Straight, sutured contacts Monocrystalline– polycrystalline Undulatory extinction Polygonal texture from recrystallization 	 ≥5% 0.05-1.5mm Equant – elongate Sub-rounded- rounded Straight, sutured contacts Albite twinning 	 Concentrated in matrix along pebble boundaries 5-10% Pyrite Trace chalcopyrite Trace galena 0.05–0.75mm Equant Sub-rounded-angular Euhedral – anhedral 	 >5% thorite 0.25-0.5mm Equant – elongate Sub-rounded- rounded Trace brannerite 0.25-0.5mm Elongate Sub-rounded Needle-like internal structure 	 ~5% Primarily Fe-muscovite Very fine grained Infilling interstitial spaces and fractures Trace zircon Trace monazite

Table 2.B.4. Thin section description, LB04218 – Quartzose Conglomerate

- Some pyrite appears to be detrital
 Some pyrite appears to cross cut detrital grains
 Chalcopyrite and pyrrhotite encompasses quartz, feldspar and pyrite grains

Framework (65-70%)				М	latrix (30-35%)				
Quartz	Quartz		K-Feldspar		Sulfides		Uranium Minerals		Other
 100% 5-20mm Equant–oblate Sub-rounded-rounded Straight contacts Monocrystalline – polycrystalline 	 ~35% 0.05 - 2mm Equant - oblate Sub-rounded – rounded Straight, sutured contacts Monocrystalline– polycrystalline Undulatory extinction Polygonal texture from recrystallization 	• • • •	≥5% 0.05-1.5mm Equant – elongate Sub-rounded- rounded Straight, sutured contacts Albite twinning	•	Concentrated in matrix along pebble boundaries ~40-45% Pyrite ~5% chalcopyrite >5% pyrrhotite Trace galena 0.05–0.75mm Equant Sub-rounded- angular Eubedral –	• • • • •	~5% thorite 0.25-1mm Equant – elongate Sub-rounded- rounded ≥5% brannerite 0.25-1mm Elongate Sub-rounded Needle-like internal structure	•	5-7% Primarily Fe-muscovite Very fine grained Infilling interstitial spaces and fractures Trace zircon Trace monazite
	from recrystamzation				anhedral				monazite

Table 2.B.5. Thin section description, LB04219 - Quartzose Conglomerate

- Some pyrite appears to be detrital ٠
- Some pyrite appears to cross cut detrital grains
 Chalcopyrite and pyrrhotite encompasses quartz, feldspar and pyrite grains

	Framework (70%)]	Matrix (30%)				
	Quartz		Quartz		K-Feldspar		Sulfides		Uranium Minerals		Other
• • • •	100% 5-20mm Equant–oblate Sub-rounded- rounded Straight contacts Monocrystalline – polycrystalline	•	~25% 0.05 - 2mm Equant - oblate Sub-rounded – rounded Straight, sutured contacts Monocrystalline– polycrystalline Undulatory extinction Polygonal texture from recrystallization	•	≥5% 0.05-1.5mm Equant – elongate Sub-rounded- rounded Straight, sutured contacts Albite twinning	•	Concentrated in matrix along pebble boundaries ~50% Pyrite ~5% chalcopyrite >5% pyrrhotite Trace galena 0.05–0.75mm Equant Sub-rounded- angular Euhedral – anhedral	•	~5% thorite 0.25-1mm Equant – elongate Sub-rounded- rounded ≥5% brannerite 0.25-1mm Elongate Sub-rounded Needle-like internal structure	•	5-7% Primarily Fe-muscovite Very fine grained Infilling interstitial spaces and fractures Trace zircon Trace monazite

Table 2.B.6. Thin section description, LB04220 - Quartzose Conglomerate

- Some pyrite appears to be detrital
 Some pyrite appears to cross cut detrital grains
 Chalcopyrite and pyrrhotite encompasses quartz, feldspar and pyrite grains

Framework (75%)			Matrix (25%)		
Quartz	Quartz	K-Feldspar	Sulfides	Uranium Minerals	Other
 100% 5-20mm Equant–oblate Sub-rounded- rounded Straight contacts Monocrystalline – polycrystalline 	 ~25% 0.05 - 2mm Equant - oblate Sub-rounded – rounded Straight, sutured contacts Monocrystalline– polycrystalline Undulatory extinction Polygonal texture from recrystallization 	 ≥5% 0.05-1.5mm Equant – elongate Sub-rounded- rounded Straight, sutured contacts Albite twinning 	 Concentrated in matrix along pebble boundaries ~50% Pyrite >5% Galena ~5% chalcopyrite >5% pyrrhotite Trace galena 0.05–0.75mm Equant Sub-rounded-angular Euhedral – anhedral 	 ~5% thorite 0.25-1mm Equant – elongate Sub-rounded-rounded ≥5% brannerite 0.25-1mm Elongate Sub-rounded Needle-like internal structure 	 5-7% Primarily Fe-muscovite Very fine grained Infilling interstitial spaces and fractures Trace zircon Trace monazite

Table 2.B.7. Thin section description, LB04221 - Quartzose Conglomerate

- Some pyrite appears to be detrital
- Some pyrite appears to cross cut detrital grains
- Chalcopyrite and pyrrhotite encompasses quartz, feldspar and pyrite grains

Framework (85%)		Matrix (15%)	
Quartz	Quartz	K-Feldspar Sulfides	Uranium Minerals Other
 100% 5-20mm Equant–oblate Sub-rounded-rounded Straight contacts Monocrystalline – polycrystalline 	 ~40-45% 0.05 - 2mm Equant - oblate Sub-rounded – rounded Straight, sutured contacts Monocrystalline– polycrystalline Undulatory extinction Polygonal texture from recrystallization 	 ≥5% 0.05-1.5mm Equant – elongate Sub-rounded- rounded Straight, sutured contacts Albite twinning Concentrated in matrix along pebble boundaries ~20% Pyrite >5% Galena ~5% chalcopyrite >5% pyrrhotite Trace galena 0.05–0.75mm Equant Sub-rounded- angular Euhedral – anhedral 	 >5% thorite 0.25-1mm Equant – elongate Sub-rounded-rounded ≥5% brannerite 0.25-1mm Elongate Sub-rounded Sub-rounded Needle-like internal structure Infilling interstitial spaces and fractures Trace zircon Trace monazite

Table 2.B.8. Thin section description, LB04222 – Q	Quartzose	Conglomerate
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- Some pyrite appears to be detrital ٠
- Some pyrite appears to cross cut detrital grains
 Chalcopyrite and pyrrhotite encompasses quartz, feldspar and pyrite grains

Framework (30%)			Matrix (60%)		
Quartz	Quartz	K-Feldspar	Sulfides	Uranium Minerals	Other
 100% 5-20mm Equant–oblate Sub-rounded- rounded Straight contacts Monocrystalline – polycrystalline 	 ~50% 0.05 - 2mm Equant - oblate Sub-rounded – rounded Straight, sutured contacts Monocrystalline– polycrystalline Undulatory extinction Polygonal texture from recrystallization 	 ≥5% 0.05-1.5mm Equant – elongate Sub-rounded- rounded Straight, sutured contacts Albite twinning 	 Concentrated in matrix along pebble boundaries >5% Pyrite >5% Galena ~5% chalcopyrite >5% pyrrhotite Trace galena 0.05–0.75mm Equant Sub-rounded-angular Euhedral – anhedral 	 Trace thorite 0.25-1mm Equant – elongate Sub-rounded- rounded Trace brannerite 0.25-1mm Elongate Sub-rounded Needle-like internal structure 	 35% Primarily Fe-muscovite Very fine grained Infilling interstitial spaces and fractures Trace zircon Trace monazite

Table 2.B.9. Thin section description, LB04223 - Quartzose Conglomerate

• Some pyrite appears to be detrital

• Some pyrite appears to cross cut detrital grains

Chalcopyrite and pyrrhotite encompasses quartz, feldspar and pyrite grains

Appendix 2.C Electron Microprobe Analysis Data

Thorite	#	Si	U	Ca	Ti	Fe	Pb	Al	Th	S	Na	K	V	Р	0	Total
LB04220	1	7.64	13.02	0.20	0.02	0.09	0.76	0.15	45.57	0.07	0.03	0.07	-0.05	0.40	17.64	85.66
LB04220	2	8.37	13.26	0.23	0.03	0.25	0.37	0.29	44.77	0.04	0.02	0.08	-0.02	0.39	18.54	86.63
LB04220	3	7.88	11.06	0.37	0.04	0.24	1.90	0.21	48.81	0.11	0.03	0.06	0.08	0.39	18.51	89.69
LB04220	4	7.44	13.59	0.29	0.02	0.11	1.53	0.15	42.59	0.23	0.05	0.07	-0.02	0.30	17.22	83.58
LB04220	5	7.58	11.05	0.28	0.02	0.20	2.15	0.13	47.95	0.16	0.04	0.06	-0.03	0.38	17.87	87.85
LB04220	6	8.15	12.12	0.26	0.02	0.09	1.06	0.15	44.75	0.11	0.06	0.06	-0.01	0.34	18.02	85.19
LB04220	7	8.09	9.69	0.30	0.02	0.12	1.32	0.09	46.71	0.12	0.05	0.06	0.02	0.33	17.93	84.87
LB04220	8	8.10	8.96	0.30	0.04	0.19	1.02	0.10	49.93	0.09	0.06	0.05	-0.06	0.40	18.31	87.56
LB04220	9	8.18	12.21	0.39	0.02	0.13	1.26	0.09	45.24	0.15	0.02	0.07	0.01	0.37	18.26	86.40
LB04220	10	7.61	12.25	0.34	0.03	0.09	7.80	0.07	40.75	1.13	0.06	0.06	-0.07	0.34	18.34	88.89
LB04220	11	8.17	10.79	0.25	0.09	0.23	0.41	0.31	49.33	0.07	0.03	0.07	-0.02	0.58	18.95	89.29
LB04220	12	8.16	13.28	0.21	0.00	0.22	0.48	0.22	47.82	0.11	0.05	0.05	0.00	0.61	19.02	90.24
LB04220	13	7.76	12.39	0.27	0.02	1.40	1.38	0.15	45.56	1.38	0.00	0.06	0.04	0.53	19.86	90.81
LB04220	14	8.09	11.06	0.35	0.04	0.25	0.59	0.13	50.63	0.17	0.01	0.04	0.00	0.60	19.08	91.05
LB04220	15	7.87	10.42	0.25	0.02	0.21	0.49	0.17	49.47	0.04	0.00	0.05	-0.05	0.60	18.37	87.98
LB04220	16	8.01	11.02	0.17	0.02	0.14	0.98	0.16	47.92	0.17	0.03	0.07	0.01	0.37	18.25	87.32
LB04220	17	8.24	11.52	0.24	0.02	0.20	0.86	0.35	47.42	0.08	0.02	0.06	0.00	0.37	18.63	88.01
LB04220	18	8.11	11.91	0.25	0.05	0.20	0.93	0.26	47.48	0.10	0.04	0.08	0.01	0.43	18.60	88.44
LB04220	19	8.49	9.07	0.16	0.05	0.08	0.26	0.30	50.47	0.07	0.02	0.05	-0.02	0.39	18.85	88.27
LB04220	20	8.30	10.01	0.28	0.02	0.13	0.74	0.13	48.75	0.07	0.04	0.05	0.01	0.36	18.45	87.34
LB04220	21	8.03	8.01	0.25	0.02	0.14	1.20	0.15	48.27	0.22	0.03	0.04	0.01	0.36	17.99	84.73
LB04220	22	8.13	9.96	0.25	-0.01	0.23	0.49	0.12	47.76	0.19	0.04	0.05	-0.03	0.35	18.17	85.72
LB04220	23	10.81	9.80	0.26	0.05	1.19	0.81	3.51	38.55	0.28	0.01	0.45	0.05	0.28	23.57	89.63
LB04220	24	8.50	10.11	0.27	0.01	0.75	0.54	0.30	47.84	0.20	0.00	0.05	0.03	0.37	19.10	88.06
LB04220	25	8.46	10.61	0.26	0.01	0.32	0.32	0.30	46.81	0.11	0.02	0.05	0.00	0.38	18.69	86.35
LB04217	41	8.38	15.25	0.25	0.04	1.99	0.41	0.46	42.96	1.72	-0.01	0.07	0.02	0.47	21.28	93.28
LB04217	42	8.50	12.86	0.25	0.03	0.59	1.24	0.51	45.84	0.42	0.02	0.06	-0.04	0.50	19.72	90.55
LB04217	43	8.40	15.83	0.33	0.03	0.19	0.51	0.30	46.12	0.07	0.01	0.07	0.05	0.45	19.31	91.67
LB04217	44	8.74	13.37	0.45	0.03	0.09	0.70	0.36	47.60	0.06	0.01	0.06	0.04	0.48	19.65	91.64
LB04217	45	8.62	15.02	0.32	0.02	0.19	0.49	0.24	47.38	0.05	-0.03	0.06	-0.01	0.50	19.54	92.42
LB04217	46	8.39	14.66	0.35	0.03	0.17	0.44	0.39	45.18	0.03	-0.01	0.08	0.04	0.48	19.06	89.28

Table 2.C.1. Elemental wt% of electron microprobe analyses of Thorite from sample LB04220, LB04217 and LB04219, for the Elliot Lake Quartz-Pebble Conglomerate Uranium Deposit, Elliot Lake District, Ontario, Canada.

Thorite	#	Si	U	Ca	Ti	Fe	Pb	Al	Th	S	Na	Κ	V	Р	0	Total
LB04217	47	8.51	11.17	0.36	0.03	0.18	0.44	0.36	47.64	0.05	0.01	0.06	0.04	0.41	18.98	88.22
LB04217	48	8.37	11.16	0.48	0.04	0.30	0.64	0.15	50.57	0.04	0.00	0.06	0.03	0.44	19.19	91.47
LB04217	49	8.13	10.17	0.42	0.07	0.16	3.25	0.16	47.39	0.49	0.01	0.04	-0.02	0.42	18.86	89.56
LB04217	50	8.11	12.12	0.13	0.05	0.49	1.02	0.39	48.11	0.41	0.01	0.05	0.01	0.39	19.15	90.42
LB04217	51	8.32	11.33	0.29	0.05	0.18	2.00	0.18	46.30	0.18	0.03	0.05	0.03	0.35	18.62	87.91
LB04217	52	7.90	14.69	0.07	0.02	0.08	2.22	0.15	38.32	0.20	0.01	0.06	-0.01	0.41	17.37	81.49
LB04217	53	7.72	13.24	0.07	0.04	-0.01	1.90	0.13	38.99	0.35	0.01	0.06	-0.01	0.46	17.20	80.16
LB04217	54	7.38	11.25	0.06	0.03	-0.02	4.74	0.10	41.36	0.47	0.01	0.04	-0.04	0.43	17.13	83.01
LB04217	55	7.61	12.22	0.06	0.00	0.09	1.78	0.09	42.10	0.29	-0.01	0.04	-0.08	0.47	17.25	82.01
LB04217	56	7.39	13.29	0.07	0.03	0.05	4.77	0.11	37.44	0.37	0.02	0.05	0.02	0.44	16.87	80.91
LB04217	57	7.41	11.41	0.05	0.05	0.02	5.86	0.10	37.25	0.94	0.00	0.06	0.03	0.38	17.18	80.73
LB04217	69	8.37	14.17	0.20	2.14	0.28	0.47	0.99	35.62	0.07	0.04	0.18	0.02	0.84	20.12	83.51
LB04217	70	6.03	12.71	0.46	0.04	0.27	1.78	0.35	48.14	0.31	0.02	0.06	0.02	0.92	17.53	88.64
LB04217	71	8.57	32.99	0.19	0.42	0.19	2.53	0.74	16.72	0.27	0.00	0.11	0.00	0.35	18.54	81.63
LB04217	72	7.23	30.93	0.24	0.08	0.13	3.60	0.55	20.10	0.38	0.01	0.10	-0.04	0.43	17.06	80.83
LB04219	75	7.25	6.80	1.36	0.03	2.14	0.52	0.24	50.24	1.71	-0.02	0.05	-0.03	1.71	21.74	93.79
LB04219	76	7.47	8.83	1.35	0.06	0.79	0.46	0.17	50.99	0.58	-0.01	0.06	0.00	1.57	20.45	92.79
LB04219	77	7.29	6.85	1.54	0.03	2.02	0.52	0.30	50.20	1.47	-0.01	0.05	-0.04	1.68	21.57	93.52
LB04219	78	3.37	0.72	0.32	0.04	2.22	0.40	0.18	40.03	0.96	0.00	0.02	0.03	0.44	12.30	61.02
LB04219	82	6.22	5.06	0.82	0.03	4.02	0.49	0.15	47.69	4.10	0.03	0.04	-0.01	1.86	23.09	93.59
LB04219	83	6.90	1.95	0.91	0.04	1.58	0.63	0.20	56.04	0.76	0.01	0.03	0.01	1.80	20.25	91.10
LB04219	84	6.87	3.75	0.97	0.06	1.76	0.58	0.17	54.64	0.81	0.00	0.03	0.04	1.75	20.36	91.80
LB04219	85	6.58	8.20	0.72	0.32	2.59	0.33	0.22	44.32	1.90	-0.03	0.03	0.04	1.89	20.92	88.07
LB04219	86	6.43	8.21	0.94	0.07	2.82	0.63	0.28	49.58	1.97	-0.01	0.04	0.01	1.55	21.16	93.68
LB04219	87	5.91	7.11	1.89	0.05	8.75	0.86	0.09	36.77	10.13	0.07	0.05	0.00	2.13	30.35	104.17
LB04219	88	7.14	6.10	2.30	0.04	0.75	0.67	0.14	46.06	0.80	0.08	0.05	0.05	2.84	21.28	88.27
LB04219	89	7.17	7.75	2.24	0.03	0.99	0.43	0.14	47.88	1.30	0.08	0.05	0.00	2.02	21.25	91.33
LB04219	90	7.07	7.84	2.01	0.02	0.37	0.34	0.09	50.27	0.15	0.03	0.05	-0.02	2.01	19.88	90.13
LB04219	91	6.83	7.71	2.20	0.03	0.65	0.42	0.08	47.02	0.63	0.06	0.05	-0.01	2.62	20.62	88.90
Average Sta Deviation	andard (wt%)	0.11	1.02	0.05	0.05	0.07	0.18	0.03	1.08	0.03	0.03	0.02	0.08	0.05		

Brannerite	#	Si	U	Ca	Ti	Fe	Pb	Al	Th	S	Na	K	V	Р	0	Total
LB04219	27	4.24	25.47	1.11	19.33	1.99	1.08	3.09	1.69	0.12	0.09	0.52	0.21	-0.02	25.93	84.86
LB04219	28	1.96	29.43	1.09	23.74	1.28	1.06	0.22	1.81	0.07	0.04	0.09	0.28	-0.03	23.85	84.93
LB04219	29	5.47	27.10	0.87	20.61	1.52	1.02	0.24	2.14	0.09	0.06	0.08	0.29	-0.01	25.57	85.06
LB04219	30	1.98	28.39	1.50	22.46	1.84	1.06	0.28	2.61	0.04	0.07	0.09	0.25	-0.03	23.39	83.95
LB04219	31	1.99	29.36	1.36	21.84	1.76	1.20	0.27	1.78	0.04	0.05	0.11	0.21	-0.02	22.91	82.87
LB04219	39	2.94	27.79	1.05	21.63	1.75	0.78	0.32	3.41	0.03	0.07	0.11	0.20	0.02	23.78	83.89
LB04219	40	3.86	25.86	0.81	23.96	1.40	0.70	0.61	2.24	0.11	0.06	0.13	0.21	-0.01	26.02	85.96
LB04219	58	2.09	26.52	0.79	21.95	1.53	0.92	0.33	2.43	0.08	0.01	0.09	0.24	0.00	22.57	79.55
LB04219	59	1.96	26.08	0.96	21.40	1.46	0.97	0.29	2.05	0.05	-0.01	0.08	0.23	0.00	21.89	77.40
LB04219	60	5.12	20.92	0.77	17.59	4.21	2.11	3.58	1.60	0.34	0.03	0.50	0.20	0.00	26.68	83.63
LB04219	61	1.91	26.74	1.10	21.17	1.61	0.88	0.24	3.34	0.02	0.01	0.09	0.25	0.00	22.03	79.40
Average Stand Deviation (w	dard t%)	0.07	1.62	0.07	0.41	0.10	0.17	0.04	0.16	0.02	0.03	0.02	0.10	0.02		

Table 2.C.2. Elemental wt% of electron microprobe analyses of Brannerite from sample LB04219, for the Elliot Lake Quartz-Pebble Conglomerate Uranium Deposit, Elliot Lake District, Ontario, Canada.

