LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

LLNL-TR-421182

# Nuclear Forensics in Central Asia: Report on Efforts to Date and Next Steps in Cooperative Engagement

D. K. Smith

December 10, 2009

## Disclaimer



This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

# Nuclear Forensics in Central Asia: Report on Efforts to Date and Next Steps in Cooperative Engagement

Prepared for the U.S. National Nuclear Security Administration
Office of Global Security Engagement and Cooperation (NA-242)

David K. Smith
Global Security Principal Directorate
Lawrence Livermore National Laboratory
Mail Stop L-186
7000 East Avenue
Livermore, California 94550 USA
unclassified e-mail: smith24@llnl.gov

December, 2009



This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

## Summary of Findings

From 2006 to the present, the National Nuclear Security Administration's Office of Global Security Engagement and Cooperation (GSEC) in partnership with Lawrence Livermore National Laboratory (LLNL) has undertaken an engagement program with Tajikistan, Kyrgyzstan, and Uzbekistan to access nuclear forensic samples, data, and subject matter expertise important to enhancing nuclear security response in Central Asia as well as addressing needs of the international nuclear forensics community. Regional security engagement in Central Asia successfully utilizes nuclear forensics to develop technical capacity and build confidence to address the threat from nuclear proliferation and the illicit trafficking of radioactive materials outside of administrative control.

The Central Asian states are strategically located between Russian, China, and south Asia and continue to play a pivotal role in the worldwide production of uranium and other strategic resources including oil and gas. Due to the emerging political structure and economies of these former Soviet republics, their mutually shared borders, a history involving ethnic violence and trafficking of contraband, there is a legitimate concern about stemming the movement of nuclear materials that could pose a threat to regional stability. Regional security engagement here focuses on the security of legacy uranium situated at mine dumps and tailings that supported the atomic weapons enterprise of the Soviet Union. These sites represent both a lasting environmental and security legacy throughout the region.

The present study has returned samples from four sites in the Republic of Tajikstan Tajikistan and six sites in the Kyrgyz Republic representing major uranium mine dumps and tailing sites. In each country GSEC and LLNL developed close technical partnerships with national technical experts who have jurisdictional responsibility for and access to the sampling sites. Of note, these experts also provide unprecedented insight to the process history of production operations having been involved during the time when uranium was extracted and milled for the atomic weapons defense of the Soviet Union. These partners have also been responsive in designing a relevant field program, collecting samples, providing the necessary radiological categorization to protect personnel in the field and to enable international air freight, and subsequently shipping the samples to Lawrence Livermore National Laboratory for nuclear forensics analysis. Five to ten gram representative samples of uranium sediment taken from each site were collected and transported to the United States. The samples were analyzed for constituent mineralogy by x-ray diffraction, and for major uranium isotopes (uranium-234, uranium-235, and uranium-238) and an array of trace elements by mass spectrometry. Interpretation of the samples is complicated by the heterogeneity of the mine dumps and tailings that composite many different source materials and are highly mixed.

The analytical data is consistent with the heterogeneous nature of geologic materials returned from uranium mine dumps and mill tailings piles in Tajikistan

and Kyrgyzstan. The samples are radioactive and contain uranium (several hundred parts per million) at levels approaching ore grade. While the inherent mixing of effluent streams from different source terrains or process contamination complicates nuclear forensics interpretation, isotopic and chemical analysis suggests that unique sources may be discriminated both between regions as well as within individual uranium ore mine and mill sites.

GSEC's presence in the region focused on nuclear nonproliferation objectives. Former Soviet scientists responsible for uranium mining and milling in Tajikistan, Kyrgyzstan, and Uzbekistan partnered with their US counterparts throughout as part of a program of confidence building. Through regular travel over a three year period to Central Asia, and regional nuclear security technical workshops convened by GSEC, scientists, law enforcement personnel, and decision makers formulated a program in technical response – including a nascent nuclear forensics capability - to address regional proliferation and trafficking threats. Engagement also provided unprecedented access to samples and insight to the nuclear security posture throughout the region and positions GSEC the option to acquire additional higher purity uranium ore and ore concentrate samples consistent with future programmatic priorities particularly in Uzbekistan and Kazakhstan.

## Table of Contents

## Introduction

The states of Central Asia[1] are important partners for the United States, especially in the area of nuclear security. They are geographically situated at the crossroads of states of interest for the United States: nuclear powers Russia and China, possible nuclear aspirant Iran, war-torn Afghanistan, and the two nuclear adversaries India and Pakistan. The states of Central Asia were the chief sources of uranium for the Soviet nuclear weapons program, and today they remain abundant in strategic resources, including one of the world's largest proven reserves of uranium. However, these states also present a strategic challenge for the United States. The states of Central Asia have newly established governments, legacies of ethno-sectarian violence, interwoven political borders, and are vulnerable to all forms of illicit smuggling, including the smuggling of nuclear materials. In Kyrgyzstan and Tajikistan alone, there are more than 575 million metric tons of uranium mining waste of varying levels of radioactivity, representing both an environmental hazard and a security threat to these states, the broader region, and, especially in the post-September 11, 2001 era of violent extremism, to the United States.

Under the sponsorship of the U.S. Department of Energy's National Nuclear Security Administration's Office of Global Security Engagement and Cooperation (GSEC), Lawrence Livermore National Laboratory (LLNL) is conducting regional security engagement in Central Asia to address the threat posed by legacy deposits of poorly secured radiological waste materials. Central to this effort is access to 'front end' nuclear fuel cycle uranium (e.g., ores, tailings, and concentrates) for nuclear forensic analysis. Nuclear forensics is a powerful capability to respond to incidents of nuclear smuggling through the identification of unknown nuclear materials, including their point of origin, their application, and the processes used to create them.

The purpose of this report is to provide results to-date of nuclear forensics investigations sponsored by GSEC in Central Asia with a focus on work conducted in Tajikistan and Kyrgyzstan. In partnership with GSEC, LLNL began an engagement program with Tajikistan and Kyrgyzstan in January 2006 and launched a nuclear forensics engagement effort with the Institute of Nuclear Physics in the Republic of Uzbekistan in 2009. The report provides an outline of work completed in Central Asia to-date, as well as identifies possible next-steps and overarching goals of nuclear forensics cooperation with these countries. The report begins with an overview of the regional security situation and potential nonproliferation benefits of nuclear forensics to situate the work in the broader framework of international nonproliferation engagement and cooperation.

[1] Defined in this report as Kazakhstan, Turkmenistan, Uzbekistan, Tajikistan, and Kyrgyzstan.

**Regional Security in Central Asia**

After the demise of the former Soviet Union, Central Asia was confronted by a considerable legacy of atomic weapons research and development activities conducted within the borders of the newly independent states of Kazakhstan, Uzbekistan, Kyrgyzstan, Tajikistan, and Turkmenistan (Figure 1). In the 1990s, security problems of particular interest for NNSA and other nuclear security organizations included un- or under-protected quantities of weapons usable nuclear and radiological materials, the lack of financial support and infrastructure for highly trained former weapons scientists, as well as national borders conducive to the smuggling of contraband including radioactive materials. Some of these issues were addressed as part of the cooperative threat reduction programs funded by Western partners.


Figure 1. Political map of Central Asia showing proximity of China and Russia and complex mutually shared borders, especially in the Fergana Valley tri-border region of Uzbekistan, Kyrgyzstan, and Tajikistan.

Especially since the September 11, 2001 terrorist attacks in the United States, Central Asia has contended with the influence of extreme Islam and resurgences in smuggling networks associated with the burgeoning drug trade. There are tensions inherent in the deployment of the US military to the region to support operations in Afghanistan, and as well as in the influence of the Russian Federation in the region. The region as a whole faces challenges with democratization, corruption, poverty, and environmental remediation.

The presence of nuclear and radiological material in Central Asia poses a terrorism and proliferation threat. Highly enriched uranium (HEU) existed at the Aktau BN-350 nuclear reactor in Kazakhstan, the Ust-Kamenogorsk nuclear fuel processing plant in Kazakhstan, and at the Institute of Nuclear Physics in Uzbekistan. However, most of the HEU has been removed and replaced with low enriched uranium (LEU) fuel that reduces the threat. Of equal or greater concern throughout the region are the dangers presented by radiological materials that might be employed in a radiological dispersal device (i.e., a "dirty bomb" or RDD). Mitigation of this threat includes the deployment of radiation portal monitors at checkpoints in Uzbekistan and Kazakhstan as well as inventories and registries of orphan radiation sources residual from the Soviet-era in Tajikistan and other Central Asian republics.

Central Asian states are pursuing active program to counter the threat posed by proliferation and trafficking of nuclear materials. The extensive length of shared common borders, especially in the ethnically diverse and volatile Fergana Valley, exacerbates the problem. Uzbekistan has installed radiation portal monitors at 30 vehicle, railway, and airport checkpoints (Petrenko et al., 2008). Kyrgyzstan has installed five radiation portal monitors and seven more installations are planned. Tajikistan is undertaking a design basis threat to identify vulnerable border ports of entry for future detector installations.

In 2007, news reports in Kyrgyzstan stated that there was increasing concern from Central Asia anti-terrorism experts that terrorists are seeking materials from uranium mines in Kyrgyzstan, Kazakhstan, Uzbekistan, and Tajikistan to use in the construction of an RDD. Kazakhstan, Kyrgyzstan, Tajikistan, and Uzbekistan pledged in 2009 to take cooperative measures to reduce the threat posed by the residual materials remaining from the atomic weapons enterprise of the former Soviet Union. These countries point to the approximately 800 million tons of uranium mine and mill tailings throughout the entire region as a completely unprotected source term that could potentially be misappropriated by terrorists to construct an RDD. To address this problem these Central Asian countries agreed to work in partnership to build regulatory frameworks and national response capabilities, as well as encourage economic development to exploit these inventories for economic gain (Nuclear Threat Initiative, 2009).

Unauthorized movement of radiological materials has been reported in Central Asia. Notably, a regional workshop convened in November, 2007 in Dushanbe, Tajikistan emphasized the nature of these threats (International Science and Technology Center, 2007). Data collected in the open literature since 2001 indicates that there have been single incidents of illicit nuclear trafficking in Uzbekistan, Tajikistan, and Kyrgyzstan and multiple incidents in Kazakhtsan (Kozak, 2006). In November 2007, a border radiation detection and alarm system at the Nazarbek checkpoint in Uzbekistan was responsible for detecting a railway carriage carrying scrap materials bound for Iran contaminated with $^{137}Cs$, other fission products, and $^{238}U$ daughters. The railway car had passed several other shared national borders in the region without alarm before being stopped at the Uzbek railway radiation monitor

(Radio Free Europe, 2008). Other alarms involved detection of radioactively contaminated scrap metal (Nuclear Threat Initiative, 2009).

**Elements of Nuclear Forensic Science Applied to Nonproliferation**

Nuclear forensics uses three sources of signatures to identify unknown nuclear material (see Moody et al., 2005). The first signature is the isotopic composition of the material, which includes isotope ratios of uranium, plutonium, as well as fission products. The second is chemical properties of the material including the presence and concentrations of major and trace elements. Also relevant are the physical signatures of the material that includes levels of inherent naturally occurring radioactivity, grain size, shape, color, sorting, inclusions, and alterations.

For credible attribution, nuclear forensics relies on a sequential process of investigation. First, samples must be collected. Second, those samples must be analyzed for their identifying signatures. Finally, that information must be interpreted through comparison with previously identified material and through analysis of the circumstances under which that material was collected. Some of the information that can be gleaned through forensic analysis includes determining a material's point of origin, its subsequent history, the application of the material, and the process that were used to create the material. These capabilities make nuclear forensics a useful tool for a variety of nonproliferation applications.