Thorite	#	SiO ₂	UO ₂	CaO	TiO ₂	Fe ₂ O ₃	PbO	Al_2O_3	ThO ₂	SO ₂	Na ₂ O	K ₂ O	V_2O_5	P_2O_5	Total
LB04220	1	16.35	14.77	0.28	0.04	0.13	0.82	0.28	51.85	0.15	0.04	0.08	-0.09	0.92	85.70
LB04220	2	17.90	15.04	0.33	0.05	0.35	0.40	0.55	50.94	0.08	0.03	0.09	-0.03	0.89	86.64
LB04220	3	16.85	12.55	0.52	0.07	0.35	2.05	0.39	55.54	0.23	0.04	0.07	0.15	0.89	89.69
LB04220	4	15.92	15.42	0.40	0.03	0.16	1.65	0.28	48.47	0.45	0.07	0.08	-0.04	0.68	83.60
LB04220	5	16.22	12.53	0.39	0.03	0.29	2.32	0.24	54.56	0.32	0.05	0.08	-0.05	0.86	87.88
LB04220	6	17.44	13.75	0.37	0.03	0.12	1.15	0.28	50.93	0.21	0.07	0.07	-0.02	0.77	85.20
LB04220	7	17.32	11.00	0.42	0.03	0.18	1.43	0.17	53.16	0.25	0.07	0.08	0.03	0.76	84.87
LB04220	8	17.34	10.17	0.42	0.06	0.27	1.10	0.19	56.81	0.19	0.08	0.06	-0.11	0.92	87.61
LB04220	9	17.50	13.85	0.54	0.04	0.19	1.36	0.17	51.48	0.30	0.03	0.09	0.02	0.84	86.40
LB04220	10	16.28	13.90	0.48	0.05	0.13	8.41	0.13	46.37	2.26	0.08	0.08	-0.12	0.78	88.94
LB04220	11	17.48	12.24	0.36	0.15	0.32	0.44	0.59	56.14	0.14	0.04	0.08	-0.03	1.32	89.30
LB04220	12	17.45	15.07	0.29	0.00	0.32	0.52	0.41	54.42	0.23	0.06	0.07	0.00	1.40	90.24
LB04220	13	16.60	14.05	0.38	0.03	2.00	1.49	0.28	51.84	2.76	0.00	0.07	0.07	1.22	90.81
LB04220	14	17.32	12.54	0.50	0.07	0.36	0.63	0.24	57.62	0.34	0.02	0.05	0.00	1.37	91.05
LB04220	15	16.84	11.83	0.35	0.04	0.30	0.53	0.33	56.30	0.09	0.01	0.06	-0.09	1.36	88.02
LB04220	16	17.14	12.50	0.24	0.04	0.19	1.06	0.30	54.53	0.33	0.04	0.08	0.02	0.84	87.32
LB04220	17	17.63	13.07	0.33	0.04	0.28	0.93	0.67	53.96	0.15	0.02	0.07	0.00	0.86	88.01
LB04220	18	17.34	13.52	0.34	0.08	0.28	1.00	0.48	54.02	0.20	0.06	0.09	0.01	0.99	88.44
LB04220	19	18.17	10.29	0.22	0.08	0.11	0.28	0.57	57.43	0.14	0.03	0.06	-0.04	0.89	88.29
LB04220	20	17.75	11.35	0.39	0.04	0.19	0.79	0.25	55.47	0.14	0.05	0.05	0.01	0.83	87.34
LB04220	21	17.19	9.09	0.35	0.03	0.21	1.29	0.28	54.93	0.43	0.05	0.05	0.02	0.82	84.73
LB04220	22	17.39	11.29	0.35	-0.01	0.32	0.53	0.23	54.34	0.37	0.05	0.06	-0.04	0.80	85.74
LB04220	23	23.13	11.12	0.37	0.08	1.70	0.87	6.64	43.86	0.57	0.02	0.54	0.08	0.65	89.63
LB04220	24	18.19	11.47	0.38	0.02	1.07	0.58	0.56	54.44	0.40	0.00	0.06	0.05	0.85	88.06
LB04220	25	18.09	12.04	0.37	0.02	0.46	0.35	0.57	53.26	0.21	0.03	0.06	0.01	0.88	86.35
LB04217	41	17.92	17.30	0.35	0.06	2.84	0.44	0.87	48.88	3.44	-0.01	0.09	0.03	1.07	93.29
LB04217	42	18.18	14.59	0.35	0.06	0.85	1.34	0.97	52.17	0.84	0.02	0.07	-0.07	1.15	90.58
LB04217	43	17.96	17.96	0.46	0.05	0.27	0.55	0.57	52.49	0.15	0.01	0.09	0.09	1.04	91.67
LB04217	44	18.69	15.16	0.62	0.05	0.13	0.75	0.68	54.17	0.13	0.02	0.07	0.07	1.10	91.64
LB04217	45	18.44	17.04	0.45	0.03	0.27	0.53	0.46	53.91	0.10	-0.04	0.07	-0.01	1.14	92.43
LB04217	46	17.94	16.63	0.49	0.04	0.24	0.47	0.74	51.41	0.05	-0.02	0.09	0.07	1.10	89.28

Table 2.C.3. Oxide wt% of electron microprobe analyses of Thorite from sample LB04220, LB04217 and LB04219, for the Elliot Lake Quartz-Pebble Conglomerate Uranium Deposit, Elliot Lake District, Ontario, Canada.

Thorite	#	SiO ₂	UO ₂	CaO	TiO ₂	Fe ₂ O ₃	PbO	Al_2O_3	ThO ₂	SO ₂	Na ₂ O	K ₂ O	V_2O_5	P_2O_5	Total
LB04217	47	18.20	12.67	0.51	0.04	0.25	0.48	0.68	54.21	0.10	0.01	0.07	0.07	0.93	88.22
LB04217	48	17.90	12.66	0.67	0.07	0.43	0.69	0.28	57.54	0.08	0.00	0.07	0.06	1.02	91.47
LB04217	49	17.40	11.53	0.59	0.12	0.24	3.50	0.30	53.92	0.98	0.01	0.04	-0.04	0.95	89.58
LB04217	50	17.35	13.75	0.18	0.08	0.70	1.09	0.73	54.75	0.82	0.01	0.07	0.01	0.90	90.42
LB04217	51	17.80	12.85	0.41	0.08	0.25	2.15	0.34	52.68	0.37	0.04	0.06	0.06	0.81	87.91
LB04217	52	16.89	16.66	0.09	0.04	0.11	2.39	0.28	43.61	0.40	0.02	0.07	-0.02	0.94	81.50
LB04217	53	16.51	15.02	0.09	0.07	-0.01	2.04	0.24	44.37	0.69	0.01	0.08	-0.02	1.04	80.17
LB04217	54	15.80	12.76	0.08	0.06	-0.03	5.11	0.20	47.06	0.93	0.01	0.05	-0.08	0.99	83.05
LB04217	55	16.28	13.86	0.08	0.00	0.13	1.92	0.18	47.91	0.57	-0.02	0.05	-0.13	1.09	82.07
LB04217	56	15.80	15.07	0.10	0.05	0.07	5.14	0.21	42.60	0.75	0.03	0.06	0.03	1.00	80.91
LB04217	57	15.86	12.94	0.07	0.09	0.03	6.31	0.18	42.38	1.87	0.00	0.07	0.05	0.86	80.73
LB04217	69	17.90	16.08	0.28	3.57	0.39	0.51	1.87	40.53	0.15	0.06	0.21	0.03	1.92	83.51
LB04217	70	12.91	14.42	0.64	0.07	0.39	1.92	0.67	54.78	0.61	0.03	0.07	0.03	2.11	88.64
LB04217	71	18.34	37.43	0.27	0.71	0.27	2.73	1.40	19.03	0.54	-0.01	0.13	-0.01	0.79	81.64
LB04217	72	15.47	35.08	0.34	0.13	0.19	3.88	1.04	22.87	0.76	0.01	0.12	-0.08	0.98	80.86
LB04219	75	15.51	7.71	1.90	0.04	3.06	0.56	0.46	57.17	3.41	-0.02	0.06	-0.05	3.93	93.82
LB04219	76	15.97	10.02	1.89	0.10	1.14	0.50	0.32	58.03	1.16	-0.01	0.07	-0.01	3.61	92.79
LB04219	77	15.59	7.77	2.16	0.05	2.89	0.56	0.57	57.13	2.94	-0.01	0.06	-0.06	3.84	93.55
LB04219	78	7.20	0.81	0.44	0.07	3.17	0.43	0.33	45.55	1.92	0.00	0.03	0.05	1.00	61.02
LB04219	82	13.30	5.74	1.15	0.04	5.74	0.52	0.29	54.27	8.20	0.04	0.05	-0.02	4.25	93.60
LB04219	83	14.77	2.21	1.27	0.06	2.26	0.67	0.37	63.77	1.52	0.01	0.04	0.01	4.13	91.10
LB04219	84	14.69	4.25	1.35	0.10	2.52	0.63	0.33	62.17	1.62	0.00	0.04	0.08	4.02	91.80
LB04219	85	14.07	9.30	1.00	0.53	3.71	0.35	0.42	50.43	3.80	-0.04	0.04	0.08	4.34	88.08
LB04219	86	13.75	9.32	1.32	0.11	4.03	0.68	0.53	56.41	3.93	-0.01	0.05	0.01	3.54	93.68
LB04219	87	12.65	8.06	2.64	0.08	12.52	0.93	0.17	41.84	20.24	0.10	0.06	0.00	4.88	104.17
LB04219	88	15.27	6.92	3.21	0.06	1.07	0.72	0.26	52.41	1.60	0.11	0.06	0.09	6.50	88.27
LB04219	89	15.34	8.79	3.14	0.05	1.42	0.46	0.26	54.48	2.59	0.10	0.06	-0.01	4.64	91.34
LB04219	90	15.12	8.90	2.81	0.04	0.52	0.37	0.17	57.20	0.30	0.05	0.06	-0.04	4.61	90.15
LB04219	91	14.61	8.74	3.08	0.05	0.93	0.45	0.15	53.50	1.26	0.08	0.06	-0.01	6.01	88.91

Brannerite	#	SiO ₂	UO ₂	CaO	TiO ₂	Fe ₂ O ₃	PbO	Al_2O_3	ThO ₂	SO ₂	Na ₂ O	K ₂ O	V_2O_5	P_2O_5	Total
LB04219	27	9.08	28.89	1.55	32.24	2.85	1.17	5.84	1.92	0.23	0.12	0.63	0.37	-0.05	84.89
LB04219	28	4.19	33.39	1.53	39.60	1.83	1.15	0.42	2.06	0.15	0.05	0.11	0.49	-0.06	84.97
LB04219	29	11.69	30.75	1.21	34.38	2.17	1.10	0.46	2.44	0.18	0.08	0.09	0.51	-0.03	85.08
LB04219	30	4.23	32.20	2.09	37.47	2.63	1.14	0.53	2.97	0.08	0.09	0.11	0.44	-0.07	83.99
LB04219	31	4.26	33.30	1.91	36.43	2.52	1.29	0.52	2.02	0.08	0.07	0.13	0.37	-0.04	82.89
LB04219	39	6.28	31.53	1.47	36.08	2.50	0.84	0.61	3.88	0.06	0.10	0.13	0.36	0.04	83.89
LB04219	40	8.26	29.33	1.13	39.96	2.00	0.76	1.16	2.55	0.21	0.07	0.16	0.38	-0.03	85.97
LB04219	58	4.47	30.09	1.11	36.62	2.19	0.99	0.62	2.77	0.15	0.01	0.11	0.43	-0.01	79.56
LB04219	59	4.19	29.58	1.34	35.69	2.09	1.04	0.54	2.34	0.09	-0.01	0.10	0.41	-0.01	77.41
LB04219	60	10.94	23.73	1.08	29.34	6.02	2.27	6.76	1.82	0.67	0.04	0.60	0.36	0.00	83.63
LB04219	61	4.08	30.34	1.54	35.32	2.30	0.95	0.46	3.80	0.04	0.02	0.10	0.45	0.00	79.40

Table 2.C.4. Oxide wt% of electron microprobe analyses of Brannerite from sample LB04219, for the Elliot Lake Quartz-Pebble Conglomerate Uranium Deposit, Elliot Lake District, Ontario, Canada.
Appendix 2.D

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September 5, 2012

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Sincerely,

Appendix 3.A Field Photographs



Figure 3.A.1. Photograph of Lorado Mill Tailings, taken from former mill site looking towards Nero Lake (2011).



Figure 3.A.2. Photograph of Lorado Mill Tailings, showing discontinuous salt crust formation over portions of the tailings (2011).



Figure 3.A.3. Photograph of Lorado Mill Tailings, showing formation of salt crust on elevated areas near standing water on tailings surface (2011).



Figure 3.A.4. Photograph of Lorado Mill Tailings, showing formation of salt crust on westward facing surfaces suggesting evaporative origin (2011).



Figure 3.A.5. Photograph of Lorado Mill Tailings, showing formation of salt crust on westward facing surfaces suggesting evaporative origin (2011).



Figure 3.A.6. Photograph of core sampling procedure showing initial hammering of the core into tailings (2011).



Figure 3.A.7. Photograph of core sampling procedure showing core in place while being exhumed (2011).



Figure 3.A.8. Photograph of core sampling procedure showing pit after core exhumation (2011).

Appendix 3.B

Tailings Core Photographs



Figure 3.B.1. Photograph of core LB-LT-11-C1A&B, 0-1 m.



Figure 3.B.2. Photograph of core LB-LT-11-C2A, 0-0.5 m.



Figure 3.B.3. Photograph of core LB-LT-11-C3A, 0-0.5 m.



Figure 3.B.4. Photograph of core LB-LT-11-C4A, 0-0.5 m.



Figure 3.B.5. Photograph of core LB-LT-11-C5A, 0-0.5 m.



Figure 3.B.6. Photograph of core LB-LT-11-SC1A, 0-0.5 m.



Figure 3.B.7. Photograph of core LB-LT-11-SC2A, 0-0.5 m.



Figure 3.B.8. Photograph of core LB-LT-11-SC3A, 0-0.5 m.



Figure 3.B.9. Photograph of core LB-LT-11-SC4A, 0-0.5 m.



Figure 3.B.10. Photograph of core LB-LT-11-SC5A, 0-0.5 m.



Figure 3.B.11. Photograph of core LB-LT-11-SC6A, 0-0.5 m.

Appendix 3.C

Stratigraphic Section of Lorado Mill Tailings



Figure 3.C.1. Stratigraphic section illustrating the change in U concentration with depth as well as lateral and vertical extent of the major units within the tailings.

Appendix 3.D

Salt Photographs



Figure 3.D.1. Photographs illustrating the colour variability of the salt crust.

Appendix 3.E

Salt Sample X-ray Diffraction Spectra







Figure 3.C.2. XRD spectra of a brown-grey salt sample with mineralogy consisting of: quartz, gypsum, albite and epsomite.



Figure 3.C.3. XRD spectra of a representative white salt sample with mineralogy consisting of: hexahydrite, millosevichite and pickeringite.



Figure 3.C.4. XRD spectra of a mixed coloured salt sample with mineralogy consisting of: epsomite, hexahydrite, bilinite, gypsum and pickeringite.



Figure 3.C.5. XRD spectra of a representative orange salt sample with mineralogy consisting of: gypsum, romerite, millosevichite, halotrichite and epsomite.



Figure 3.C.6. XRD spectra of a representative orange salt sample with mineralogy consisting of: hexahydrite, bilinite and romerite.

Appendix 3.F Salt Bulk Chemistry

Table 3.F.1. Bulk Trace Element Chemistry of Salt Crust samples by colour, Mixed includes some mixture of white, yellow, green and orange.

		Brown-	Brown-													
		grey	grey	White	White	Mixed	Mixed	Mixed	Mixed	Mixed	Mixed	Mixed	Mixed	Mixed	Orange	Orange
Ag	ppm	0.32	0.21	0.02	0.2	0.04	0.02	0.02	0.02	0.02	0.03	0.03	0.04	0.03	0.05	0.02
Al	%	1.81	1.4	1.51	1.43	2.5	2.55	1.44	1.31	0.81	1.7	2.04	1.25	1.61	2.76	1.7
As	ppm	22.5	5.1	1.9	3.2	0.5	0.4	1.6	1.6	3.3	1.6	1.1	4.1	1.2	1.8	1.1
Au	ppm	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
В	ppm	30	20	<10	10	<10	<10	<10	10	10	<10	<10	10	10	<10	<10
Ва	ppm	40	40	20	30	<10	<10	10	30	30	<10	10	30	20	10	10
Be	ppm	1.58	1.19	1.68	1.46	2.22	3.22	1.53	1.13	0.88	2.24	2.88	1.77	1.73	4.31	2.66
Bi	ppm	1.05	0.63	0.05	0.09	0.02	< 0.01	0.03	0.07	0.11	0.01	0.02	0.07	0.06	0.05	0.02
Ca	%	2.58	5	0.44	5.84	0.14	0.06	1.82	5.38	4.45	0.29	1.01	4.17	3.03	0.43	0.6
Cd	ppm	0.19	0.12	0.2	0.23	0.34	0.51	0.35	0.2	0.13	0.48	0.6	0.39	0.34	0.89	0.51
Ce	ppm	66	46	140.5	197	132.5	169.5	268	236	154	226	237	243	190.5	219	232
Co	ppm	37.2	36.6	97.4	54	100.5	104.5	106	66.7	69.4	117.5	108	69.5	83.3	96.8	118
Cr	ppm	58	30	37	24	11	32	22	14	16	21	18	25	12	22	19
Cs	ppm	0.45	0.3	0.07	0.09	< 0.05	< 0.05	< 0.05	0.06	0.08	< 0.05	< 0.05	0.1	0.05	0.05	< 0.05
Cu	ppm	53.7	59.1	8.9	14.8	12.5	13.5	14.3	7.6	11.4	19.8	18.2	15.8	10.9	24.7	15.2
Fe	%	2.79	1.46	0.53	0.58	0.05	0.15	0.59	1.28	0.81	0.55	0.45	1.04	1.06	0.56	0.52
Ga	ppm	6.33	4.33	1.57	2	0.82	1.09	1.7	1.36	1.4	1.57	1.49	2.06	1.19	1.77	1.51
Ge	ppm	0.14	0.1	0.14	0.2	0.18	0.22	0.32	0.24	0.16	0.29	0.29	0.3	0.18	0.28	0.3
Hf	ppm	0.68	0.6	0.15	0.15	0.08	0.1	0.15	0.12	0.14	0.13	0.15	0.22	0.12	0.21	0.14
Hg	ppm	0.03	0.02	< 0.01	0.01	0.01	0.01	0.01	< 0.01	< 0.01	0.01	0.01	0.01	< 0.01	0.01	0.01
In	ppm	0.022	0.012	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	0.005	< 0.005	< 0.005	0.005	< 0.005	< 0.005	< 0.005
Κ	%	0.2	0.12	0.02	0.03	0.01	< 0.01	0.01	0.03	0.03	< 0.01	< 0.01	0.04	0.02	0.01	0.01
La	ppm	32.3	22.8	54.1	60.2	58.2	75.1	98.2	76.1	48.3	90.8	92.6	81.8	73.3	86.1	91.2
Li	ppm	64.3	52.5	43.3	65.2	93.1	88.2	40.9	40.3	31.7	57.1	81.5	47.2	64.9	140	83.2
Mg	%	2.81	2.36	7.03	4.11	6.9	6.81	6.28	4.87	5.11	7.06	6.45	4.28	5.95	5.76	7.2
Mn	ppm	998	701	1870	1380	2840	3210	2580	1520	1200	3210	3350	1980	2050	4500	3070

Mo	ppm	13.2	4.56	0.89	1.58	0.11	0.11	0.67	1.18	1.77	0.15	0.3	1.73	0.87	0.46	0.3
Na	%	0.12	0.09	0.07	0.14	0.17	0.13	0.09	0.17	0.1	0.08	0.13	0.13	0.17	0.19	0.14
Nb	ppm	0.22	0.25	0.1	0.15	0.05	0.07	0.07	0.13	0.15	0.27	0.14	0.14	0.1	0.06	0.05
Ni	ppm	93.7	80.6	245	136.5	240	236	238	166	181	263	235	156	200	193.5	269
Р	ppm	490	440	80	90	10	10	80	30	70	90	60	110	40	120	70
Pb	ppm	249	146	10.5	23	0.8	1.1	10.9	21.8	28.5	11.1	9	25.9	16	10.5	6.1
Rb	ppm	11.3	6.7	1.7	2.5	0.4	0.1	1	1.9	1.9	0.3	0.5	2.4	1.4	0.9	0.6
Re	ppm	0.049	0.061	0.024	0.039	0.051	0.05	0.028	0.031	0.026	0.041	0.052	0.037	0.051	0.09	0.052
S	%	7.81	9.1	>10.0	>10.0	>10.0	>10.0	>10.0	>10.0	>10.0	>10.0	>10.0	>10.0	>10.0	>10.0	>10.0
Sb	ppm	0.25	0.09	0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.26	< 0.05	< 0.05
Sc	ppm	4.6	2.7	1.5	1.7	1.2	2.9	1.3	1.1	1.2	1.9	2.2	1.8	1.2	2.5	1.6
Se	ppm	4.4	3.5	1.4	2	1.8	2.4	2.5	1.2	1.6	2.7	2.9	2.7	1.5	4.2	2.6
Sn	ppm	1.3	1	0.3	0.3	< 0.2	< 0.2	0.2	0.2	0.3	0.2	< 0.2	0.3	0.2	0.3	< 0.2
Sr	ppm	58.8	87.4	16.2	112	13.2	4.2	13.2	78	19.7	3	7.9	31.2	51.4	7.5	5
Та	ppm	0.01	< 0.01	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.03	0.03	0.02	0.01	0.04	0.03
Te	ppm	0.06	0.05	0.01	0.01	< 0.01	< 0.01	0.01	< 0.01	0.01	0.01	0.01	0.01	< 0.01	0.01	0.01
Th	ppm	9.3	4.7	2	1.7	0.8	3.2	2.1	1.2	1.3	2.9	2.5	2.4	0.8	1.5	1.3
Ti	%	0.015	0.013	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005
Tl	ppm	0.31	0.2	0.03	0.08	< 0.02	< 0.02	0.02	0.06	0.04	< 0.02	0.02	0.05	0.05	0.02	< 0.02
U	ppm	344	74	561	510	759	1340	1195	459	366	1700	1995	1385	801	3230	2150
V	ppm	233	115	40	54	3	2	23	37	58	13	12	55	24	20	16
W	ppm	1.3	0.68	0.17	0.23	0.14	0.22	0.2	0.18	0.24	0.68	0.36	0.34	0.17	0.26	0.2
Y	ppm	29.6	18.9	48	45.9	75.3	115.5	108.5	45.3	31.8	132.5	150.5	103	67	217	138.5
Zn	ppm	89	74	215	134	210	234	235	148	145	246	246	160	193	245	270
Zr	ppm	35.4	29.2	5.6	6.8	< 0.5	< 0.5	2.8	4.6	6.8	0.8	1.1	7.7	4.1	2.6	1.1

Appendix 3.G

Salt Sample Electron Microprobe Analysis Data

	Si	U	Ca	Ti	Fe	Pb	Na	Al	Th	S	K	V	Р	Zr	La	Ce	Nd	Eu	0	Total
3230 ppm U	0.15	1.86	0	0	0.28	0	0.03	17.9	0	17.75	0	0.01	0.04	0.26	0	0.03	0.07	0.07	34.37	72.82
3230 ppm U	0.14	0.62	0	0	0.34	0	0.1	16.05	0	19.48	0	0	0.02	0.02	0.05	0.02	0	0.17	34.21	71.22
3230 ppm U	0.02	0.51	0.01	0	18.37	0	1.71	3.74	0	20.23	0	0.02	0.12	0	0.02	0	0	0	32.28	77.03
3230 ppm U	2.02	1.68	0.03	0	0.37	0	0.02	15.87	0	15.94	0	0.02	0.03	0.15	0.01	0	0	0.01	32.85	69.07
3230 ppm U	9.66	3.03	0.02	0.35	0.87	0	0.02	14.72	0	15.05	0.01	0	0.04	0.63	0	0.18	0.09	0.03	40.48	85.2
3230 ppm U	0.19	2.68	0	0.01	0.53	0	0.03	18.92	0.01	17.23	0	0.01	0.04	0.02	0.02	0.08	0.04	0	34.96	74.86
3230 ppm U	0.27	2.17	0.02	0	0.52	0	0.03	16.68	0.01	18.64	0	0.01	0.03	0.05	0.02	0	0	0.16	34.38	73.01
3230 ppm U	0.03	4.23	0	0	0.82	0	0.02	18.27	0	18.06	0	0	0.04	0.02	0.01	0	0	0.09	35.31	76.9
3230 ppm U	0.03	1.51	0	0	0.37	0	0.03	18.97	0	18.92	0	0.01	0.02	0.01	0	0	0.12	0.3	36.29	76.82
3230 ppm U	0.05	5.12	0	0	0.92	0	0.01	16.94	0	17.17	0.01	0.01	0.05	0.06	0.01	0.01	0	0.03	33.47	73.94
3230 ppm U	0.11	2.51	0	0	0.53	0	0.02	15.24	0.01	19.12	0	0	0.02	0.02	0.01	0	0	0.02	33.38	70.99
3230 ppm U	0.15	3.04	0	0.01	0.56	0	0.04	16.96	0	17.11	0	0	0.04	0.02	0.01	0	0.02	0.09	33.08	71.18
3230 ppm U	0.25	5.03	0.08	0	0.78	0	0.04	18.56	0	15.53	0.01	0	0.04	0.04	0	0.04	0.07	0.19	33.46	74.15
3230 ppm U	0.07	1.09	0	0	0.81	0	0.11	19.43	0	21.2	0	0.01	0.03	0.01	0.04	0.07	0	0	39.14	82.05

Table 3.G.1. Electron microprobe (EMP) data in weight % for the 3230 ppm U orange salt sample.

						11														
	Si	U	Са	Ti	Fe	Pb	Na	Al	Th	S	К	V	Р	Zr	La	Ce	Nd	Eu	0	Total
1195 ppm U	0.16	0.39	0.04	0	12.7	0	1.19	10.69	0	17.51	0	0	0.14	0.01	0.07	0	0.08	0	33.32	76.3
1195 ppm U	0.13	1.31	0.01	0	2.79	0	0.06	18.53	0	17.84	0	0	0.13	0	0.02	0.01	0.05	0	36.02	76.89
1195 ppm U	0.05	0.25	0.01	0	1.19	0	0.03	19.79	0	18.1	0	0	0.01	0	0	0.02	0.02	0	36.32	75.8
1195 ppm U	0.17	0	40.53	0	0.01	0	0	0.06	0.02	14.97	0	0.01	0.01	0	0.03	0.07	0	0.12	31.42	87.43
1195 ppm U	0.17	0.46	0	0.01	1.44	0	0.01	18.79	0	16.24	0	0.01	0.06	0	0.06	0	0	0.05	33.92	71.32
1195 ppm U	0.11	0.3	0.26	0.01	7.94	0	0.32	12.83	0.03	22.3	0	0	0.1	0	0.06	0	0	0	37.62	81.89
1195 ppm U	0.02	0.03	30.86	0.01	0.28	0	0.06	0.6	0.03	17.7	0	0.02	0.02	0	0.18	0.29	0.1	0	30.84	81.1
1195 ppm U	0.26	1.06	0.02	0.01	2.46	0	0.11	16.5	0	17.94	0	0.01	0.09	0	0	0.05	0	0	34.26	72.78
1195 ppm U	0.03	0.99	0.02	0	2.88	0	0.06	19.07	0.02	18.43	0.01	0.01	0.08	0.01	0	0.02	0	0.03	36.91	78.53
1195 ppm U	0.21	1.32	0.01	0	3.32	0	0.04	17.76	0	18.8	0	0.01	0.1	0	0	0.02	0.07	0	36.59	78.37
1195 ppm U	0.51	0.79	0.24	0	2.73	0	0.13	19.88	0	11.14	0	0	0.09	0	0	0.02	0	0	30.92	66.45
1195 ppm U	0.11	0.8	0.02	0	2.2	0	0.05	19.11	0	18.01	0	0	0.09	0	0.01	0.05	0.01	0	36.3	76.75
1195 ppm U	31.88	0	0.02	0	0.13	0	4.71	11.06	0.01	0.11	0.02	0.01	0	0	0	0	0.04	0.07	48.02	96.19
1195 ppm U	3.44	0.72	0.03	0	17.84	0	2.95	5.68	0.01	7.68	0.18	0.01	0.06	0	0	0	0	0	25.56	64.19
1195 ppm U	0.18	0.81	0.01	0	2.44	0	0.1	17.8	0.01	19.53	0	0.04	0.1	0	0.04	0	0.1	0	36.91	78.2
1195 ppm U	0.13	1.32	0.05	0	3.25	0	0.07	16.03	0	19	0	0.02	0.08	0.01	0.04	0.18	0.01	0	35.16	75.43

Table 3.G.2. Electron microprobe (EMP) data in weight % for the 1195 ppm U mixed colour salt sample.

Appendix 3.H

Tailings X-ray Diffraction Spectra



Figure 3.H.1. XRD spectra of a representative sample from the upper orange-brown sandy tailings horizon with mineralogy consisting of: quartz, gypsum, albite and muscovite.



Figure 3.H.2. XRD spectra of a representative sample from the lower purple-grey silty tailings horizon with mineralogy consisting of: gypsum, quartz, clinochlore, albite and muscovite.



Figure 3.H.3. XRD spectra of a representative sample from the purple-red layers thoughout the purple-grey silty tailings horizon with mineralogy consisting of: quartz, hematite and a magnesium nickel iron oxide.
Appendix 3.I

Tailings Bulk Chemistry

Table 3.I.1. Bulk Trace Element Chemistry, Core LB-LT-11-C1A.

		0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50
		cm									
Ag	ppm	0.3	0.32	0.37	0.41	0.25	0.44	0.3	0.3	0.31	1.04
Al	%	1.36	1.22	1.25	1.26	1.27	1.32	1.52	1.55	1.29	1.08
As	ppm	10	11.2	16.9	15.5	14.3	14.9	18.2	15.8	12.1	20.5
Au	ppm	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
В	ppm	160	20	90	20	80	10	50	30	50	10
Ba	ppm	120	200	190	90	200	50	170	100	50	40
Be	ppm	0.71	0.76	0.57	0.76	0.51	0.72	0.63	0.83	0.68	0.46
Bi	ppm	0.64	0.67	0.72	1.14	0.65	0.97	0.8	1.04	0.73	2.38
Ca	%	1.66	0.8	1.18	3.27	1.37	3.34	1.56	2.63	4.19	0.23
Cd	ppm	0.05	0.01	0.03	0.01	< 0.01	0.02	0.01	< 0.01	0.02	0.25
Ce	ppm	35.7	35.5	34.4	48.6	34.3	43.8	35.3	44.5	40.1	46.1
Co	ppm	12.3	6.8	5.4	5	5.2	15.2	8.4	6.2	15.1	100
Cr	ppm	72	50	108	38	74	35	90	55	43	43
Cs	ppm	0.38	0.34	0.4	0.47	0.46	0.52	0.42	0.48	0.44	0.25
Cu	ppm	73.7	56.5	89.9	43.5	60.4	100	73.6	52.3	92.5	102
Fe	%	2.96	3.34	4.24	3.1	3.72	3.17	4.18	4.34	3.45	24.6
Ga	ppm	6.67	6.61	7.27	6.64	6.43	7.37	8.23	8.31	7.45	4.4
Ge	ppm	0.11	0.14	0.12	0.14	0.08	0.13	0.1	0.14	0.1	0.18
Hf	ppm	0.48	0.39	0.35	0.59	0.4	0.69	0.47	0.57	0.78	0.14
Hg	ppm	0.02	0.02	0.03	0.04	0.04	0.05	0.03	0.04	0.04	0.01
In	ppm	0.016	0.017	0.018	0.019	0.017	0.024	0.027	0.033	0.036	0.016
Κ	%	0.17	0.16	0.17	0.2	0.19	0.17	0.21	0.24	0.19	0.19
La	ppm	19.3	17.4	19.1	22.7	23.3	19.2	22.8	21.6	18.2	22.5
Li	ppm	28.8	23.1	21.6	20.7	22.7	21.1	25	24.4	25.8	10.4
Mg	%	1.08	0.74	0.71	0.66	0.69	0.71	0.86	0.83	0.69	0.54
Mn	ppm	271	169	159	149	143	170	182	162	142	311
Mo	ppm	5.94	5.5	6.26	7.15	5.44	6.34	6.6	10.45	7.19	26.6
Na	%	0.09	0.07	0.08	0.07	0.09	0.04	0.06	0.04	0.04	0.01
Nb	ppm	0.13	0.07	0.11	0.11	0.11	0.11	0.1	0.09	0.12	0.05
Ni	ppm	32.1	16.7	16.9	12.8	15.1	28.7	23.3	18.5	38.9	326
Р	ppm	870	820	880	890	840	1090	1020	1000	740	1060
Pb	ppm	115.5	129	145	223	132.5	164.5	127	282	144	45.9
Rb	ppm	7.8	7.2	8.1	9.1	10.1	8.5	12.4	11.4	10.8	8.7
Re	ppm	0.016	0.006	0.008	0.012	0.01	0.015	0.013	0.012	0.01	0.007
S	%	2.53	1.21	1.36	3.4	1.5	4.77	1.92	2.79	4.46	0.29
Sb	ppm	0.27	0.2	0.23	0.26	0.24	0.25	0.25	0.25	0.27	1.74
Sc	ppm	3.1	2.8	3.2	2.9	3.1	3.6	3.7	4.1	4.1	3.2
Se	ppm	2.7	2.9	3.8	3.8	3.4	3.5	3.6	4.3	3.2	0.7
Sn	ppm	13.9	5.8	16.3	4	6.4	4.2	5.9	4.1	2.8	6.7
Sr	ppm	43.6	28.1	41.6	92.6	39.1	73.5	36.8	63.8	88.3	15.4
Та	ppm	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Te	ppm	0.06	0.07	0.06	0.08	0.08	0.1	0.08	0.08	0.08	0.1
Th	ppm	5.6	5.4	6.2	9.3	7.5	12.7	11	13.4	10.2	7.6
Ti	%	0.021	0.019	0.023	0.022	0.022	0.019	0.019	0.022	0.018	0.007
Tl	ppm	0.26	0.25	0.29	0.33	0.28	0.38	0.27	0.29	0.28	1.01
U	ppm	32.2	24.3	20.9	28.6	16.7	31.4	20.1	30.5	28.3	30.5
										138	

V ppm 1	204	229	205	201	160	205	269	144	154
W ppm 0.	.59 0.56	0.63	1.15	0.57	0.85	0.71	1.19	0.78	1.39
Y ppm 6.	.52 4.19	4.32	6.76	4.39	6.97	5.58	6.15	8.6	3.64
Zn ppm	35 25	27	21	22	24	28	28	25	50
Zr ppm 27	7.3 23.7	23.5	33.3	26.8	36.7	31.4	38.8	46.5	5.8