Primarily, nuclear forensics is a tool for attribution of illicit or undeclared nuclear materials. Forensic analysis is therefore extremely useful for investigating cases of nuclear smuggling. If interdicted materials can be traced back to their place of origin, then there is a greater chance that smuggling networks can be discovered and disrupted. Also, tracing materials to their point of origin can help national authorities allocate resources toward the greatest threats.

Additionally, there is an increasing recognition of the utility of nuclear forensics to provide an independent and objective measure of state safeguards declarations concerning nuclear capabilities as well as their application and intent (Dreicer et al., 2009). Nonproliferation nuclear forensic tools may encourage governments to better secure vulnerable inventories of nuclear materials as well as deter others producing or transferring nuclear materials for malfeasant purposes. By identifying proliferators, there are severe consequences attached to the provider of nuclear material that finds its way into unauthorized hands.

The requirements for national programs in nuclear forensics exceed those of commercial and international verification regimes. Nuclear forensics investigations require the sharing of validated protocols not only on major and minor isotopes, chemical (trace element) compositions, and physical forms (grain size, sorting, admixtures) of the materials, but also the processes used in facilities that are part of the nuclear fuel cycle (Chivers et al., 2008; Niemeyer and Smith, 2007; Dunlop and Smith, 2006; American Association for the Advancement of Sciences/American

Physical Society, 2008; Moody et al., 2005). Access to this broad suite of information is critical for the evaluation of the source and route of smuggled or proliferated pieces. There is also a compelling need to ensure that states that conduct nuclear forensics measurements – either independently or cooperatively – have access to sufficient data for rigorous, high confidence, interpretation.

This presents a challenge for nuclear forensics because the need to share data by necessity may infringe on proprietary or national security information that must be addressed at the outset of any exchange. While opportunities for international cooperation exist, the potential to reveal specific capabilities or methods used by states as part of their counter-terrorism and nonproliferation programs may complicate an unfettered exchange.

To overcome this challenge, a program such as NNSA Global Security Engagement and Cooperation is an ideal sponsor for nuclear forensics work. GSEC incorporates technical partnerships and builds indigenous capacity as well as awareness to best respond to nuclear proliferation threats. This mission can achieve synergies with states or regions with legacy stockpiles of nuclear materials and are also interested in developing domestic capacities for nuclear safety, security, and safeguards. The states of Central Asia fit this description and are therefore important partners in this work.

**Nuclear Forensics in Central Asia**

By returning data related to the origin and producer, age, potential point of diversion, transit route, and end-use of nuclear and radioactive materials, national and international authorities may fashion an appropriate response to acts involving their authorized possession. To accomplish these objectives, an understanding of the end-member and range in compositions of uranium samples in Central Asia is required to allow direct comparisons between samples of interest (i.e, unknowns or questioned samples) and samples from mines and mills situated in Central Asia (i.e., known sample sites). In this context, uranium ores, ore concentrates, and residual materials collected from Central Asia constitute elements of an emerging regional library of nuclear forensics reference samples. In addition to the regional library of nuclear forensic reference samples, it is equally important to understand the processes and timelines associated with the production of nuclear materials in order to provide scientists and law enforcement officials with an interpretative context. These efforts in concert with the exchange of information and reference materials provide an opportunity to build an international community of experts that understand the requirements and methods of nuclear forensics who are able to respond to cases of nuclear trafficking.

LLNL has partnered with specialists from State Enterprise Vostokredmet in Tajikistan and the Ministry of Emergency Situations in Kyrgyzstan to characterize uranium sourced in Central Asia. The goal of these collaborations is to gather samples from ore processing facilities and mine tailings and chemically characterize

this material. An important element is to fully introduce and define the topic of nuclear forensics so that best practices can be applied to nuclear material as it is encountered outside of administrative control. In this sense, nuclear forensics engagement is truly a collaborative enterprise involving sampling and radiological categorization of samples in Central Asia followed by shipment of the samples to LLNL for nuclear forensics analysis.

As noted above, several Central Asia states including Uzbekistan and Kyrgyzstan have already installed radiation portal monitors at principal border crossings and ports of entry to screen for radioactive materials transiting the country. At a recent nuclear security workshop convened by GSEC in Bishkek, Kyrgyzstan in November 2008, U.S. and Central Asian experts recognized the need to apply nuclear forensics capabilities to understand the source and history of radioactive materials that trigger radiation alarms (Smith, 2009). Coupling nuclear forensics to an existing network of radiation alarms provides information on necessary to make an informed response to acts of involving the unauthorized possession or proliferation of nuclear or radioactive materials. To combat illicit trafficking requires technical experts, law enforcement, and border officials in Central Asia to be oriented to elements of a national nuclear forensics capability in concert with cooperation with regional neighbors and the international community.

**Nuclear Forensics Signatures**

Nuclear forensic analysis uses isotopic, chemical, and physical characteristics, otherwise known as "signatures", to provide insight to the origin and history of samples of interest. In Central Asia these nuclear forensic signatures are restricted to the front-end of the nuclear fuel cycle where uranium was mined and milled into a concentrate that contains approximately 75-80% pure uranium oxide for subsequent manufacturing into nuclear fuels. The isotopic, chemical and physical signatures that are exploited in this study are incorporated in the samples by geologic (i.e., natural) processes associated with the formation of the unique ore bodies and provide insight into distinct regional sources that are characterized by variations in the constituent isotopic enrichment and major and trace element chemical composition. In addition, the processing of these ore samples may impart addition signatures due to the introduction of contaminants or fluids that might perturb the trace element or isotopic signatures (e.g., acid leaching). In a related study, nuclear forensic measurements have recently been applied to source Australian uranium ore concentrates (Keegan et al., 2009). The sequence of nuclear forensic analysis and discussion of analytical protocols is contained in Appendix I. In-depth discussion of nuclear forensics signatures and their application to nuclear security studies is provided in other sources and will not be repeated here (International Atomic Energy Agency, 2006; Moody et al., 2005; Smith et al., 2008).