		50-55	55-60	60-65	65-70	70-75	75-80	80-85	85-90	90-95	95-100
		cm	cm	cm	cm	cm	cm	cm	cm	cm	cm
Ag	ppm	1.34	1.1	1.34	1.08	0.87	0.64	0.54	0.28	0.38	0.34
Al	%	1.35	1.25	1.45	2.42	2.24	2.82	2.9	2.09	2.67	2.29
As	ppm	21.2	23.8	26.2	40.4	33.9	26.7	41	29.7	32.3	28.7
Au	ppm	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	<0.2
В	ppm	40	20	40	40	60	50	70	20	50	30
Ba	ppm	70	70	50	80	100	40	50	130	70	120
Be	ppm	0.44	0.69	0.5	1.66	1.23	1.93	1.74	1.32	1.42	1.37
Bi	ppm	2.61	2.49	3.1	2.91	2.02	2.55	1.98	1.19	1.63	1.13
Ca	%	0.59	0.38	0.31	2.8	3.02	4.8	4.14	1.68	4.4	2.57
Cd	ppm	0.22	0.18	0.21	0.12	0.07	0.08	0.06	0.09	0.11	0.17
Ce	ppm	40	41.8	35.5	56.5	50.1	66.9	54.4	34.1	49.7	38.7
Со	ppm	84.5	99.8	103	68.7	50	25.5	23.7	13.8	19.6	17.7
Cr	ppm	71	39	112	54	64	63	71	49	59	46
Cs	ppm	0.36	0.29	0.36	0.79	0.78	1.15	1.02	0.56	0.84	0.58
Cu	ppm	125	101	215	448	307	186.5	156.5	69.6	86.3	93.3
Fe	%	24.1	24.7	29.2	18.25	12.05	5.39	5.2	3.75	4.05	3.84
Ga	ppm	5.85	5.27	5.29	9.13	10.65	11.6	12.7	7.42	10.6	8.38
Ge	ppm	0.36	0.17	0.43	0.17	0.21	0.16	0.15	0.13	0.12	0.16
Hf	ppm	0.23	0.23	0.25	0.72	0.78	1.22	0.52	0.61	0.39	0.48
Hg	ppm	0.03	0.02	0.03	0.03	0.05	0.05	0.07	0.03	0.04	0.03
In	ppm	0.017	0.019	0.027	0.032	0.029	0.055	0.037	0.025	0.031	0.026
K	%	0.25	0.19	0.23	0.33	0.28	0.37	0.34	0.21	0.28	0.23
La	ppm	26.5	20.2	23.6	25.1	24	29.4	25.1	16.8	24.8	17.9
Li	ppm	15.3	15.1	15.7	47.9	49.7	54.4	69.7	38.8	63.9	44.9
Mg	%	0.68	0.63	0.71	1.18	1.24	1.53	1.68	1.26	1.62	1.39
Mn	ppm	307	297	328	328	312	363	374	274	349	316
Mo	ppm	29.7	31.2	45.3	47.3	37.6	36.8	24.2	11.8	17.9	11.8
Na	%	0.03	0.02	0.02	0.03	0.05	0.04	0.05	0.02	0.04	0.02
Nb	ppm	0.31	0.05	0.38	0.08	0.15	0.1	0.12	0.08	0.13	0.08
N1	ppm	309	301	352	196	14/	55.1	6/.4	41.6	55.2	45.4
P DL	ppm	910 52 7	1090	1210	990	930	800	950	860	1110	1060
PD Dh	ppm	33./ 14	52.5	50.4	559 167	200	20.2	318	198.5	20.1	230
KD Da	ppm	14	9.6	12.0	10./	18.1	20.3	24	11.8	20.1	13.7
Re S	ppm o/	0.012	0.01	0.010	0.027	0.018	0.025	0.024	0.017	0.02	0.015
0 Sh	70 nnm	0.08	0.05	0.07	5.57 1.24	5.50 0.97	5.55 0.42	4./	2.04	4.93	5.44 0.27
50	ppm	1.85	1.//	2.17	1.54	0.87	0.42	0.41	0.23	0.24 6.2	0.27
SC So	ppm	4.0	5.9 0.7	5.5 0.6	/./	7.9	0 2 5	/./ 5./	4.5	0.5	3.1
Se	ppm	0.0	0.7	0.0	5.1 10.6	5.0 40.1	5.5 12.5	5.4	2.9	4.0	5.5
SII Sr	ppin	0.9 24 7	5.5 16 7	10.2	62.5	40.1 68.2	02.0	70.2	22.2	92.0	18.3
SI To	ppm	24.7	10.7	19.2	02.3 <0.01	00.5	93.9 <0.01	/9.5	22.2 20.01	0.01	40.5
та Те	ppm	~0.01 0 2	~0.01 0.15	0.01	~0.01 0.25	~0.01 0.17	~0.01 0.12	0.01	0.01	0.01	0.01
Th	ppin	0.2	0.13 & &	11.2	0.23	11 2	1/ 8	12	12 8	11 8	10.3
Ti	ррш %	<i>9.9</i> 0.012	0.0	0 000	0.01/	0.017	0.021	0.02	12.0	0.010	0.016
T1	70 nnm	1 20	1 01	1 50	1 21	0.017	0.021	0.02	0.017	0.019	0.33
11	hhm	1.49	1.01	1.59	1.41	0.91	0.09	0.49	0.5	0.57	0.55

U	ppm	33.2	48.1	61.7	91.7	61.8	87.3	90.5	141.5	131.5	129
V	ppm	167	161	151	292	262	329	373	265	312	264
W	ppm	1.48	1.47	1.83	2.14	1.6	1.95	1.82	0.91	1.34	0.92
Y	ppm	4.97	4.92	6.45	9.22	10.05	11.1	12.95	8.44	14.4	10.35
Zn	ppm	51	45	47	71	85	89	82	81	107	91
Zr	ppm	13.2	11.2	11.9	44.9	50.2	64.8	40	40.4	34.6	40.5

		0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50
		cm	cm	cm	cm	cm	cm	cm	cm	cm	cm
Ag	ppm	0.42	0.38	0.53	0.49	0.52	0.66	0.42	0.86	0.73	0.5
Al	%	0.98	0.79	1.06	1.01	1.33	1.17	1.14	0.97	1.3	1.14
As	ppm	30.8	19.7	27.2	17.7	12	7.7	9.9	6.5	12.3	16.4
Au	ppm	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
В	ppm	30	10	30	20	40	20	30	10	30	20
Ba	ppm	210	310	300	260	250	240	230	220	250	190
Be	ppm	0.59	0.58	0.55	0.66	0.6	0.7	0.45	0.46	0.53	0.54
Bi	ppm	0.82	0.89	1.15	1.04	1.06	1.3	0.8	1.31	1.1	1.01
Ca	%	0.89	0.57	0.83	1.01	0.85	0.75	0.89	0.94	0.95	1.19
Cd	ppm	< 0.01	0.01	0.01	0.02	0.01	< 0.01	0.01	< 0.01	0.01	< 0.01
Ce	ppm	26.6	28.8	32.5	39.5	31.2	32.5	24.6	27.7	25.4	28.3
Co	ppm	5.2	4	3.7	3.3	2.9	2.6	2.4	1.7	2.1	2.1
Cr	ppm	94	49	92	44	107	43	95	40	101	41
Cs	ppm	0.42	0.34	0.42	0.44	0.53	0.45	0.42	0.4	0.5	0.53
Cu	ppm	57	28.5	50.2	55.8	64.2	57.5	31.9	36.8	41.9	55.2
Fe	%	3.51	2.73	3.77	3.84	3.47	2.72	2.94	2.04	3.06	3.87
Ga	ppm	6.12	5.88	6.9	7.08	8.98	7.74	5.94	4.44	6.75	6.56
Ge	ppm	0.12	0.12	0.14	0.13	0.12	0.13	0.1	0.12	0.11	0.13
Hf	ppm	0.45	0.42	0.5	0.55	0.45	0.43	0.39	0.39	0.44	0.43
Hg	ppm	0.1	0.31	0.18	0.05	0.07	0.07	0.03	0.05	0.06	0.03
In	ppm	0.011	0.013	0.016	0.013	0.013	0.013	0.009	0.009	0.01	0.006
K	%	0.22	0.17	0.23	0.23	0.28	0.21	0.22	0.19	0.27	0.24
La	ppm	18.3	15.3	22.3	19.8	21.6	17	17	13.4	17.7	13
Li	ppm	17.9	12.9	17	17.5	22.4	19.5	17.2	14.6	19.1	14.5
Mg	%	0.55	0.37	0.47	0.47	0.62	0.59	0.57	0.5	0.62	0.55
Mn	ppm	164	86	112	119	187	189	191	199	213	170
Mo	ppm	9.39	4.4	7.98	8.06	7.54	7.82	9.33	9.26	14.9	15.1
Na	%	0.09	0.05	0.08	0.06	0.1	0.06	0.1	0.06	0.1	0.07
ND NI:	ppm	0.12	0.08	0.13	0.11	0.09	0.06	0.08	0.06	0.09	0.07
N1 D	ppm	18.2	13	14.2	11.1	13.5	10.3	10.2	200	11.4	8.1 540
Р Dh	ppm	450	320 160	440	450	590 200	490	460	300	480	540 228
PU Dh	ppm	14/	100	12.6	11.0	200	244	190	239	198	238 12.5
RU Do	ppin	12.7	9.5	0.008	0.008	0.014	0.012	0.015	0.017	0.018	13.3
RE S	ppm %	0.013	0.004	1.08	1 30	0.014	0.015	1.06	0.017	0.018	0.010
S Sh	70 DDD	0.34	0.79	0.43	0.36	0.26	0.26	0.24	0.37	0.42	0.33
Sc	ppin	2.5	23	0.43	0.30	3.2	2.8	0.24	22	0.42	23
Se	ppin	2.3 4.8	2.5	66	2.7 5.8	53	2.8 4 9	2.7	2.2	58	2.3 7 4
Sn	nnm	12.3	2.5	3.8	7 9	5.5 7 4	67	3.3	5.8	5.0	12.9
Sr	nnm	27	2.5	29.2	31.6	30.9	27.7	27.2	25.6	30.4	29.1
Ta	nnm	<0.01	<0.01	< 0.01	< 0.01	<0.01	<0.01	< 0.01	<0.01	<0.01	<0.01
Te	nnm	0.01	0.07	0.01	0.12	0.06	0.04	0.14	0.12	0.19	0.28
Th	nnm	4.6	3.8	47	4 2	4 8	4	4	3	4	34
Ti	гг <u>ш</u> %	0.016	0.012	0.017	0 015	0.015	0.011	0.013	0 011	0 014	0.014
Tl	ppm	0.41	0.28	0.46	0.47	0.58	0.76	0.38	0.92	0.71	0.38
-	T.T										

U	ppm	33.4	25	21.4	24.8	17.75	18.4	16	15.55	15.1	21.3
V	ppm	280	123	224	266	240	179	192	129	203	221
W	ppm	0.75	0.63	0.82	0.83	0.65	1.11	0.7	0.92	1.09	0.81
Y	ppm	4.11	2.6	3.25	3.18	3.7	3.29	3.51	3.33	3.84	3.16
Zn	ppm	21	13	19	17	20	16	15	13	16	20
Zr	ppm	27.7	23.5	30.4	26.7	26.8	22.1	22.7	19.4	25.2	21.6

Table 3.I.4. Bulk	Trace Element	Chemistry, C	Core LB-LT-11-C3A.
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		0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50
		cm									
Ag	ppm	0.46	0.57	0.57	0.4	0.34	0.51	0.28	0.18	0.26	0.35
Al	%	1.69	1.63	1.58	1.45	1.54	1.48	1.59	1.52	1.52	1.22
As	ppm	19.7	20.3	25.5	22	22.2	19.4	14	10.6	13.7	8.2
Au	ppm	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
В	ppm	30	30	30	20	30	20	30	20	20	20
Ba	ppm	70	130	230	220	210	190	200	180	200	120
Be	ppm	1.18	1.01	0.67	0.77	0.81	0.81	0.96	0.89	0.88	0.71
Bi	ppm	2.21	2.41	1.99	1.67	1.91	1.76	0.98	0.72	0.86	0.83
Ca	%	3.62	2.81	1.01	0.6	0.7	1.29	1.14	0.9	0.7	2.57
Cd	ppm	0.02	0.01	0.01	0.02	< 0.01	0.01	< 0.01	0.01	0.01	<0.01
Ce	ppm	41.7	34	27.8	30.6	30.4	35.2	37.9	31.3	37.2	46.6
Co	ppm	15.9	6.2	4.7	5.3	6.4	6.5	7.7	7	7.6	6.7
Cr	ppm	69	43	94	72	78	61	95	79	94	54
Cs	ppm	0.69	0.74	0.66	0.56	0.57	0.5	0.41	0.37	0.39	0.32
Cu	ppm	65.8	43.2	47	43.6	50.1	59.8	54.8	46.8	58.3	48.5
Fe	%	4.11	4.02	4.47	4.45	4.69	4.62	4.47	3.91	4.02	3.4
Ga	ppm	9.44	8.92	8.92	8.78	8.88	8.49	8.68	7.95	8.34	6.59
Ge	ppm	0.16	0.14	0.12	0.14	0.07	0.14	0.07	0.12	0.06	0.15
Hf	ppm	0.7	0.41	0.25	0.39	0.37	0.37	0.49	0.52	0.43	0.61
Hg	ppm	0.05	0.06	0.07	0.05	0.04	0.05	0.03	0.02	0.03	0.04
In	ppm	0.024	0.018	0.015	0.017	0.017	0.018	0.022	0.02	0.019	0.012
K	%	0.27	0.29	0.29	0.22	0.24	0.2	0.22	0.18	0.21	0.16
La	ppm	25.5	16.6	19.2	15.1	16.6	16.5	20.2	15.3	20.3	22.7
Li	ppm	34.3	25.9	25.1	22.6	24	24.1	28.1	26.6	27.7	21
Mg	%	1.45	0.86	0.76	0.73	0.8	0.83	0.93	0.9	0.86	0.79
Mn	ppm	364	196	172	167	182	186	201	192	191	183
Мо	ppm	14.85	15.75	13.2	13.05	14.25	13.4	12.4	10.65	11.25	6.06
Na	%	0.11	0.08	0.11	0.05	0.07	0.09	0.1	0.07	0.1	0.12
Nb	ppm	0.15	0.08	0.09	0.06	0.05	0.06	0.06	0.06	0.06	0.1
Ni	ppm	39.2	16.5	14.7	14.8	17.9	17.4	22.9	19.5	22.6	17.6
Р	ppm	890	1050	930	880	820	910	780	680	710	800
Pb	ppm	328	288	196	163	154.5	215	161.5	151	141	183.5
Rb	ppm	15.5	14.7	17.4	12	13	10.5	11.3	9.2	11.4	7.4
Re	ppm	0.036	0.014	0.01	0.009	0.009	0.01	0.01	0.008	0.009	0.01
S	%	4.55	2.99	1.15	0.75	0.86	1.58	1.3	1.12	0.86	2.77
Sb	ppm	0.3	0.34	0.35	0.28	0.21	0.27	0.17	0.13	0.15	0.17
Sc	ppm	4.6	3.9	3.6	3.2	3.2	3.6	3.6	3.5	3.6	3.2
Se	ppm	4.9	4.5	4.6	3.9	3.9	4.3	3.2	3.1	3.8	4.4
Sn	ppm	28.3	4.4	2.7	2.3	6.3	6.5	3.7	4	5.4	7.7
Sr	ppm	70.5	57.9	30.2	17.6	21.8	37.5	33.4	25	26.9	79.8
Та	ppm	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Те	ppm	0.13	0.11	0.12	0.08	0.07	0.11	0.07	0.06	0.06	0.08
Th	ppm	11.7	7.8	5.1	4.3	4.6	4.9	6.1	5.7	5.9	6.7
Ti	%	0.024	0.025	0.026	0.022	0.023	0.022	0.021	0.018	0.02	0.023

	ΤI	ppm	0.49	0.64	0.62	0.42	0.35	0.45	0.29	0.23	0.27	0.28
	U	ppm	72	47	26.9	27.8	27.4	25.5	25.4	23.1	23.2	24.7
	V	ppm	350	314	307	302	302	316	349	332	323	256
	W	ppm	1.44	1.23	0.72	0.55	0.54	0.68	0.58	0.51	0.48	0.76
	Y	ppm	8.86	5.22	4.05	3.4	3.62	4.68	4.77	4.14	4.53	6.06
	Zn	ppm	49	34	32	33	39	36	38	36	36	30
_	Zr	ppm	45.5	27.4	17.8	21.6	20	23.3	28.7	28.4	25.1	33.6
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Table 3.I.5. Bulk Trace Element Chemistry, Core LB-LT-11-C4A.

		0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50
		cm									
Ag	ppm	0.27	0.21	0.34	0.33	0.47	0.37	0.4	0.43	0.29	0.29
Al	%	1.45	1.37	1.67	2.04	2.05	1.52	1.76	1.86	1.63	1.66
As	ppm	17	11.9	17.1	17.7	15.4	17.1	17.3	16.2	14.8	11.8
Au	ppm	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
В	ppm	30	20	30	40	30	10	20	20	20	20
Ba	ppm	40	50	50	40	40	120	70	70	130	170
Be	ppm	0.99	0.81	1.01	1.4	1.4	0.99	1.21	1.34	1.11	1.11
Bi	ppm	1.22	1.09	1.52	1.9	1.75	0.71	0.84	1.03	0.66	0.77
Са	%	4.57	4.22	4.6	4.4	4.47	1.72	2.68	3.09	0.93	1.03
Cd	ppm	< 0.01	0.02	< 0.01	0.01	0.02	0.06	0.03	0.03	0.03	0.03
Ce	ppm	95	84.1	76.3	63.9	57.2	40.7	39.8	46.5	37.5	38.9
Со	ppm	12.5	9.7	13.4	12.1	19.7	18	22.1	20.9	19.1	16.2
Cr	ppm	41	45	79	61	52	67	87	62	139	68
Cs	ppm	0.51	0.45	0.61	0.65	0.56	0.32	0.38	0.41	0.35	0.39
Cu	ppm	54.3	39	50.6	34.8	128	149	110	93.5	92.4	96
Fe	%	4.71	4.34	4.32	4.52	3.79	3.7	4.05	3.54	3.6	3.1
Ga	ppm	8.36	6.95	9.02	9.83	10.05	7.37	7.83	7.62	7.59	7.45
Ge	ppm	0.14	0.17	0.11	0.15	0.08	0.14	0.07	0.14	0.08	0.13
Hf	ppm	0.62	0.55	0.76	0.94	1.12	0.74	0.8	0.74	0.54	0.63
Hg	ppm	0.05	0.05	0.07	0.12	0.04	0.04	0.03	0.05	0.02	0.02
In	ppm	0.019	0.022	0.022	0.029	0.03	0.027	0.024	0.019	0.018	0.013
K	%	0.22	0.18	0.25	0.27	0.27	0.14	0.16	0.17	0.16	0.16
La	ppm	55.1	44.5	40.5	31.1	28	19.1	19.7	20.9	19.7	18
Li	ppm	26.4	22.3	31.2	33.1	46	31.6	41.1	45.2	39.2	36.3
Mg	%	1.2	1.11	1.26	1.39	1.34	1.07	1.22	1.26	1.15	1.16
Mn	ppm	393	362	374	382	319	241	280	275	244	248
Мо	ppm	10.95	8.78	12.3	14.1	19.75	6.36	8.47	7.38	5.9	5.75
Na	%	0.31	0.27	0.21	0.13	0.06	0.04	0.04	0.04	0.06	0.04
Nb	ppm	0.12	0.12	0.12	0.11	0.1	0.1	0.11	0.1	0.08	0.07
Ni	ppm	28.9	21.5	30.8	28.6	41.6	36.1	45.4	39.3	41.4	32.2
Р	ppm	640	690	730	1040	740	920	860	1020	850	800
Pb	ppm	242	234	309	359	396	148	181	173.5	112.5	149
Rb	ppm	12.5	8.9	12.9	12.8	13	6.4	8.6	8.7	8.8	7.6
Re	ppm	0.027	0.018	0.02	0.016	0.022	0.01	0.013	0.012	0.01	0.012
S	%	6.26	5.67	5.54	5.94	5.17	3.16	3.96	4.3	2.06	1.92
Sb	ppm	0.24	0.22	0.26	0.36	0.24	0.23	0.25	0.26	0.24	0.21
Sc	ppm	4.2	3.7	4.6	4.9	5.6	4.2	4.8	4.6	4	4.1
Se	ppm	4	3.3	4.4	4.6	4.3	4.1	5.2	4.5	3.4	3
Sn	ppm	7.8	4.8	6.9	3.3	3.9	3	3	3.1	5.4	13.2
Sr	ppm	192.5	189	166	120.5	109.5	44.7	72	80.3	29.3	30.1
Та	ppm	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Te	ppm	0.09	0.1	0.11	0.11	0.11	0.09	0.1	0.11	0.08	0.07
Th	ppm	6.5	6.6	9.2	12.5	14.8	10.1	9.8	8.9	7.7	8.4
Ti	%	0.021	0.019	0.023	0.025	0.025	0.021	0.026	0.023	0.021	0.02
TI	ppm	0.32	0.31	0.31	0.36	0.35	0.25	0.35	0.31	0.24	0.2
U	ppm	30	29.8	36	41.4	44.4	34.3	60.2	47	34.6	38.3

V	ppm	283	261	311	401	355	229	243	257	212	213
W	ppm	1.16	1.14	1.44	1.7	1.33	0.75	0.8	0.86	0.59	0.68
Y	ppm	11.8	10.4	12.4	10.75	9.47	6.93	7.97	8.76	6.54	6.23
Zn	ppm	35	32	38	43	50	45	49	54	42	43
Zr	ppm	35.5	30.9	42.8	52.3	62.3	38.4	42.4	40.9	32.3	36.8

Table 3.I.6. Bulk Trace Element Chemistry, Core LB-LT-11-C5A.