Isotopes

In this study isotopic compositions were measured by digesting the samples with strong acids to completely dissolve and digest the samples. Once the samples are in solution, the uranium is subsequent extracted and purified using an ion exchange resin and measured for uranium isotopic composition on an inductively coupled plasma (ICP) mass spectrometer. The ICP mass spectrometer measures the isotopic abundance of the major uranium isotopes of uranium-234, uranium-235, and uranium-238 with high precision (0.1% or 1 part in 1000). Because the samples from Central Asia reflect are uranium ores that have not been subsequently isotopically enriched for use in a nuclear reactor, only natural variations in these isotopic ratios are expected. The half-life of uranium-235 is $0.704 \times 10^9$ years and the half life of uranium-238 is $4.468 \times 10^9$ years. Because of their long half-lives, the ratio of $^{238}U/^{235}U$ is (relatively) invariant and the isotope ratio fixed in nature is 137.88.

The half-life of uranium-234 is $2.47 \times 10^5$ years. However, there are variations from secular equilibrium (i.e., the isotope ratio based on radioactive decay alone) in the $^{234}U/^{235}U$ ratio in geologic samples relative to the $^{235}U/^{238}U$ ratio due to preferential removal of uranium-234 by radioactive decay, recoil of emitted alpha particles, and resulting damage to the mineral lattice. In the presence of water, the $^{234}U$ becomes concentrated. For this reason the ratio of $^{234}U/^{235}U$ in groundwater may be higher than natural (secular equilibrium or that expected only by radioactive decay) due to the preferential enrichment of uranium-234 in the aqueous medium. Conversely, the abundance of uranium-234 maybe less than natural in minerals exposed to weathering due to the uranium-234 that has been preferentially removed by recoil and subsequent dissolution. These disequilibria allow the $^{235}U/^{234}U$ isotope ratio in the Central Asia to vary the result of unique chemical weathering and water-rock reactions associated with the geologic formation of uranium deposits.

Major and Trace Elements

Major and trace elements constitute the chemical composition of the sample. The chemical composition may reflect those elements that have been incorporated in the samples during their formation as uranium ores or may represent anthropogenic (man-made) inputs introduced during mining and subsequent ore processing. Major and trace elements may differentiate unique sample sources both between individual mines and mills as well as different effluent streams within each.

The major elements are those elements in abundance greater than 0.01 weight percent (or 10,000 parts per million). In geological samples the major elements consist of silica ($SiO_2$), titanium ($TiO_2$), alumina ($Al_2O_{3)}$, iron (FeO), manganese (MnO), magnesium (MgO), calcium (CaO), sodium ($Na_2O$), and potassium ($K_2O$) and determine the bulk composition of a sample. Trace elements are present in much smaller abundance than the major elements are measured in concentration of parts per billion (1 part in a billion or nanogram/gram) or parts per million (1 part in a

million or microgram/gram). Trace elements include the transition elements vanadium (V), chromium (Cr), nickel (Ni), copper (Cu), zinc (Zn), zirconium (Zr), niobium (Nb), and others), halogens (chlorine (Cl) , bromine (Br), and iodine (I), and rare earth elements (including cerium (Ce), neodymium (Nd), samarium (Sm), europium (Eu), gadolinium (Gd) and others). The trace elements are highly sensitive to chemical fractionation associated with the formation of uranium ore bodies; as well they are extremely sensitive tags of anthropogenic processes including contamination and batch mixing.

The major elements and trace elements can be measured either by dissolving the samples in acid and analysis of the dilute solution using inductively coupled plasma mass spectrometry. Sample concentrations are determined relative to instrumental response to calibration standards of like matrix but of varying concentration.

Physical Characteristics

Physical characteristics include the molecular form of the sample (i.e,, silicate verses oxide matrix), grain size, as well as naturally occurring radioactivity (alpha and gamma emitting radionuclides). The physical form of samples in Central Asia is important; because most of the samples originate from mine dumps and tailings piles the samples in this study retain their geologic signature.

## Central Asian Uranium Resources, Geology, and Production History

Large, commercially viable, proven reserves of uranium exist in Central Asia where the material is concentrated in ores (in excess of 1000 parts per million uranium or 0.1%). During the Cold War, Central Asia figured prominently as a source of uranium for both military and civilian applications. The nuclear weapons program of the former Soviet Union would not have been able to produce the substantive arsenal that existed during the height of the Cold war without the supporting infrastructure to process and weaponize nuclear materials. The Soviet military nuclear fuel cycle was started just after the close of World War II, reached its peak in the mid-1980's and went into decline with the demise of the Soviet Union as a state in the early 1990's. Recently however, with increasing demand for energy generated from nuclear power and spot prices for uranium ore concentrate close to $100 USD/pound, a portion of this infrastructure has been recapitalized and placed back in production. If projections for a nuclear renaissance hold, Central Asia is likely to remain an important source of uranium in the 21$^{st}$ century.

Uranium production in the former Soviet Union began in 1945 in Tajikistan and nearby deposits in Kyrgyzstan and Uzbekistan. The uranium used as fuel for the first nuclear weapon detonated by the Soviet Union at Semipalatinsk, Kazakhstan in August 1949 was extracted from mines in northern Tajikistan. Uranium exploration was accelerated in the 1940's and uranium deposits in Central Asia, the Caucasus, and the Ukraine were opened and fully exploited (Podvig, 2001). In the 1950's large deposits of uranium were discovered in Uzbekistan and Kazakhstan through the use

of airborne gamma surveys. Based on these discoveries, large uranium mills were established at the Stepnogorsk and Aktau combines in Kazakhstan and Navoi combine in Uzbekistan. To complement indigenous supplies of uranium, large amounts of uranium were imported to the Soviet Union from East Germany, Czechoslovakia, Bulgaria, and Hungary. The commerce of uranium ores is important for present-day nuclear forensic interpretations in Central Asia; many of the uranium mills in the region (e.g., Kara Balta in Kyrgyzstan and Vostokredmet in Tajikistan) imported and processed ore from many different sources that were mixed and complicate identification of signatures from individual mines.

As part of the nuclear forensic engagement program in Central Asia, LLNL teamed with technical counterparts in Tajikistan and Kyrgyzstan to identify, categorize, sample, ship, and analyze samples from principal uranium mining centers in Kyrgyzstan and Tajikistan. Besides access to samples, the value of peer-to-peer collaboration is critical to understanding the processes and history of uranium mining as well as accessing the best available samples. For this reason, the engagement program included site visits to the principal mines and mills as well as collaboration with experts who were involved in the actual extraction and production of uranium from the 1970's to the 1990's. In the case of Kyrgyzstan and Tajikistan, archived records from the time of the former Soviet Union were used to guide sample selection.

Sampling sites in Kyrgyzstan and Tajikistan included in the present work are listed below.

| **Country** | **Uranium Mines, Mills and Dumps** | **Years of Operation** |
|---|---|---|
| Tajikistan | Karta 1-9 | 1949-1967 |
| Tajikistan | Taboshar Dump I-II | 1945-1959 |
| Tajikistan | Taboshar Dump IV | 1949-1965 |
| Tajikistan | Adrasman | 1944-1955 |
| Kyrgyzstan | Kaji-Say | 1948-1966 |
| Kyrgyzstan | Ming Kush - Taldy Bulak | 1946-1968 |
| Kyrgyzstan | Ming Kush - Kak | 1946-1968 |
| Kyrgyzstan | Ming Kush - Dalnee | 1946-1968 |
| Kyrgyzstan | Ming Kush – Tuuk-Suu | 1946-1968 |
| Kyrgyzstan | Ming Kush - Dumps | 1946-1968 |

Table I. Sampling sites for nuclear forensic analysis in Central Asia.

The legacy from Cold War production of uranium in Central Asia is considerable. Uranium ore mining and milling produces significant amounts of legacy or residual materials. These materials fall into two distinct categories. Radioactive waste from low-grade unusable ores is captured in uranium mine dumps. The solid, liquid, and gaseous radioactive and chemical waste from hydrometallurgical plants involved in

the production of uranium ore concentrate is composited in tailings piles (Sevcik, 2003).

Over 800 million tons of waste from uranium mining and production of radioactive materials is incorporated in tailings and mining waste dumps of both functioning and derelict mines in Kyrgyzstan, Tajikistan, Uzbekistan, and Kazakhstan. Of this amount, 440 million tons or 54% of this residual material is radioactive waste that has been deposited in extensive tailings piles.

The tailings piles are larger than the mine dumps since the piles include uranium sources imported from eastern Germany, Bulgaria, the Czech Republic, and China (United Nations in Kyrgyzstan, 2009). These deposits lack physical protection at their perimeters to restrict access as well as appropriate engineering controls to prevent catastrophic structural failures including landslides. Thin gravel caps cover some tailings piles to prevent airborne resuspension of radioactive dust particulates (Knapp et al., 2002; Buckley et al., 2003; Sevick, 2003). In many cases, due to the Cold War secrecy involving the mining operations, indigenous populations were not aware of the significant environmental legacy posed by the uranium tailings piles and now routinely access these lands to recover scrap metals and recyclable materials to augment their daily subsistence.

There has been considerable attention afforded the regional security implications of uranium mine dumps and mill tailings throughout Central Asia (Sevcik, 2003), and the studies will not be repeated here. A critical component of the program in regional security engagement in Central Asia has been full recognition of the security threat posed by the mine tailings and mine dumps in addition to the serious implications for human health and the environment. Radiological threat awareness and the role of national response capabilities, including nuclear forensics, has been a consistent requirement in engagement with the Central Asian states.

The Fergana Valley hosted most of the sources of uranium known to the Soviet Union in the 1940's in Uzbekistan, Tajikistan, and Kyrgyzstan. In the Fergana Valley uranium is associated with sandstone deposits with bed oxidation zones. The sandstone was deposited by large paleo-channels. Uranium occurs in sandstone and breccia complex deposits that occur in Mesozoic to Cenozoic depressions filled with sediments. The uranium is concentrated in 50m to 600m deep roll-front deposits (oxidation zones) in sandstones and gravels. The uranium is postulated to have formed in the mid-Tertiary and was created up to recent geologic time (Fyodorov, 2001). These depositional conditions are unique and make Fergana Valley uranium deposits distinct from uranium formed by hydrothermal veins.

Uranium Occurrence in Tajikistan

In Tajikistan, the Taboshar deposit of uranium was first mined by the Soviet Union in 1943 where it occurs in a granitic host rock. The Adrasman deposit was first mined in 1944 where it also occurs in granite. These mines produced

approximately 600 metric tons of uranium from the mid-1940's to the mid-1950's before a majority of these deposits were depleted (Organization for Economic Co-Operation and Development, 2001).

Uranium Occurrence in Kyrgyzstan

In Kyrgyzstan, the Mailluu-Suu uranium deposit was discovered in 1942 in early Tertiary (Paleogene) bituminous limestones in the Fergana Valley. Elsewhere in Kyrgyzstan, small uranium deposits were discovered in the Ming Kush basin as well as in uranium bearing coal deposits at Kaji-Say on the south shore of Lake Issyk-Kul. Approximately 10,000 metric tons of uranium was mined in Kyrgyzstan between 1946 and 1967.