$\begin{array}{c c c c c c c c c c c c c c c c c c c $			0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50
Ag ppm 0.14 0.18 0.44 0.55 0.44 1.35 1.45 0.32 0.33 AI % 1.26 1.17 1.55 1.64 1.47 1.44 1.61 1.35 1.49 1.47 Au ppm 13.3 14.9 2.5.1 17.1 22.2 16 14.3 14.9 1.3.3 14.9 2.3.1 B ppm 20 10 20 20 20 20 30 21.5 20.6 23.5 18.5 16.5			cm	cm	cm	cm	cm	cm	cm	cm	cm	cm
Ai % 1.26 1.17 1.55 1.64 1.47 1.61 1.35 1.49 1.43 As ppm 13.3 14.9 25.1 17.1 22.2 16 14.3 14.9 13.3 14.8 Au ppm 20.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2	Ag	ppm	0.14	0.18	0.4	0.41	0.56	0.49	1.35	0.45	0.32	0.34
As ppm 13.3 14.9 25.1 17.1 22.2 16 14.3 14.3 14.3 14.3 14.3 Au ppm 20 10 20 20.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 20 21.5 20.6 23.5 18.5 16.5 17.4 16.2 16.7 76 60 73 72 66 73 72 66 73 73	Al	%	1.26	1.17	1.55	1.64	1.47	1.44	1.61	1.35	1.49	1.47
Au ppm <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.3 <0.3 <0.4 <0.3 <0.3 <0.3 <0.3 <0.3 <0.3 <0.3 <0.3 <0.3 <0.3 <0.3 <0.3 <0.3 <0.3 <0.3 <0	As	ppm	13.3	14.9	25.1	17.1	22.2	16	14.3	14.9	13.3	14.8
B ppm 10 10 20 20 20 30 20 20 20 Ba ppm 180 190 100 60 40 170 40 50 140 140 Be ppm 0.66 0.79 0.99 1.14 1.13 1.02 1.4 0.95 1.18 0.88 Ga $\%$ 0.76 0.56 0.73 0.89 0.87 0.7 1.08 0.79 0.66 0.68 Cd ppm <0.01 0.01 0.02 0.03 0.04 0.03	Au	ppm	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Ba ppm 180 190 100 60 40 170 40 55 140 140 Be ppm 0.68 0.79 0.99 1.14 1.13 1.02 1.4 0.95 1.18 0.82 Bi ppm 0.66 0.56 0.73 0.89 0.87 0.7 1.08 0.79 0.6 0.68 Ca ppm 0.01 0.01 0.02 0.03 0.04 0.03 0.03 0.04 Ce ppm 39.7 36.5 38.6 44.2 57.2 34.6 59.8 44.5 54.2 32.4 Co ppm 156 71 125 56 57 80 65 63 72 69 Cs 32.47.73 5.4 3.55 3.87 3.51 3.04 31.8 3.08 3.18 Ga ppm 0.70 0.13 0.08 0.12 0.07 0.13 0.08	В	ppm	20	10	20	20	20	20	30	20	20	20
Be ppm 0.68 0.79 0.99 1.14 1.13 1.02 1.4 0.75 0.68 0.73 0.89 0.87 0.7 1.08 0.79 0.6 0.68 Ca % 0.37 0.18 0.26 2.65 4.4 0.53 3.87 2.84 1.31 0.98 Cd ppm 30.7 36.5 38.6 44.2 57.2 34.6 59.8 44.5 42.2 32.4 Co ppm 156 71 125 56 57 80 65 63 72 69 Cs ppm 1.49 0.43 0.47 0.33 0.33 0.33 0.33 0.33 0.33 0.33 0.33 0.34 3.18 3.08 3.14 11 110 104 115 7.17 8.48 8.17 8.11 110 104 1.15 1.71 8.48 8.17 8.11 110 0.60 0.80 1.44	Ba	ppm	180	190	100	60	40	170	40	50	140	140
Bi ppm 0.76 0.56 0.73 0.87 0.77 1.08 0.79 0.66 0.68 Ca % 0.37 0.18 0.26 2.65 4.4 0.5 3.87 2.84 1.31 0.98 Cd ppm 40.01 0.01 0.02 0.03 0.04 0.03 0.03 0.03 0.04 Ce ppm 39.7 36.5 38.6 44.2 57.2 34.6 59.8 44.5 42.2 32.4 Co ppm 0.29 0.29 0.32 0.38 0.49 0.31 0.47 0.33 0.35 0.33 Cu ppm 0.49 5.94 6.87 7.31 7.1 6.73 8.11 6.19 7.31 7 Ge ppm 0.07 0.13 0.08 0.14 0.1 0.12 0.09 0.13 0.08 0.12 Hf ppm 0.01 0.02 0.02 0.01 <td>Be</td> <td>ppm</td> <td>0.68</td> <td>0.79</td> <td>0.99</td> <td>1.14</td> <td>1.13</td> <td>1.02</td> <td>1.4</td> <td>0.95</td> <td>1.18</td> <td>0.82</td>	Be	ppm	0.68	0.79	0.99	1.14	1.13	1.02	1.4	0.95	1.18	0.82
Ca % 0.37 0.18 0.26 2.65 4.4 0.5 3.87 2.84 1.31 0.98 Cd ppm 30.7 0.01 0.01 0.02 0.03 0.04 0.03 0.03 0.03 0.04 Ce ppm 39.7 36.5 38.6 44.2 57.2 34.6 59.8 44.5 42.2 32.4 Co ppm 156 71 125 56 57 80 65 63 72 69 Cu ppm 74.9 74.2 110 104 115 71.7 84.8 81.7 81.1 110 Fe % 53.2 4.73 5.4 3.55 3.87 3.51 3.04 3.18 3.08 3.48 Ga ppm 0.41 0.47 0.64 0.57 0.8 0.59 0.78 0.77 0.6 0.58 Ge ppm 0.01 0.04 0.03	Bi	ppm	0.76	0.56	0.73	0.89	0.87	0.7	1.08	0.79	0.6	0.68
Cd ppm <0.01 0.01 0.02 0.03 0.04 0.03 0.03 0.03 0.03 0.04 Ce ppm 39.7 36.5 38.6 44.2 57.2 34.6 59.8 44.5 42.2 32.4 Co ppm 9.5 21.5 20.6 23.5 18.5 16.5 17.4 16.2 16.7 Cr ppm 156 71 125 56 57 80 655 63 72 69 Cu ppm 74.2 110 104 115 71.7 84.8 81.7 81.1 110 Fe % 5.32 4.73 5.4 3.55 3.87 3.51 3.04 3.18 3.08 3.48 Ga ppm 0.01 0.13 0.08 0.01 0.01 0.12 0.08 0.77 0.6 0.58 Hg ppm 0.01 0.01 0.01 0.01 0.0	Ca	%	0.37	0.18	0.26	2.65	4.4	0.5	3.87	2.84	1.31	0.98
Ce ppm 39.7 36.5 38.6 44.2 57.2 34.6 59.8 44.5 42.2 32.4 Co ppm 9 9.5 21.5 20.6 23.5 18.5 16.5 17.4 16.2 16.7 Cr ppm 156 71 125 56 57 80 65 63 72 69 Cs ppm 74.9 74.2 110 104 115 71.7 84.8 81.7 81.1 110 Fe % 5.32 4.73 5.4 3.55 3.87 3.51 3.04 3.18 3.08 3.48 Ga ppm 6.49 5.94 6.87 7.31 7.1 6.73 0.18 0.12 0.09 0.33 0.02 0.03 0.02 0.03 0.02 0.03 0.02 0.03 0.02 0.03 0.02 0.03 0.02 0.03 0.02 0.03 0.02 0.03 0.02	Cd	ppm	< 0.01	0.01	0.01	0.02	0.03	0.04	0.03	0.03	0.03	0.04
Co ppm 9 9.5 21.5 20.6 23.5 18.5 16.5 17.4 16.2 16.7 Cr ppm 156 71 125 56 57 80 63 63 72 69 Cs ppm 74.9 74.2 110 104 115 71.7 84.8 81.7 81.1 110 Fe % 5.32 4.73 5.4 3.55 3.87 3.51 3.04 3.18 3.08 3.48 Ga ppm 0.07 0.13 0.08 0.14 0.1 0.12 0.09 0.13 0.08 0.12 Hf ppm 0.01 0.08 0.02 0.01 0.013 0.08 0.02 0.01 0.013 0.02 0.01 In ppm 0.10 0.15 0.19 0.17 0.16 0.16 0.2 0.16 0.18 K % 0.17 0.15 0.17	Ce	ppm	39.7	36.5	38.6	44.2	57.2	34.6	59.8	44.5	42.2	32.4
Cr ppm 156 71 125 56 57 80 65 63 72 69 Cs ppm 0.29 0.32 0.32 0.49 0.31 0.47 0.33 0.33 0.33 Cu ppm 74.9 74.2 110 104 115 71.7 84.8 81.7 81.1 110 Fe % 5.32 4.73 5.4 3.55 3.87 3.51 3.04 3.18 3.08 3.48 Ga ppm 0.41 0.47 0.64 0.57 0.8 0.59 0.78 0.77 0.6 0.58 Hg ppm 0.013 0.008 0.02 0.017 0.018 0.02 0.017 0.16 0.16 0.16 0.16 La ppm 21.7 18 21 20.8 21.7 21.4 Li ppm 21.7 19.5 27.7 36.2 31.7 27.1 37.3	Co	ppm	9	9.5	21.5	20.6	23.5	18.5	16.5	17.4	16.2	16.7
Cs ppm 0.29 0.29 0.32 0.38 0.49 0.31 0.47 0.33 0.33 0.33 Cu ppm 74.9 74.2 110 104 115 71.7 84.8 81.7 81.1 110 Fe % 5.32 4.73 5.4 3.55 3.87 3.51 3.04 3.18 3.08 3.48 Ga ppm 6.49 5.94 6.87 7.31 7.1 6.73 8.11 6.19 7.31 7 Ge ppm 0.01 0.41 0.47 0.64 0.57 0.8 0.59 0.78 0.77 0.66 0.58 Hg ppm 0.013 0.008 0.02 0.017 0.018 0.022 0.017 0.018 0.22 0.017 0.016 0.18 K % 0.17 0.15 0.19 0.17 0.16 0.16 0.22 0.017 0.018 0.022 0.17 <	Cr	ppm	156	71	125	56	57	80	65	63	72	69
Cu ppm 74.9 74.2 110 104 115 71.7 84.8 81.7 81.1 110 Fe % 5.32 4.73 5.4 3.55 3.87 3.51 3.04 3.18 3.08 3.48 Ga ppm 6.49 5.94 6.87 7.31 7.1 6.73 8.11 6.19 7.31 7.7 Ge ppm 0.01 0.01 0.08 0.14 0.11 0.12 0.09 0.13 0.008 0.12 Hf ppm 0.01 0.02 0.02 0.04 0.03 0.03 0.02 0.01 0.018 0.12 K % 0.17 0.15 0.19 0.17 0.16 0.16 0.22 0.016 0.18 0.18 La ppm 21.7 19.5 27.7 36.2 31.7 27.1 37.3 25.2 31.3 30.4 M ppm 21.7 11.8	Cs	ppm	0.29	0.29	0.32	0.38	0.49	0.31	0.47	0.33	0.35	0.33
Fe % 5.32 4.73 5.4 3.55 3.87 3.51 3.04 3.18 3.08 3.48 Ga ppm 6.49 5.94 6.87 7.31 7.1 6.73 8.11 6.19 7.31 7 Hf ppm 0.07 0.13 0.08 0.14 0.1 0.12 0.09 0.13 0.08 0.12 Hf ppm 0.41 0.47 0.64 0.057 0.8 0.59 0.78 0.77 0.66 0.58 Hg ppm 0.013 0.008 0.02 0.017 0.016 0.02 0.01 0.016 0.02 0.01 0.016 0.02 0.01 0.016 0.02 0.01 0.016 0.02 0.01 0.016 0.02 0.01 0.016 0.01 0.01 0.016 0.03 0.02 0.011 0.016 0.03 0.04 0.04 0.04 0.04 0.04 0.05 0.03 0.04 <th< td=""><td>Cu</td><td>ppm</td><td>74.9</td><td>74.2</td><td>110</td><td>104</td><td>115</td><td>71.7</td><td>84.8</td><td>81.7</td><td>81.1</td><td>110</td></th<>	Cu	ppm	74.9	74.2	110	104	115	71.7	84.8	81.7	81.1	110
Ga ppm 6.49 5.94 6.87 7.31 7.1 6.73 8.11 6.19 7.31 7 Ge ppm 0.07 0.13 0.08 0.14 0.1 0.12 0.09 0.13 0.08 0.12 Hf ppm 0.41 0.47 0.64 0.57 0.8 0.59 0.78 0.77 0.66 0.58 Hg ppm 0.013 0.008 0.02 0.017 0.016 0.022 0.03 0.02 0.03 0.02 0.03 0.02 0.017 0.016 0.18 0.15 La ppm 0.17 0.15 0.19 0.17 0.16 0.12 0.016 0.18 0.17 21.1 Mg 0.82 0.73 1.09 1.18 1.07 1 1.14 0.92 1.09 1.1 Mn ppm 223 209 265 293 272 232 282 243 267 268<	Fe	%	5.32	4.73	5.4	3.55	3.87	3.51	3.04	3.18	3.08	3.48
Ge ppm 0.07 0.13 0.08 0.14 0.1 0.12 0.09 0.13 0.08 0.12 Hf ppm 0.41 0.47 0.64 0.57 0.8 0.59 0.78 0.77 0.6 0.58 Hg ppm 0.013 0.02 0.02 0.017 0.017 0.018 0.022 0.017 0.016 0.02 0.017 0.016 0.02 0.017 0.016 0.02 0.017 0.016 0.02 0.017 0.018 0.022 0.017 0.016 0.02 0.017 0.016 0.02 0.017 0.016 0.02 0.017 0.016 0.018 0.11 La ppm 21.7 18 21 20.8 21.7 21.4 11 0.14 0.92 31.3 30.4 Mg 0.82 0.73 1.09 1.18 1.07 1 1.14 0.92 1.03 20.6 21.7 23.7 Mo	Ga	ppm	6.49	5.94	6.87	7.31	7.1	6.73	8.11	6.19	7.31	7
Hf ppm 0.41 0.47 0.64 0.57 0.8 0.59 0.78 0.77 0.66 0.58 Hg ppm 0.02 0.02 0.04 0.04 0.03 0.02 0.03 0.02 0.03 0.02 0.03 0.02 0.03 0.02 0.03 In ppm 0.017 0.115 0.19 0.17 0.16 0.16 0.22 0.17 0.118 0.15 La ppm 21.2 18 21 20.8 26.9 17.2 28.6 19.8 21.7 21.4 Li ppm 21.7 19.5 27.7 36.2 31.7 27.1 37.3 25.2 31.3 30.4 Mg % 0.82 0.73 1.09 1.18 1.07 1 1.14 0.92 1.09 1.1 Mn ppm 223 209 265 5.98 6.17 4.5 6.92 5.65 5.48 5.17 </td <td>Ge</td> <td>ppm</td> <td>0.07</td> <td>0.13</td> <td>0.08</td> <td>0.14</td> <td>0.1</td> <td>0.12</td> <td>0.09</td> <td>0.13</td> <td>0.08</td> <td>0.12</td>	Ge	ppm	0.07	0.13	0.08	0.14	0.1	0.12	0.09	0.13	0.08	0.12
Hgppm0.020.020.040.040.030.030.020.030.020.03Inppm0.0130.0080.020.0170.0170.0180.0220.0170.0160.018K%0.170.150.190.170.160.160.20.160.180.15Lappm21.7182120.826.917.228.619.821.721.4Lippm21.719.527.736.231.727.137.325.231.330.4Mg%0.820.731.091.181.0711.140.921.091.1Mnppm4.924.85.625.986.174.56.925.655.485.17Na%0.070.060.080.040.040.040.050.030.040.06Nbppm0.190.180.10.090.120.080.110.10.080.11Nippm23.722.644.236.443.636.532.831.434.735.2Pppm6407007901030980770770840710820Pbppm7387.793.8187.5211131228185162112Rbppm86.88.27.78.37.6107.6 <t< td=""><td>Hf</td><td>ppm</td><td>0.41</td><td>0.47</td><td>0.64</td><td>0.57</td><td>0.8</td><td>0.59</td><td>0.78</td><td>0.77</td><td>0.6</td><td>0.58</td></t<>	Hf	ppm	0.41	0.47	0.64	0.57	0.8	0.59	0.78	0.77	0.6	0.58
In ppm 0.013 0.008 0.02 0.017 0.017 0.018 0.022 0.017 0.016 0.018 K % 0.17 0.15 0.19 0.17 0.16 0.16 0.22 0.017 0.016 0.018 0.15 La ppm 21.2 18 21 20.8 26.9 17.2 28.6 19.8 21.7 21.4 Li ppm 21.7 19.5 27.7 36.2 31.7 27.1 37.3 25.2 31.3 30.4 Mg 0.82 0.73 1.09 1.18 1.07 1 1.14 0.92 1.09 1.1 Mn ppm 223 209 265 293 272 232 282 243 267 268 Mo ppm 4.92 4.8 5.62 5.98 6.17 4.5 6.92 5.65 5.48 5.17 Na 0.07 0.18 0.11	Hg	ppm	0.02	0.02	0.04	0.04	0.03	0.03	0.02	0.03	0.02	0.03
K % 0.17 0.15 0.19 0.17 0.16 0.16 0.2 0.16 0.18 0.17 La ppm 21.2 18 21 20.8 26.9 17.2 28.6 19.8 21.7 21.4 Li ppm 21.7 19.5 27.7 36.2 31.7 27.1 37.3 25.2 31.3 30.4 Mg % 0.82 0.73 1.09 1.18 1.07 1 1.14 0.92 1.09 1.1 Mn ppm 223 209 265 293 272 232 282 243 267 268 Mo ppm 4.92 4.8 5.62 5.98 6.17 4.5 6.92 5.65 5.48 5.17 Na % 0.07 0.06 0.08 0.04 0.04 0.06 0.11 0.08 0.11 0.16 0.33 31.4 34.7 35.2 P </td <td>In</td> <td>ppm</td> <td>0.013</td> <td>0.008</td> <td>0.02</td> <td>0.017</td> <td>0.017</td> <td>0.018</td> <td>0.022</td> <td>0.017</td> <td>0.016</td> <td>0.018</td>	In	ppm	0.013	0.008	0.02	0.017	0.017	0.018	0.022	0.017	0.016	0.018
La ppm 21.2 18 21 20.8 26.9 17.2 28.6 19.8 21.7 21.4 Li ppm 21.7 19.5 27.7 36.2 31.7 27.1 37.3 25.2 31.3 30.4 Mg % 0.82 0.73 1.09 1.18 1.07 1 1.14 0.92 1.09 1.1 Mn ppm 223 209 265 293 272 232 282 243 267 268 Mo ppm 4.92 4.8 5.62 5.98 6.17 4.5 6.92 5.65 5.48 5.17 Na % 0.07 0.06 0.08 0.04 0.04 0.04 0.05 0.03 0.04 0.06 Nb ppm 0.19 0.18 0.1 0.09 0.12 0.8 0.11 0.10 0.8 0.11 0.10 840 710 820 P ppm 640 700 790 1030 980 770 770 840	Κ	%	0.17	0.15	0.19	0.17	0.16	0.16	0.2	0.16	0.18	0.15
Li ppm 21.7 19.5 27.7 36.2 31.7 27.1 37.3 25.2 31.3 30.4 Mg % 0.82 0.73 1.09 1.18 1.07 1 1.14 0.92 1.09 1.1 Mn ppm 223 209 265 293 272 232 282 243 267 268 Mo ppm 4.92 4.8 5.62 5.98 6.17 4.5 6.92 5.65 5.48 5.17 Na % 0.07 0.06 0.08 0.04 0.04 0.04 0.05 0.03 0.04 0.06 Nb ppm 0.19 0.18 0.1 0.09 0.12 0.08 0.11 0.1 0.08 0.11 Ni ppm 23.7 22.6 44.2 36.4 43.6 36.5 32.8 31.4 34.7 35.2 P ppm 640 700 790 1030 980 770 770 840 710 820 Pb ppm 73 87.7 93.8 187.5 211 131 228 185 162 112 Rb ppm 8 6.8 8.2 7.7 8.3 7.6 10 7.6 9.1 8.8 Re ppm 0.004 0.006 0.011 0.009 0.011 0.008 0.009 0.008 0.009 0.01 S % 1.07 1.31 2.68 4.08 6 2.03 4.2 4.1 2.08 2.22 Sb ppm 0.24 0.23 0.32 0.27 0.3 0.21 0.25 0.24 0.2 0.23 Sc ppm 2.6 2.9 3.5 3.9 3.6 3.6 4.4 3.5 3.9 3.8 Se ppm 2.6 3 5.4 4.1 6.4 4.3 3.4 3.4 3.1 3.7 Sn ppm 14.2 9 8.7 4.5 6.1 4 3.8 3.3 5.9 10.2 Sr ppm 21.9 18.5 18.5 60.5 96.7 19.6 92.2 65.1 37.1 30.9 Ta ppm 4.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 F ppm 0.05 0.07 0.1 0.08 0.1 0.07 0.07 0.07 0.08 0.09 Th ppm 5.3 5.4 7.3 7.1 6.7 8.2 9.1 7.8 7.8 7.7 Ti % 0.02 0.019 0.024 0.21 0.21 0.02 0.023 0.019 0.02 0.021 TI ppm 0.14 0.19 0.36 0.3 0.31 0.25 0.18 0.26 0.19 0.23 U ppm 27.5 45.1 47.8 48.2 47.2 49.9 64 51.2 54.1 44.2	La	ppm	21.2	18	21	20.8	26.9	17.2	28.6	19.8	21.7	21.4
Mg % 0.82 0.73 1.09 1.18 1.07 1 1.14 0.92 1.09 1.1 Mn ppm 223 209 265 293 272 232 282 243 267 268 Mo ppm 4.92 4.8 5.62 5.98 6.17 4.5 6.92 5.65 5.48 5.17 Na % 0.07 0.06 0.08 0.04 0.04 0.04 0.05 0.03 0.04 0.06 Nb ppm 0.19 0.18 0.1 0.09 0.12 0.08 0.11 0.10 0.08 0.11 Ni ppm 23.7 22.6 44.2 36.4 43.6 36.5 32.8 31.4 34.7 35.2 P pm 640 700 790 1030 980 770 70 840 710 820 Pb ppm 6.3 8.7 7.7	Li	ppm	21.7	19.5	27.7	36.2	31.7	27.1	37.3	25.2	31.3	30.4
Mn ppm 223 209 265 293 272 232 282 243 267 268 Mo ppm 4.92 4.8 5.62 5.98 6.17 4.5 6.92 5.65 5.48 5.17 Na % 0.07 0.06 0.08 0.04 0.04 0.04 0.05 0.03 0.04 0.06 Nb ppm 0.19 0.18 0.1 0.09 0.12 0.08 0.11 0.1 0.08 0.11 Ni ppm 23.7 22.6 44.2 36.4 43.6 36.5 32.8 31.4 34.7 35.2 P ppm 640 700 790 1030 980 770 770 840 710 820 Pb pf 73 87.7 93.8 187.5 211 131 228 185 162 112 Rb pf 0.04 0.060 0.011	Mg	%	0.82	0.73	1.09	1.18	1.07	1	1.14	0.92	1.09	1.1
Moppm4.924.85.625.986.174.56.925.655.485.17Na%0.070.060.080.040.040.040.050.030.040.06Nbppm0.190.180.10.090.120.080.110.10.080.11Nippm23.722.644.236.443.636.532.831.434.735.2Pppm6407007901030980770770840710820Pbppm7387.793.8187.5211131228185162112Rbppm86.88.27.78.37.6107.69.18.8Reppm0.0040.0060.0110.0090.0110.0080.0090.0080.0090.01S%1.071.312.684.0862.034.24.12.082.22Sbppm0.240.230.320.270.30.210.250.240.20.23Scppm2.62.93.53.93.63.64.43.53.93.8Seppm2.635.44.16.44.33.43.13.7Snppm14.298.74.56.143.83.35.910.2Sr	Mn	ppm	223	209	265	293	272	232	282	243	267	268
Na % 0.07 0.06 0.08 0.04 0.04 0.04 0.05 0.03 0.04 0.06 Nb ppm 0.19 0.18 0.1 0.09 0.12 0.08 0.11 0.1 0.08 0.11 Ni ppm 23.7 22.6 44.2 36.4 43.6 36.5 32.8 31.4 34.7 35.2 P ppm 640 700 790 1030 980 770 770 840 710 820 Pb ppm 73 87.7 93.8 187.5 211 131 228 185 162 112 Rb ppm 8 6.8 8.2 7.7 8.3 7.6 10 7.6 9.1 8.8 Re ppm 0.004 0.006 0.011 0.009 0.011 0.008 0.009 0.008 0.009 0.01 S ppm 0.24 0.23 0.32	Мо	ppm	4.92	4.8	5.62	5.98	6.17	4.5	6.92	5.65	5.48	5.17
Nb ppm 0.19 0.18 0.1 0.09 0.12 0.08 0.11 0.1 0.08 0.11 Ni ppm 23.7 22.6 44.2 36.4 43.6 36.5 32.8 31.4 34.7 35.2 P ppm 640 700 790 1030 980 770 770 840 710 820 Pb ppm 73 87.7 93.8 187.5 211 131 228 185 162 112 Rb ppm 8 6.8 8.2 7.7 8.3 7.6 10 7.6 9.1 8.8 Re ppm 0.004 0.006 0.011 0.009 0.011 0.008 0.009 0.008 0.009 0.013 S \u007 1.31 2.68 4.08 6 2.03 4.2 4.1 2.08 2.22 Sb ppm 0.24 0.23 0.32 0.27	Na	%	0.07	0.06	0.08	0.04	0.04	0.04	0.05	0.03	0.04	0.06
Ni ppm 23.7 22.6 44.2 36.4 43.6 36.5 32.8 31.4 34.7 35.2 P ppm 640 700 790 1030 980 770 770 840 710 820 Pb ppm 73 87.7 93.8 187.5 211 131 228 185 162 112 Rb ppm 8 6.8 8.2 7.7 8.3 7.6 10 7.6 9.1 8.8 Re ppm 0.004 0.006 0.011 0.009 0.011 0.008 0.009 0.008 0.009 0.01 S % 1.07 1.31 2.68 4.08 6 2.03 4.2 4.1 2.08 2.22 Sb ppm 0.24 0.23 0.32 0.27 0.3 0.21 0.25 0.24 0.2 0.23 Sc ppm 2.66 3 5.4	Nb	ppm	0.19	0.18	0.1	0.09	0.12	0.08	0.11	0.1	0.08	0.11
P ppm 640 700 790 1030 980 770 770 840 710 820 Pb ppm 73 87.7 93.8 187.5 211 131 228 185 162 112 Rb ppm 8 6.8 8.2 7.7 8.3 7.6 10 7.6 9.1 8.8 Re ppm 0.004 0.006 0.011 0.009 0.011 0.008 0.009 0.008 0.009 0.01 S % 1.07 1.31 2.68 4.08 6 2.03 4.2 4.1 2.08 2.22 Sb ppm 0.24 0.23 0.32 0.27 0.3 0.21 0.25 0.24 0.2 0.23 Sc ppm 2.6 2.9 3.5 3.9 3.6 3.6 4.4 3.3 3.1 3.7 Sn ppm 2.6 3 5.4 4.	Ni	ppm	23.7	22.6	44.2	36.4	43.6	36.5	32.8	31.4	34.7	35.2
Pbppm7387.793.8187.5211131228185162112Rbppm86.88.27.78.37.6107.69.18.8Reppm0.0040.0060.0110.0090.0110.0080.0090.0080.0090.011S%1.071.312.684.0862.034.24.12.082.22Sbppm0.240.230.320.270.30.210.250.240.20.23Scppm2.62.93.53.93.63.64.43.53.93.8Seppm2.635.44.16.44.33.43.43.13.7Snppm14.298.74.56.143.83.35.910.2Srppm21.918.518.560.596.719.692.265.137.130.9Tappm<0.01<0.01<0.01<0.01<0.01<0.01<0.01<0.01<0.01<0.01<0.01Teppm0.050.070.10.080.10.070.070.070.080.09Thppm5.35.47.37.16.78.29.17.87.87.7Ti%0.020.0190.0240.0210.0210.020.0230.019<	Р	ppm	640	700	790	1030	980	770	770	840	710	820
Rbppm86.88.27.78.37.6107.69.18.8Reppm0.0040.0060.0110.0090.0110.0080.0090.0080.0090.011S%1.071.312.684.0862.034.24.12.082.22Sbppm0.240.230.320.270.30.210.250.240.20.23Scppm2.62.93.53.93.63.64.43.53.93.8Seppm2.635.44.16.44.33.43.43.13.7Snppm14.298.74.56.143.83.35.910.2Srppm21.918.518.560.596.719.692.265.137.130.9Tappm<0.01<0.01<0.01<0.01<0.01<0.01<0.01<0.01<0.01<0.01Teppm0.050.070.10.080.10.070.070.070.080.09Thppm5.35.47.37.16.78.29.17.87.87.7Ti%0.020.0190.0240.0210.0210.020.0230.0190.020.021Thppm0.140.190.360.30.310.250.180.260.19	Pb	ppm	73	87.7	93.8	187.5	211	131	228	185	162	112
Reppm0.0040.0060.0110.0090.0110.0080.0090.0080.0090.011S%1.071.312.684.0862.034.24.12.082.22Sbppm0.240.230.320.270.30.210.250.240.20.23Scppm2.62.93.53.93.63.64.43.53.93.8Seppm2.635.44.16.44.33.43.43.13.7Snppm14.298.74.56.143.83.35.910.2Srppm21.918.518.560.596.719.692.265.137.130.9Tappm<0.01	Rb	ppm	8	6.8	8.2	7.7	8.3	7.6	10	7.6	9.1	8.8
S % 1.07 1.31 2.68 4.08 6 2.03 4.2 4.1 2.08 2.22 Sb ppm 0.24 0.23 0.32 0.27 0.3 0.21 0.25 0.24 0.2 0.23 Sc ppm 2.6 2.9 3.5 3.9 3.6 3.6 4.4 3.5 3.9 3.8 Se ppm 2.6 3 5.4 4.1 6.4 4.3 3.4 3.4 3.1 3.7 Sn ppm 14.2 9 8.7 4.5 6.1 4 3.8 3.3 5.9 10.2 Sr ppm 21.9 18.5 18.5 60.5 96.7 19.6 92.2 65.1 37.1 30.9 Ta ppm <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.	Re	ppm	0.004	0.006	0.011	0.009	0.011	0.008	0.009	0.008	0.009	0.01
Sb ppm 0.24 0.23 0.32 0.27 0.3 0.21 0.25 0.24 0.2 0.23 Sc ppm 2.6 2.9 3.5 3.9 3.6 3.6 3.6 4.4 3.5 3.9 3.8 Se ppm 2.6 3 5.4 4.1 6.4 4.3 3.4 3.4 3.1 3.7 Sn ppm 14.2 9 8.7 4.5 6.1 4 3.8 3.3 5.9 10.2 Sr ppm 21.9 18.5 18.5 60.5 96.7 19.6 92.2 65.1 37.1 30.9 Ta ppm <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <	S	%	1.07	1.31	2.68	4.08	6	2.03	4.2	4.1	2.08	2.22
Sc ppm 2.6 2.9 3.5 3.9 3.6 3.6 3.6 4.4 3.5 3.9 3.8 Se ppm 2.6 3 5.4 4.1 6.4 4.3 3.4 3.4 3.1 3.7 Sn ppm 14.2 9 8.7 4.5 6.1 4 3.8 3.3 5.9 10.2 Sr ppm 21.9 18.5 18.5 60.5 96.7 19.6 92.2 65.1 37.1 30.9 Ta ppm <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <th< td=""><td>Sb</td><td>ppm</td><td>0.24</td><td>0.23</td><td>0.32</td><td>0.27</td><td>0.3</td><td>0.21</td><td>0.25</td><td>0.24</td><td>0.2</td><td>0.23</td></th<>	Sb	ppm	0.24	0.23	0.32	0.27	0.3	0.21	0.25	0.24	0.2	0.23
Se ppm 2.6 3 5.4 4.1 6.4 4.3 3.4 3.4 3.1 3.7 Sn ppm 14.2 9 8.7 4.5 6.1 4 3.8 3.3 5.9 10.2 Sr ppm 21.9 18.5 18.5 60.5 96.7 19.6 92.2 65.1 37.1 30.9 Ta ppm <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01	Sc	ppm	2.6	2.9	3.5	3.9	3.6	3.6	4.4	3.5	3.9	3.8
Sn ppm 14.2 9 8.7 4.5 6.1 4 3.8 3.3 5.9 10.2 Sr ppm 21.9 18.5 18.5 60.5 96.7 19.6 92.2 65.1 37.1 30.9 Ta ppm <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.02 <0.021 <0.021<	Se	ppm	2.6	3	5.4	4.1	6.4	4.3	3.4	3.4	3.1	3.7
Sr ppm 21.9 18.5 18.5 60.5 96.7 19.6 92.2 65.1 37.1 30.9 Ta ppm <0.01	Sn	ppm	14.2	9	8.7	4.5	6.1	4	3.8	3.3	5.9	10.2
Ta ppm <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.02 <0.021 <0.02 <0.023 <0.019 <0.02 <0.021 <0.021 <0.02 <0.023 <0.019 <0.023 <0.021 <0.021 <0.025 <0.18 <0.26 <0.19 <0.23 <0.11 <0.12 <0.11 <0.44	Sr	ppm	21.9	18.5	18.5	60.5	96.7	19.6	92.2	65.1	37.1	30.9
Teppm0.050.070.10.080.10.070.070.070.080.09Thppm5.35.47.37.16.78.29.17.87.87.7Ti%0.020.0190.0240.0210.0210.020.0230.0190.020.021Tlppm0.140.190.360.30.310.250.180.260.190.23Uppm27.545.147.848.247.249.96451.254.144.2	Та	ppm	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Thppm5.35.47.37.16.78.29.17.87.87.7Ti%0.020.0190.0240.0210.0210.020.0230.0190.020.021TIppm0.140.190.360.30.310.250.180.260.190.23Uppm27.545.147.848.247.249.96451.254.144.2	Те	ppm	0.05	0.07	0.1	0.08	0.1	0.07	0.07	0.07	0.08	0.09
Ti%0.020.0190.0240.0210.0210.020.0230.0190.020.021TIppm0.140.190.360.30.310.250.180.260.190.23Uppm27.545.147.848.247.249.96451.254.144.2	Th	ppm	5.3	5.4	7.3	7.1	6.7	8.2	9.1	7.8	7.8	7.7
TIppm0.140.190.360.30.310.250.180.260.190.23Uppm27.545.147.848.247.249.96451.254.144.2	Ti	%	0.02	0.019	0.024	0.021	0.021	0.02	0.023	0.019	0.02	0.021
U ppm 27.5 45.1 47.8 48.2 47.2 49.9 64 51.2 54.1 44.2	TI	ppm	0.14	0.19	0.36	0.3	0.31	0.25	0.18	0.26	0.19	0.23
	U	ppm	27.5	45.1	47.8	48.2	47.2	49.9	64	51.2	54.1	44.2

V	ppm	245	236	281	212	217	225	203	184	220	208
W	ppm	0.48	0.51	0.71	0.77	0.85	0.57	2.38	0.62	0.54	0.56
Y	ppm	4.69	5.19	6.23	9.26	11.1	5.69	10.55	8.17	7.21	6.94
Zn	ppm	34	30	44	45	42	43	37	33	40	44
Zr	ppm	25	25.1	31.6	35.6	43.5	31.6	49	41.9	37.4	36.3

Table 3.I.7. Bulk Trace Element Chemistry, Core LB-LT-11-SC1A.

		0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50
		cm	cm	cm	cm	cm	cm	cm	cm	cm	cm
Ag	ppm	0.26	0.28	0.16	0.25	0.32	0.43	0.47	0.38	0.33	0.49
Al	%	1.3	0.97	0.91	1.06	1.38	1.53	1.66	1.71	1.82	1.78
As	ppm	24.8	22.1	27.5	32.5	30.9	30.4	34.8	22.5	22	28.8
Au	ppm	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
В	ppm	40	40	30	30	30	40	30	40	40	40
Ba	ppm	80	80	130	70	50	80	100	110	130	80
Be	ppm	0.93	0.55	0.72	0.57	1.11	1.04	1.26	1.05	1.33	1.09
Bi	ppm	0.81	0.75	0.56	0.62	0.89	1.03	0.95	0.79	0.81	1.06
Ca	%	1.56	1.96	1.15	1.86	1.85	1.49	0.95	1.33	1.61	1.64
Cd	ppm	0.07	0.03	0.04	0.05	0.09	0.11	0.14	0.08	0.09	0.24
Ce	ppm	51.5	43.1	37.9	39.1	41.8	37.9	37.6	35.8	39.6	37.2
Co	ppm	15.1	6.6	7.7	9.8	18.4	20.4	22.9	16.9	16.4	20
Cr	ppm	118	32	56	53	55	53	66	62	57	67
Cs	ppm	0.64	0.47	0.4	0.42	0.45	0.62	0.48	0.56	0.57	0.52
Cu	ppm	66.4	46.9	67.1	62.3	95.8	90	108	100.5	75.2	100
Fe	%	3.57	4.87	10.15	7.35	4.78	3.5	3.67	3.3	3.4	3.71
Ga	ppm	7.27	6.6	6.52	5.62	7.22	7.09	7.49	7.59	8.24	7.85
Ge	ppm	0.17	0.2	0.09	0.23	0.08	0.18	0.08	0.17	0.08	0.18
Hf	ppm	0.7	0.54	0.49	0.57	0.75	0.74	0.59	0.66	0.69	0.63
Hg	ppm	0.03	0.03	0.02	0.04	0.06	0.05	0.02	0.03	0.02	0.04
In	ppm	0.023	0.02	0.021	0.021	0.019	0.027	0.035	0.029	0.029	0.027
K	%	0.22	0.23	0.34	0.25	0.23	0.18	0.19	0.2	0.21	0.2
La	ppm	25.5	28.3	20.5	19.2	21.3	18.2	19.2	18	20.7	18.2
Li	ppm	28.6	16.6	17.5	19	31.1	35.3	38.4	40.6	47.5	39.9
Mg	%	1.08	0.65	0.63	0.74	1.04	1.16	1.19	1.23	1.3	1.24
Mn	ppm	288	187	184	195	258	2/3	287	302	31/	315
Mo	ppm	15.2	10.75	9.45	13.4	15.35	18.7	22.7	22.1	17.95	17.25
ina	%	0.13	0.2	0.12	0.09	0.08	0.06	0.06	0.05	0.05	0.06
ND	ppm	0.09	0.22	0.14	0.3	0.11	0.19	0.08	0.17	0.11	0.3
NI D	ppm	38.6	17.2	19.5	23	42.4	46.2	46	36.1	38.7	46.4
P	ppm	550	630	520	550	620	650	740	690	640	870
PD	ppm	183	197		290	242	248	2/0	253	260	299
KD Da	ppm	12.8	10.8	11./	11.4	11.9	10.3	11.3	11.5	13.1	11.8
ке	ppm	0.017	0.01	0.01	0.012	0.018	0.017		0.018	0.024	0.041
S Ch	% 	2.//	3.11	2.53	3.20	3.35	3.1	2.54	2.43	2.38	3.12
SD	ppm	0.24	0.25	0.26	0.27	0.32	0.31	0.24	0.22	0.19	0.35
50	ppm	3.Z	2.3	2.4	2.3	3.4 ∡ 2	3.7	5.9	4.1	4.0	4.1
Se	ppm	3./	3.5	 ∕	3.3 2 4	4.5	4.8	4	2.9	2.8	4.1
50	ppm	4.3	2.0 104 E	4.3 EC 4	3.4 16 0)./ 2./	4.1	ס.כ ד דר	9.5 77	3.4 41 7	9.0 42 E
51 T-	hhu	52.8 20.01	104.J		40.0 20.01	40.0	39.3	Z/./	/د ۱۰ ۵۰	41./	43.5
	hhu	<0.01					0.01	<0.01		<0.01	0.01
те ть	ppm	0.00 2 E	0.05	0.05	0.05	0.05 7 7	0.05	0.07	0.05	0.00	0.08
111 T:	0/2 hhiii				5.9 0.014	/.3	7.9	0.1 0.014	0.3 0.016	0.0 0.01 <i>6</i>	0.J
11 	70 nr	0.015	0.015	0.013	0.014	0.015	0.010	0.014	0.010	0.010	0.015
11	ppm	0.30 77 F	0.34 11 E	30 E 0.31	U.∠/ ∕0 ⊃	0.39	U.30 75 2	U.JI 71 0	0.44 70	102 5	122
U	hhui	//.5	41.5	29.2	40.3	70.4	/5.5	/1.9	12	103.3	132
										150	

V	ppm	312	371	283	319	310	266	209	213	224	245
W	ppm	0.73	1.01	0.63	0.78	0.85	0.95	0.64	0.71	0.71	0.9
Y	ppm	7.91	5.39	5.23	6.18	8.71	8.19	7.73	7.48	8.64	8.5
Zn	ppm	48	27	31	37	53	65	79	71	71	88
Zr	ppm	42.6	36.1	34.6	41	46.4	50.6	37.2	44.8	39.8	42.5

Table 3.I.8. Bulk Trace Element Chemistry, Core LB-LT-11-SC2A.

		0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50
		cm	cm	cm	cm	cm	cm	cm	cm	cm	cm
Ag	ppm	0.26	0.28	0.16	0.25	0.32	0.43	0.47	0.38	0.33	0.49
Al	%	1.3	0.97	0.91	1.06	1.38	1.53	1.66	1.71	1.82	1.78
As	ppm	24.8	22.1	27.5	32.5	30.9	30.4	34.8	22.5	22	28.8
Au	ppm	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
В	ppm	40	40	30	30	30	40	30	40	40	40
Ba	ppm	80	80	130	70	50	80	100	110	130	80
Be	ppm	0.93	0.55	0.72	0.57	1.11	1.04	1.26	1.05	1.33	1.09
Bi	ppm	0.81	0.75	0.56	0.62	0.89	1.03	0.95	0.79	0.81	1.06
Ca	%	1.56	1.96	1.15	1.86	1.85	1.49	0.95	1.33	1.61	1.64
Cd	ppm	0.07	0.03	0.04	0.05	0.09	0.11	0.14	0.08	0.09	0.24
Ce	ppm	51.5	43.1	37.9	39.1	41.8	37.9	37.6	35.8	39.6	37.2
Со	ppm	15.1	6.6	7.7	9.8	18.4	20.4	22.9	16.9	16.4	20
Cr	ppm	118	32	56	53	55	53	66	62	57	67
Cs	ppm	0.64	0.4/	0.4	0.42	0.45	0.62	0.48	0.56	0.57	0.52
Cu	ppm	66.4	46.9	6/.1	62.3	95.8	90	108	100.5	/5.2	100
Fe	%	3.5/	4.87	10.15	/.35	4.78	3.5	3.67	3.3	3.4	3./1
Ga	ppm	/.2/	6.6	6.52	5.62	/.22	/.09	7.49	/.59	8.24	7.85
Ge	ppm	0.17	0.2	0.09	0.23		0.18	0.08	0.17	0.08	0.18
Hr	ppm	0.7	0.54	0.49	0.57	0.75	0.74	0.59	0.00	0.69	0.63
нg	ppm	0.03	0.03	0.02	0.04	0.06	0.05	0.02	0.03	0.02	0.04
IN V	ppm %	0.023	0.02	0.021	0.021	0.019	0.027	0.035	0.029	0.029	0.027
	70 DDD	25 5	20.23	20.54	10.25	0.25	10.10	10.19	10.2	20.21	10.2
La	ppm	22.5	16.6	20.5	19.2	21.5	25.2	19.Z 38 /	10 6	20.7 47 5	30.0
Ma	% %	1 08	0.65	0.63	0 74	1 04	1 16	1 10	1 23	13	1 74
Mn	nnm	288	187	184	195	258	273	287	302	317	315
Mo	nnm	15.2	10 75	9 4 5	13.4	15 35	18.7	207	22 1	17 95	17 25
Na	%	0.13	0.2	0.12	0.09	0.08	0.06	0.06	0.05	0.05	0.06
Nb	ppm	0.09	0.22	0.14	0.3	0.11	0.19	0.08	0.17	0.11	0.3
Ni	ppm	38.6	17.2	19.5	23	42.4	46.2	46	36.1	38.7	46.4
Р	ppm	550	630	520	550	620	650	740	690	640	870
Pb	ppm	183	197	166	290	242	248	270	253	260	299
Rb	ppm	12.8	10.8	11.7	11.4	11.9	10.3	11.3	11.5	13.1	11.8
Re	ppm	0.017	0.01	0.01	0.012	0.018	0.017	0.017	0.018	0.024	0.041
S	%	2.77	3.11	2.53	3.26	3.35	3.1	2.54	2.43	2.38	3.12
Sb	ppm	0.24	0.25	0.26	0.27	0.32	0.31	0.24	0.22	0.19	0.35
Sc	ppm	3.2	2.3	2.4	2.3	3.4	3.7	3.9	4.1	4.6	4.1
Se	ppm	3.7	3.5	3	3.3	4.3	4.8	4	2.9	2.8	4.1
Sn	ppm	4.3	2.8	4.3	3.4	5.7	4.1	3.6	9.5	3.4	9.6
Sr	ppm	52.8	104.5	56.4	46.8	48.5	39.3	27.7	37	41.7	43.5
Та	ppm	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.01	< 0.01	< 0.01	< 0.01	0.01
Те	ppm	0.06	0.05	0.05	0.05	0.05	0.05	0.07	0.05	0.06	0.08
Th	ppm	6.5	5	5.5	5.9	7.3	7.9	8.1	8.3	8.6	8.5
Ti	%	0.015	0.015	0.013	0.014	0.015	0.016	0.014	0.016	0.016	0.015
ΤI	ppm	0.36	0.34	0.31	0.27	0.39	0.38	0.51	0.44	0.39	0.37
U	ppm	77.5	41.5	39.5	48.3	70.4	75.3	71.9	72	103.5	132
										152	

V	ppm	312	371	283	319	310	266	209	213	224	245
W	ppm	0.73	1.01	0.63	0.78	0.85	0.95	0.64	0.71	0.71	0.9
Y	ppm	7.91	5.39	5.23	6.18	8.71	8.19	7.73	7.48	8.64	8.5
Zn	ppm	48	27	31	37	53	65	79	71	71	88
Zr	ppm	42.6	36.1	34.6	41	46.4	50.6	37.2	44.8	39.8	42.5

Table 3.I.9. Bulk Trace Element Chemistry, Core LB-LT-11-SC3A.

		0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50
		cm									
Ag	ppm	0.16	0.17	0.27	0.31	0.38	0.31	0.27	0.36	0.47	0.47
Al	%	0.94	0.86	1.18	1.48	1.47	2.18	1.62	1.47	1.74	1.61
As	ppm	34.4	43.4	38.6	38.1	40.1	33.4	30.6	29.4	41.1	37.1
Au	ppm	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
В	ppm	40	40	30	30	30	50	30	30	30	30
Ba	ppm	130	100	130	100	80	40	130	100	50	70
Be	ppm	0.66	0.39	0.89	0.76	1.02	1.13	1.22	0.92	1.46	1.28
Bi	ppm	0.79	0.65	0.71	0.96	1.26	4.24	1.74	0.97	1.55	0.98
Ca	%	1.1	0.88	1.18	0.77	0.54	2.43	0.94	0.96	2.23	1.29
Cd	ppm	0.05	0.02	0.03	0.05	0.1	0.08	0.1	0.14	0.14	0.16
Ce	ppm	54.8	32.3	42.2	33.2	44	42	36.9	33.4	44.7	32.5
Со	ppm	8.1	4.9	13.7	19.6	29	24.6	22	23.2	29.3	29.1
Cr	ppm	53	44	47	65	57	78	62	71	53	64
Cs	ppm	0.38	0.35	0.45	0.37	0.39	0.45	0.35	0.33	0.46	0.44
Cu	ppm	37.2	33	17.1	42.4	251	100.5	66.4	65	91.7	85.3
Fe	%	5.27	6.36	2.97	3.38	4.02	3.19	3.06	3.19	3.61	3.96
Ga	ppm	5.53	5.91	8.43	7.54	6.91	9.02	7.52	7.01	8.29	7.89
Ge	ppm	0.11	0.16	0.07	0.11	0.09	0.14	0.09	0.12	0.11	0.14
Hf	ppm	0.52	0.4	0.59	0.56	0.68	0.81	0.68	0.68	0.87	0.78
Hg	ppm	0.02	0.03	0.03	0.05	0.04	0.06	0.03	0.05	0.06	0.05
In	ppm	0.013	0.016	0.017	0.022	0.028	0.031	0.025	0.03	0.033	0.027
К	%	0.24	0.29	0.22	0.19	0.2	0.32	0.21	0.17	0.2	0.17
La	ppm	29.7	23.4	25.8	17.1	23.1	19.6	19.3	17.2	21.2	16
Li	ppm	17.9	11	25	26.5	32.9	44.9	42.6	28.7	43.1	41.6
Mg	%	0.65	0.46	0.77	1.09	1.12	1.5	1.17	1.03	1.21	1.03
Mn	ppm	176	144	194	251	232	277	217	218	235	206
Мо	ppm	15.9	19.75	17	12.65	8.02	8.12	7.77	9.28	13.85	15.15
Na	%	0.2	0.2	0.05	0.03	0.05	0.03	0.04	0.04	0.04	0.03
Nb	ppm	0.11	0.2	0.09	0.15	0.11	0.2	0.09	0.16	0.13	0.15
Ni	ppm	25	14.9	36.4	53.3	71.8	89.8	65.1	54.1	68	60.1
Р	ppm	440	580	670	730	740	650	590	540	580	550
Pb	ppm	147	193.5	138.5	79	81.5	308	198	217	278	229
Rb	ppm	11.2	11.2	12.8	10	11.7	15.2	11.3	9.5	11.9	10.7
Re	ppm	0.013	0.011	0.017	0.017	0.012	0.016	0.012	0.013	0.017	0.019
S	%	2.29	2.11	2.47	2.8	2.8	3.61	2.11	2.72	3.84	3.61
Sb	ppm	0.26	0.24	0.26	0.26	0.3	0.35	0.28	0.28	0.39	0.39
Sc	ppm	2.4	2.1	2.8	3.2	3.7	5.2	4.1	3.7	4.6	4.6
Se	ppm	3.1	3	3.3	3.3	6.1	4.4	4.1	5.1	6.3	6.3
Sn	ppm	4.6	1.5	1.6	1.2	1.5	1.4	1.4	1.3	1.6	1.5
Sr	ppm	65.2	81.5	30	19	19.8	50.4	26.2	23.1	45.1	27.1
Та	ppm	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Те	ppm	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.05	0.07	0.07
Th	ppm	4.5	4.4	6.7	8.3	10.1	9.3	7.8	7.7	9.3	8.4
Ti	%	0.015	0.014	0.015	0.016	0.019	0.031	0.021	0.018	0.021	0.02
ΤI	ppm	0.23	0.32	0.32	0.42	0.37	0.31	0.29	0.33	0.33	0.41
U	ppm	59.5	50.3	67.3	78.4	80	137	89.7	97.4	116.5	101.5

V	ppm	360	456	349	202	201	324	294	344	399	419
W	ppm	0.74	0.8	0.91	0.65	0.78	0.96	0.7	0.77	1.16	1.05
Y	ppm	5.65	4.42	7.49	8.31	8.43	10.65	7.26	8.11	10.45	8.76
Zn	ppm	27	19	26	37	56	62	60	63	72	64
Zr	ppm	29.9	27	39.5	38.7	41.1	48.4	39.1	40.1	49	41.9