Uranium Occurrence in Uzbekistan

In Uzbekistan, uranium production began in 1946 in the Fergana Valley. In Uzbekistan in-situ leaching was first applied in the 1960's to sandstone type uranium deposits that are located along a 400km long by 125km wide belt in the center of the country. According to the IAEA, present-day uranium reserves in Uzbekistan total 185,800 metric tons (Organization for Economic Co-Operation and Development, 2001).

## Sampling of Uranium Ores and Residuals in Central Asia

To date, LLNL has only been able to access samples in Tajikistan and Kyrgyzstan. The State Enterprise Vostokredmet in Tajikistan and the Ministry of Emergency Situations in Kyrgyzstan have jurisdiction over access to uranium samples from production sites. For this reason, as well as their access to historical data on the process history of the extraction and processing of uranium, these entities were critical in identifying and securing samples and supplying related manufacturing information. Criteria for sample selection included those sites open for access, production history, logistics involved in moving heavy equipment required for excavation, and cost for sample retrieval. Appendix II provides a general description of the sampling process and Appendix III contains the analytical data obtained from these samples.

Sampling in Tajikistan

In Tajikistan, uranium mines include those at Taboshar and Adrasman as well as the mill tailings at Karta1-9 from Combine No. 6 (now known as State Enterprise Vostokredmet). As noted above, the mines operated from the 1940's through the 1960's. The Vostokredmet mill was established in 1945 and processed ores from Taboshar and Adrasman as well as ores sourced in Kyrgyzstan and Uzbekistan. For this study, samples were obtained from the Taboshar and Adrasman mines dumps as well as the Karta 1-9 tailing pile (Figure 2). In general, 5 to 10 gram samples were returned from the field for nuclear forensic analysis.


Figure 2. Map of Tajikistan with GSEC sample locations plotted.

*Karta 1-9*: Sampling was completed in August 2006. Five sites on the tailing dump were selected for sampling. The samples consisted of granular sediment 0.1mm to 3 mm in grain size. The sampling at Karta 1-9 was designed to test the acquisition of samples and in particular the techniques required to penetrate the covering cap spread on the tailings pile and gather representative samples. At each sampling site 5 splits were collected individually that were subsequently combined into a single representative sample using a 'cone and quarter' splitting procedure (Robinson et al., 2005; see Appendix II). The depth of the sample collection was 1.5 to 1.8 meters. As collected, the material is composed of both clay and sand. Karta 1-9 field gamma surveys ranged from 280 to 1300 microroentgen / hour. Alpha field activities range from 480 to 3300 counts per second (note: natural background is 1 – 2 counts per second).

The mean value for the natural radionuclide content in soils reported by the United Nations Scientific Committee of the Effects of Atomic Radiation (UNSCEAR) for Kazakhstan is 35 Bq/kg for Ra-226, 60Bq/kg for 232-Th, and 300 Bq/kg for K-40 (United Nations Scientific Committee of the Effects of Atomic Radiation, 2000). Experts from State Enterprise Vostokredmet analyzed the samples taken from uranium processing sites for naturally occurring radionuclides using fixed gamma detectors. Samples of uranium mine dump and tailings materials are enriched in these naturally occurring radionuclides. Ra-226 is enriched by several orders of magnitude.

| Sample | Ra-226, Bq/kg | Th-232, Bq/kg | K-40, Bq/kg |
|---|---|---|---|
| 1 | 2260 | 73.3 | 301 |
| 2 | 3148 | 73.3 | Not measured |
| 3 | 4155 | 81.6 | Not measured |
| 4 | 3148 | 60.9 | Not measured |
| 5 | 2393 | 69.4 | Not measured |

Table II. Naturally occurring radioactivity at the Karta 1-9 sampling site in Tajikistan.

*Taboshar:* Sampling was conducted during August 2006. Two distinct locations were sampled at locales Tailing I-II and Tailing IV. Five samples were collected at Tailing I-II and five samples were collected at Tailing IV. The depth of sampling through the tailings protective cap to these samples is 1.5 to 1.8 meters. The matrix of the Tailing I-II samples consists of "grainy sands" and "moist clays" and tailings IV samples consist of "layers of sand, loam, and clay". Maximum levels of radioactivity from field surveys of gamma-emitting radiation are ~ 2500 microroentgen/hour. The Taboshar samples were also measured by gamma spectroscopy for naturally occurring radionuclides.

| Sample | Ra-226, Bq/kg | Th-232, Bq/kg | K-40, Bq/kg |
|---|---|---|---|
| I-II-1 | 5040 | 115 | 1010 |
| I-II-2 | 27500 | 446 | 595 |
| I-II-3 | 26300 | 410 | 1400 |
| I-II-4 | 26000 | 427 | 1580 |
| I-II-5 | 9210 | 156 | 1250 |
| IV-1 | 1440 | 61.3 | 677 |
| IV-2 | 2840 | 98.1 | 346 |
| IV-3 | 1430 | 63.3 | 694 |
| IV-4 | 1770 | 64.9 | 638 |
| IV-5 | 3130 | 108 | 698 |

Table III. Naturally occurring radioactivity at the Taboshar sampling site in Tajikistan.

*Adrasman*: In April 2007 six samples were collected at the Adrasman tailing dump. Uranium ore bodies at Adrasman are located in a geologically complex granite and tuffaceous terrain consisting of uranium veins, lenses, and "poles". Similar to other locations, five samples were combined from boring and backhoe operations at each sampling station and blended using the envelope procedure to create a representative sample. Sample depths were between 1.1 and 1.6 meters. The samples consisted of "loamy sand with pebbles". Radon-222 concentrations

measured as these samples were collected ranged from 550 to 5000 Bq/m$^3$. Field gamma surveys of the collected samples ranged from ~ 70 to ~ 2000 microroentgen/hour. Gamma spectroscopy for naturally occurring radionuclides results indicate enrichments similar to those for Karta 1-9 and Taboshar with K-40 being uniformly enriched a factor of 3 or 4 above background.

| Sample | Ra-226, Bq/kg | Th-232, Bq/kg | K-40, Bq/kg |
|---|---|---|---|
| A1 | 1310 | 63 | 1130 |
| A2 | 1160 | 54 | 1070 |
| A3 | 1330 | 59 | 1210 |
| A4 | 16900 | 396 | 1360 |
| A5 | 1280 | 66 | 976 |
| A6 | 1830 | 66 | 924 |

Table IV. Naturally occurring radioactivity at the Adrasman sampling site in Tajikistan.

Sampling in Kyrgyzstan

Uranium mining in Kyrgyzstan began in 1943 at Mailuu-Suu in the Fergana Valley. Other mines are located at Ming Kush and Kaji-Say. Uranium milling began in 1955 at the Kara Balta mill located 100km west of Bishkek. Samples for this investigation were collected at Ming Kush and Kaji-Say (Figure 4). The Kara Balta mill went through a change in ownership in 2007 that precluded access to the site. The site is presently being recapitalized and now processes 800 metric tons of uranium a year with plans to expand capacity. In 2009, the Ministry of Emergency Situations provided an option to collect samples from Kara Balta as part of future, follow-on investigations.

*Ming Kush:* In July 2007 samples were collected at Ming Kush from the "Taldy-Bulak', 'Kak', 'Dalnee' and 'Tuuk-Suu' locations as well as from affiliated conglomerate and coal piles. These sites are each located at a distance of 2 to 10 kilometers from Ming-Kush village in mountainous terrain characterized by steep hill slopes and ravines. In total seven samples were collected. Five samples were collected from relatively flat tailing dumps that are buried under an ~ 2.0 m thick protective cap. At each site, the representative samples were obtained using the same envelope splitting procedure employed in Tajikistan; five samples were taken and amalgamated to produce a single sample. Two samples from the coal and conglomerate piles were not excavated but were collected from surface exposures. The samples consist of a mixture of sands and clays; natural levels of radioactivity in these samples range from 1300 to 2200 microroentgen/hour.


Figure 3. Map of Kyrgyzstan with GSEC sample locations plotted (note: Kara Balta uranium mill was visited but not sampled).

*Kaji-Say:* Sampling was conducted in July 2008 at the tailings pond and waste dumps at Kaji-Say. Five locations were sampled; the samples were collected using both a power rotary core drill and a hand auger (see Appendix II for details). The dumps and tailings piles are located in workings situated around a uranium mill located approximately 3 kilometers east from the village of Kaji-Say and approximately 1.5 kilometers south of Lake Issyk-Kul (see Appendix II). The uranium at Kaji-Say was recovered using acid leaching, and the tailings ponds hold the ash-like residue from this recovery. The radioactive "ash" in the ponds is at a depth of 1.7 to 9.8 meters and is buried beneath a nonradioactive protective cap. In general, survey gamma emitting dose rates are near background levels although there are several locations where the protective cap have been compromised and the readings are considerably higher. In other locations, the leachate ash occurs directly on the surface in layers as thick as 2.5 meters. Survey gamma dose rates at these locations may be as higher. The radioactive sample matrix is heterogeneous and consists of wet and clay sands. Other samples were collected at mine dumps adjacent to uranium milling industrial site. Samples here consist of coal fragments as well as carbonaceous shales. One sample was also taken outside the ruins of the Kaji-Say uranium mill.

**Nuclear Forensic Analytical Results**

Major uranium isotope (i.e., $^{234}U$, $^{235}U$, $^{236}U$, $^{238}U$) and analyses of 59 major and trace elements in samples returned form Central Asia reveals the heterogeneous geochemical composition of these materials. The analytical results and accompanying geochemical variation diagrams are contained in Appendix III. All

the samples are consistent with mixed uranium-bearing geologic matrices expected in mine dumps and tailings piles. The X-ray diffraction results confirm the presence of quartz, clays, calc-silicates, and uranium bearing oxides consistent with geologic samples. Uranium concentrations measured in all the samples are lower than the approximately 1000 parts per million threshold characteristic of ore samples. All the samples are enriched in uranium above the 10 parts per million natural background concentration in average soils. While uranium concentrations of several samples approach those of uranium ores, none of the samples exhibit the concentration of uranium found in processed ore concentrates. All the $^{238}U/^{235}U$ isotope ratios are natural (137.88) and display no enrichment in U-235 that would be expected for ores that are being further processed for production of fissile fuels for civilian or military applications.

While the inherent mixing of effluent streams and / or introduction of process contaminants associated with uranium mining and milling complicates nuclear forensics interpretation, isotopic and chemical analysis suggests that unique sources may be discriminated within both Tajikistan and Kyrgyzstan as well as within individual uranium ore mine and mill sites. In particular the alkaline earths (e.g., calcium and barium) are highly enriched at the Karta 1-9 and Taboshar I-V sites. Of interest, these elements also vary between the samples taken at the same uranium mill (e.g., Taboshar I-II and Taboshar I-V in Tajikistan) owing to the introduction of different input streams at a single facility. Trace elements including nickel, cobalt, vanadium, tungsten, and titanium vary systematically as signatures of individual sources of uranium in the region. The 'disequibrium' geochemical behavior of U-234 in these samples tracks individual source locations and inputs. These trends are illustrated in the variation diagrams in Appendix III.

**Next Steps**

Having initiated nuclear forensics regional security engagement in Central Asia, GSEC is well positioned to pursue further technical opportunities the result of engagement in the region. An approach that fosters scientist-to-scientist exchange and the promotion of indigenous technical capabilities builds trust, bolsters nuclear security in emerging Central Asian republics affected by the availability of nuclear materials, and allows access to samples, data, and process knowledge expertise critical to nuclear forensic interpretation. Following are opportunities for future technical engagement that follow from the 2006-2009 investigations in the region described above.