		0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50
		cm									
Ag	ppm	0.19	0.19	0.21	0.23	0.27	0.39	0.34	0.34	0.32	0.41
Al	%	0.6	0.65	0.75	0.89	1.16	1.35	1.55	1.66	1.59	1.65
As	ppm	18.8	41	13.9	27.5	47	66.4	59.2	42.8	33.7	34.1
Au	ppm	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
В	ppm	30	30	40	50	30	30	30	40	30	30
Ba	ppm	90	110	70	60	60	40	90	70	120	60
Be	ppm	0.45	0.32	0.67	0.45	0.84	0.69	1.23	1	1.29	1.05
Bi	ppm	0.48	0.58	0.8	0.82	0.8	1.01	1.12	1.71	1.4	1.28
Ca	%	3.07	1.04	1.91	2.2	0.97	0.83	0.92	0.86	0.87	1.33
Cd	ppm	0.03	0.02	0.01	0.02	0.02	0.04	0.06	0.11	0.12	0.15
Ce	ppm	83.5	45.9	38.4	42.9	48.2	36.7	35.7	30	36.5	34.3
Со	ppm	4.6	4.7	6.2	7.2	15	19.9	23.6	23.7	22.9	25.6
Cr	ppm	30	45	31	33	32	58	53	72	53	57
Cs	ppm	0.31	0.32	0.41	0.44	0.39	0.36	0.36	0.34	0.35	0.38
Cu	ppm	29.8	48.1	24	19.4	18.8	37.8	68.4	91.9	79.7	85.6
Fe	%	4.6	8.76	4.04	7.08	5.59	4.73	4.42	3.48	3.34	3.65
Ga	ppm	5.2	6.6	4.39	5.52	6.98	7.34	7.3	7.58	7.13	7.69
Ge	ppm	0.13	0.19	0.08	0.17	0.08	0.13	0.08	0.12	0.08	0.13
Hf	ppm	0.46	0.39	0.72	0.69	0.65	0.56	0.69	0.67	0.75	0.76
Hg	ppm	0.01	0.03	0.03	0.05	0.04	0.07	0.05	0.06	0.03	0.05
In	ppm	0.012	0.014	0.009	0.013	0.017	0.02	0.022	0.025	0.023	0.025
K	%	0.17	0.19	0.22	0.33	0.36	0.3	0.22	0.21	0.2	0.19
La	ppm	31.9	28.6	19	28.4	31.5	22.4	18.1	15.3	18.2	17.9
Li	ppm	10.1	8.5	12.2	12	24.2	25.2	37.4	38.4	39.3	35
Mg	%	0.41	0.43	0.46	0.44	0.8	0.91	1.13	1.15	1.14	1.18
Mn	ppm	143	158	158	138	200	216	241	221	216	242
Мо	ppm	5.57	15.35	8.8	13.65	11.35	17.2	16.3	11.3	9.92	11.5
Na	%	0.2	0.25	0.15	0.23	0.12	0.04	0.04	0.03	0.04	0.04
Nb	ppm	0.16	0.26	0.11	0.25	0.11	0.21	0.11	0.17	0.1	0.17
Ni	ppm	13.7	13.5	17.2	19.9	38.2	51.7	60.2	76	62.3	61.8
Р	ppm	420	770	280	570	740	910	830	660	580	600
Pb	ppm	143.5	220	164	151	129	258	226	177	197	228
Rb	ppm	8.2	8.8	11.8	13.7	14.2	10.8	10.3	10.8	10.7	10
Re	ppm	0.008	0.009	0.015	0.019	0.016	0.018	0.019	0.012	0.011	0.015
S	%	3.65	2.58	2.76	3.99	3.26	3.95	3.29	2.77	2.33	3.27
Sb	ppm	0.23	0.37	0.25	0.29	0.3	0.38	0.34	0.33	0.31	0.33
Sc	ppm	1.6	1.8	2	2.3	2.7	3	3.5	4	3.8	4
Se	ppm	2.8	4.7	3.2	3.3	3.6	4.7	3.7	4.8	4.9	5.3
Sn	ppm	5	5.9	3.2	2.1	2.1	2.6	1.7	4.7	5	3.9
Sr	ppm	47.1	64.3	53.3	112	63.8	29.6	24.6	22.9	25.4	30.3
Та	ppm	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Те	ppm	0.03	0.04	0.07	0.05	0.06	0.05	0.04	0.04	0.05	0.05
Th	ppm	2.9	4.5	3.9	5.9	5.5	6.5	7.9	7.1	7.2	7.2
Ti	%	0.013	0.015	0.015	0.016	0.014	0.015	0.015	0.02	0.019	0.021
ΤI	ppm	0.22	0.35	0.27	0.37	0.47	0.69	0.61	0.4	0.31	0.36
U	ppm	42	45.9	53.1	52.6	58.1	59.3	73.6	79.1	83.4	90.8

Table 3.I.10. Bulk Trace Element Chemistry, Core LB-LT-11-SC4A.

V	ppm	389	976	397	473	252	214	267	275	307	462
W	ppm	0.67	1.02	1.22	1.38	0.8	0.79	0.89	0.66	0.71	1.1
Y	ppm	5.66	5.05	5.85	6.35	6.65	7.41	7.55	7.56	6.86	8.36
Zn	ppm	18	18	18	15	25	30	44	54	60	62
Zr	ppm	25.2	26.3	40.7	42.6	45.3	42.6	44.8	42.1	39	44.1

	,	Table 3.I.11.	Bulk Trace	Element (Chemistry.	Core LB-LT-1	1-SC5A.
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		0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50
		cm	cm	cm	cm	cm	cm	cm	cm	cm	cm
Ag	ppm	0.24	0.2	0.25	0.16	0.18	0.18	0.25	0.38	0.32	0.42
Al	%	1.19	1.33	1.54	1.34	1.33	1.16	0.99	0.97	1.1	1.66
As	ppm	16.3	19.5	24.6	20	19.2	19.1	19.6	24.5	20	36.2
Au	ppm	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
В	ppm	20	20	30	30	30	30	30	30	30	30
Ba	ppm	50	310	160	220	180	250	210	50	110	60
Ве	ppm	0.81	0.73	1.11	0.71	0.85	0.6	0.71	0.57	0.8	1.07
Bi	ppm	0.51	0.53	0.79	0.56	0.58	0.62	0.83	0.9	0.98	1.57
Са	%	4.9	0.24	1.65	1.1	1.4	0.78	1.03	2.25	1.28	1.58
Cd	ppm	0.03	< 0.01	0.01	< 0.01	0.01	0.01	< 0.01	0.03	0.02	0.1
Ce	ppm	74	41.8	46.3	38.8	42.1	30.3	34.4	37.2	34.1	34.2
Со	ppm	8.3	6.5	7.2	6.1	5.6	4.4	5.5	12.2	11.6	22.2
Cr	ppm	36	66	52	50	47	57	37	42	35	53
Cs	ppm	0.32	0.33	0.43	0.37	0.4	0.36	0.53	0.47	0.44	0.4
Cu	nnm	40.3	43.6	47.2	41.8	32.5	37.5	40.3	24.2	22.7	101.5
Fe	%	2.58	3	3.55	2.81	3.17	3.16	3.55	2.44	2.45	3.02
Ga	nnm	6.45	7.66	8.32	7.62	7.21	6.43	5.83	6.51	6.11	8.11
Ge	nnm	0.11	0.11	0.09	0.11	0.07	0.1	0.14	0.1	0.13	0.11
Hf	nnm	0.5	0.25	0.22	0.38	0.44	0.43	0.63	0.78	0.73	0.83
Ha	nnm	0.01	0.03	0.03	0.02	0.04	0.04	0.05	0.05	0.05	0.05
In	nnm	0.016	0 021	0 021	0.018	0 022	0.016	0.013	0.016	0.017	0.028
K	%	0.16	0.16	0.22	0.18	0.21	0.21	0.21	0.010	0.017	0.18
la	nnm	26.5	24.3	25.5	21.2	23.8	17.3	17.1	18.1	16.6	17.3
Lü	nnm	25.6	2113	2313	26	25.3	19.6	17 1	15.4	20.4	37.4
Ma	ېند س	0.9	0.87	0.98	0.83	0.85	0.63	0 51	0 45	0 59	1 09
Mn	nnm	206	182	203	174	185	153	136	128	150	204
Mo	nnm	6 17	6.2	8 35	6 66	6.62	6 69	9.63	12.4	9.08	12
Na	% %	0.17	0.06	0.05	0.00	0.02	0.05	0.05	0.04	0.04	0 03
Nh	nnm	0.05	0.12	0.08	0.13	0.07	0.11	0.09	0 19	0 11	0.16
Ni	nnm	24.7	21.8	23.6	20.7	18.7	16.6	17.6	31 1	31 7	59 5
P	nnm	590	800	850	730	640	610	450	270	410	530
Ph	nnm	140 5	145	195	150	164	161 5	181 5	121 5	104	185
Rh	nnm	9	89	11.6	9.8	11 3	11 4	11 5	12 5	11 5	11
Re	nnm	0.012	0.009	0.013	0.01	0 011	0 009	0.013	0 019	0 021	0 013
S	%	5 05	0.005	1 76	1 22	1 55	1 03	1 59	3 53	2 68	2 88
Sh	70 nnm	0.22	0.5	0.35	0.26	0.27	0.25	0.32	0.27	0.20	0.26
50	ppm	3.4	3 1	0.55 3 3	0.20 3	2.27	2 5	2.7	0.27 3	3	4.2
Se Se	ppm	2.4	3.1	4.6	22	2.7	2.5	2.7	31	26	55
Sn	ppm	6.4	2.4 4.5	5 1	5 1	2.7	5.2	6.4	3.1	2.0	3.0
Sr	ppm	0.7 08 0	7.J 74 4	41 Q	38.4	2.0 45 Q	36.3	26.6	41 9	28.7	3.5
Ji Ta	ppm	<pre>>0.5</pre>	~0.01	~0.01	-0.01	~0.01	-0.01	~0.01	~0.01	~0.01	∠0 01
Та	ppm	0.01	0.01	0.0E	0.01	0.01	0.02 20.01	0.01	0.01	0.01	0.01
Th	ppill	7 /	0.04 Q Q	11 Q	7 0	6 5	5.05 5 1	5.05	0.05 Q	75	0.0J
111 Ti	۵% ۱۱۱۹	0.012	0.0		7. 9 0.016	0.5	0.01/			0.016	
ו ו דו	-70 nnm	0.012	0.010	0.017	0.010	0.010	0.014	0.012	0.010	0.010	0.010
11	hhii	0.20	0.22	0.29	0.25 AA 0	0.5Z	22.5	20.5	0.44 40.0	0.4 ⊿0.2	0.20 72 0
0	hhiu	05.5	40.0	04.1	44.0	44.Z	52.5	50.2	49.9	49.3	75.2

V	ppm	289	352	595	391	445	360	245	152	179	291
W	ppm	0.78	0.69	1.23	0.8	0.88	0.76	0.75	0.85	0.84	0.73
Y	ppm	8.6	5.44	6.73	5.75	5.21	4.38	4.58	7.38	5.94	7.76
Zn	ppm	42	39	42	35	35	27	25	17	22	63
Zr	ppm	34.1	24.3	23.5	30.9	32.1	29.7	43.4	61.1	56.2	49.8

		0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50
		cm									
Ag	ppm	0.37	0.29	0.22	0.2	0.38	0.39	0.24	0.44	0.42	0.32
Al	%	1.26	1.33	1.34	1.35	1.25	1.17	1.23	1.49	1.65	1.74
As	ppm	15.5	25.8	16.8	14	32.6	25.5	32.6	24.7	26.9	30
Au	ppm	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
В	ppm	20	30	30	30	30	30	20	30	30	30
Ba	ppm	60	150	190	210	60	70	190	60	60	130
Be	ppm	0.87	0.94	1.14	0.87	0.88	0.66	1.06	0.96	1.37	1.2
Bi	ppm	0.62	0.69	0.68	0.57	1	1.13	0.96	1.16	1.33	1.35
Ca	%	3.44	0.96	1.21	0.98	2.99	1.23	0.81	1.07	1.42	1.16
Cd	ppm	0.02	0.02	0.01	0.02	0.01	0.03	0.02	0.11	0.1	0.08
Ce	ppm	66.9	36.5	40.9	36.3	60.8	34.5	38	39.4	40.3	34.2
Со	ppm	13.7	10.9	8.9	8	9.1	16.6	10.3	24.2	24	21.3
Cr	ppm	31	62	40	55	34	53	53	51	42	59
Cs	ppm	0.4	0.38	0.43	0.42	0.55	0.37	0.36	0.35	0.41	0.37
Cu	ppm	57	84.7	83.9	56.9	55.5	35.7	45.1	207	275	110.5
Fe	%	2.53	3.19	2.64	2.84	3.56	3.45	4.1	2.97	2.98	2.91
Ga	ppm	6.44	7.8	7.12	7.5	7.07	7.3	6.54	7.33	7.57	7.9
Ge	ppm	0.16	0.13	0.15	0.11	0.16	0.11	0.16	0.13	0.15	0.13
Hf	ppm	0.56	0.37	0.63	0.54	0.71	0.63	0.56	0.73	0.83	0.7
Hg	ppm	0.03	0.04	0.04	0.03	0.04	0.06	0.07	0.05	0.05	0.04
In	ppm	0.012	0.019	0.018	0.025	0.023	0.017	0.022	0.029	0.031	0.027
K	%	0.17	0.21	0.21	0.21	0.25	0.18	0.22	0.16	0.19	0.18
La	ppm	41.2	19	22	22.5	30.8	17.2	18.9	19.7	19.1	17
Li	ppm	24.7	24.3	26.7	27.4	21.7	22.3	26	33.5	39.9	41.4
Mg	%	1.16	0.88	0.92	0.87	0.84	0.79	0.88	1.18	1.22	1.2
Mn	ppm	315	237	245	222	237	204	220	277	267	239
Мо	ppm	7.43	9.33	6.21	6.01	12.35	10.95	11.05	8.68	11.85	13.95
Na	%	0.11	0.06	0.11	0.13	0.13	0.04	0.07	0.04	0.04	0.03
Nb	ppm	0.15	0.15	0.09	0.12	0.12	0.17	0.09	0.17	0.09	0.13
Ni	ppm	34.7	29.4	24.9	25.7	23.5	47.2	31	57.6	55.4	55.3
Р	ppm	660	720	600	600	680	600	600	570	530	540
Pb	ppm	156.5	197.5	195	186	255	89.4	187	94.9	166.5	175
Rb	ppm	9.6	11.2	11.4	11.9	13.8	10.3	10.5	9.6	10.3	9.7
Re	ppm	0.017	0.019	0.017	0.014	0.021	0.023	0.018	0.016	0.017	0.022
S	%	4.61	1.73	1.85	1.52	3.9	2.99	1.77	2.89	3.07	2.41
Sb	ppm	0.3	0.45	0.39	0.22	0.31	0.28	0.32	0.28	0.33	0.29
Sc	ppm	3.5	3.3	3.4	3.3	3.2	3	3.4	3.8	4.3	4.4
Se	ppm	3.2	3.8	2.9	2.5	3.7	4.1	3.7	6.1	4.9	3.4
Sn	ppm	18.1	13.4	12.9	7.1	4.3	3.2	4.1	2.2	2.7	5.4
Sr	ppm	88.3	23.8	40.1	49.2	76.1	27.5	31.4	24.4	34.3	28.2
Та	ppm	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Те	ppm	0.04	0.05	0.06	0.03	0.06	0.05	0.05	0.05	0.06	0.04
Th	ppm	8.7	9.8	8.7	7.3	10.6	6.8	6.2	7.9	9.9	9
Ti	%	0.013	0.018	0.015	0.015	0.014	0.018	0.015	0.018	0.017	0.02
ΤI	ppm	0.33	0.33	0.3	0.29	0.41	0.34	0.26	0.29	0.3	0.24
U	ppm	142.5	101	101	72.5	98.8	66	76.5	99.7	120.5	97.6

Table 3.I.12. Bulk Trace Element Chemistry, Core LB-LT-11-SC6A.

V	ppm	347	684	515	464	305	250	363	269	312	372
W	ppm	1.04	1.36	1.22	0.87	1.1	0.8	0.74	0.8	0.98	0.87
Y	ppm	11.15	7.96	7.76	7.24	9.48	8.24	7.4	10.15	9.59	8.73
Zn	ppm	52	43	44	39	35	28	35	68	72	62
Zr	ppm	34.1	30.7	41.7	36.9	45	43.7	36.8	45.1	43.2	39.4

Appendix 3.J

Tailings Back-Scattered Electron Images



Figure 3.J.1. BSE images showing U grains within tailings thin section samples. A) shows U grains encapsulated by quartz grains where B) shows an individual U grain. These grains are very small <20 μ m.

Appendix 3.K

Tailings Electron Microprobe (EMP) Analysis Data

	SELVI) and ELVII.														
	Si	U	Ca	Ті	Fe	Pb	Al	Th	S	Na	К	V	Р	0	Total
1	0.0765	76.032	0.8914	0.0904	1.5141	0.0619	0.0441	0	0	0.0313	0	0	0.0071	11.439	90.189
2	9.0183	60.901	1.5736	0.0213	2.411	0	1.0711	0	0.0819	0.0078	0.7148	0.1196	0.1567	21.620	97.698
3	9.5765	48.531	2.0676	0.055	5.5506	0.0926	3.0305	0.0172	0.0361	0.0479	1.1971	0.1041	0.9724	25.023	96.303

Table 3.K.1. Electron microprobe (EMP) data in weight % for uranium grains identified by qualitative scanning electron microscopy (SEM) and EMP.

Z	9.0183	60.901	1.5730	0.0213	2.411	0	1.0711	0	0.0819	0.0078	0.7148	0.1190	0.1207	21.020	97.098
3	9.5765	48.531	2.0676	0.055	5.5506	0.0926	3.0305	0.0172	0.0361	0.0479	1.1971	0.1041	0.9724	25.023	96.303
4	8.6643	53.205	0.4527	0.0626	0.4577	0.1336	0.9753	0.0016	0.216	0.0077	0.1786	0.1581	0.5054	19.353	84.372
5	5.5677	42.485	0.4461	0.7618	3.3428	0.5571	1.4936	1.3032	8.6238	0	0.0909	0.2089	1.2752	26.167	92.323
6	12.411	49.981	2.3575	0.906	2.0259	3.0509	1.0173	0	0.0443	0.004	0.0695	0.0292	0.0042	24.506	96.408
7	6.3261	60.426	2.3812	0.0465	0.213	0.2038	0.2369	0	0.2411	0	0	0.2181	2.3479	20.075	92.716

Appendix 3.L

Additional VESPERS X-ray Fluorescence Maps

Figure 3.L.1. Additional X-ray fluorescence (XRF) element maps for 3230 ppm uranium salt sample area 1.



Figure 3.L.2. Additional X-ray fluorescence (XRF) element maps for 3230 ppm uranium salt sample area 2.



Figure 3.L.3. Additional X-ray fluorescence (XRF) element maps for 1195 ppm uranium salt sample area 1.



Figure 3.L.4. Additional X-ray fluorescence (XRF) element maps for 1195 ppm uranium salt sample area 2.



Figure 3.L.5. Additional X-ray fluorescence (XRF) maps from Tailings Thin Section Sample of previously identified uranium grain.