<u>Potential Tajikistan Initiatives</u>

During a site visit to Tajikistan by GSEC personnel in April, 2007, approximately 25 barrels each filled with 380kg of $U_3O_8$ were identified in a barrel (drum) storage room located in the interior of a secured Vostokredmet facility in Chkalovsk. The total amount of $U_3O_8$ is calculated to be approximately 10 metric tons. This uranium concentrate has been removed from water sources near mining and milling

operations using large-scale ion exchange technology and concentrated in barrels in the storage facility.

The Republic of Tajikistan is interested in finding a buyer for this uranium oxide concentrate but has not yet concluded the sale of this material. In partnership with State Enterprise Vostokredmet and the Nuclear Radiation and Safety Agency of Tajikistan, GSEC has made inquiry about access to the uranium ore concentrate for nuclear forensic analysis.

Figure 4. Barrels containing $U_3O_8$ stored at State Enterprise Vostokredmet in Tajikistan. Each barrel has a gross weight of about 400 kg and a net $U_3O_8$ weight of about 380 kg. There are about 25 barrels, which yields a total mass of approximately 10,000 kg of $U_3O_8$.

The Republic of Tajikistan has expressed their interest in collaborative analysis of this archive. According to the Tajik experts, existing analyses that would be augmented by additional trace element and isotopic analysis of the uranium ore concentrate.

Additionally the Nuclear Radiation and Safety Agency of Tajikistan has drafted two NATO partner proposals entitled "Development of Technological Basis for Purification of Uranic Mine and Drainage Waters and Uranium Extraction From Those Waters" and "Search, Detection, and Disposal of Orphan Radioactive Sources with the Purpose of Terrorist Act Prevention". The first proposal relates to uranium extraction using ion exchange from contaminated ground waters. At a pilot scale, experts at Vostokredmet have already demonstrated this technology; it is this

technology responsible for concentrating the $U_3O_8$ at Vostokredmet described above. The second proposal is much more constrained and involves a radiological security workshop on orphaned radioactive sources proposed for December, 2009 in Dushanbe. The Tajiks are presently requesting US national laboratory partners for these proposals.

Potential Kyrgyzstan Initiatives

In March, 2008, during travel to the region, a national laboratory contract scientist visited the Kara Balta Mining and Smelting Combine. The Kara Balta site is presently active and produces yellow-cake from sources in Central Asia and elsewhere. Kara Balta is the largest uranium ore processing plant in central Asia and operated during Soviet times processing ore from Kyrgyzstan and Kazakhstan. Up to 450 MT of $U_3O_8$ was produced from ore concentrate in the mid-1990's. In February 2007 the UralPlatina Holding Company bought the plant from the state and invested $25 to $30 million USD in upgrades with the objective of recovering uranium, molybdenum, gold, and tungsten from the 50 million ton of tailings piles adjacent to the plant. Gold is present in some samples at concentrations of 0.05 weight percent (or 500 parts per million). There is also a plan to recover uranium from the tailings on-site. Plant managers provided a tour of the enormous spoils contained in adjacent tailings piles. These tailings piles cover more than 530,000 hectares.

Subsequently in November, 2008 GSEC managers and a national laboratory contract scientist met with the Deputy Minister of the Ministry of Emergency Situations of the Kyrgyz Republic during travel to Bishkek. The GSEC and national laboratory representatives explored whether access to samples could be arranged at the Kara Balta Combine. The deputy minister was open to sampling and provided contacts and a path forward with the Ministry of Emergency Situations to explore obtaining samples of mutual interest from Kara Balta in 2009. Samples would be provided for nuclear forensic analysis similar to other sites in Kyrgyzstan. A final decision on this proposal is still pending. Potential sampling at Kara Balta provides access to one of the largest active uranium processors in Central Asia.

Potential Uzbekistan Initiatives

GSEC is now expanding nuclear forensics engagement to include Uzbekistan that also has a long history of providing uranium in support of the nuclear weapons program of the former Soviet Union and now produces uranium for civilian nuclear energy markets. Technical collaboration with the Institute of Nuclear Physics (INP) in Tashkent is a priority since the INP has resident scientific expertise and capabilities (including fixed and mobile radiological laboratories) that are ideally suited to nuclear forensic analysis. Of all the Central Asian republics involved to-date, Uzbekistan has the best technical understanding of nuclear forensic capabilities that can be applied deter nuclear terrorism and proliferation.

Uzbekistan featured prominently in the supply of uranium to the atomic weapons enterprise of the former Soviet Union. In-situ leaching sites in the Navoi region of Uzbekistan continue to produce uranium ore concentrate. Navoi is southwest of the city of Tashkent and was first exploited for uranium in the early 1960's. This area was formerly a 'closed city' during Soviet times. Three sites (Uchkuduk, Zafarabad, and Nurabad) are administered by the Navoi Mining and Metallurgy Combine and produce approximately 7% of the world's output of uranium or 2,350 metric tons of uranium ore concentrate per year. Uranium production peaked in the 1980's when production was 3,800 metric tons of $U_3O_8$ per year. Prior to 1992 uranium ore concentrate shipments went exclusively to Russia and after that time shipments went to western markets including the United States.


Figure 5. Map of Uzbekistan with Navoi region plotted that is the site of in-situ leaching of uranium ore concentrate.

Uzbekistan is vulnerable to illicit trafficking of radiological contraband due to its shared borders with Afghanistan to the southeast and Central Asian republics to the north and east. A program in nuclear forensics – in the words of the Uzbekistan experts – would complement their existing efforts in radiation detection portal monitoring and 'primary analysis' (i.e., categorization using portable NaI detectors) by providing more 'detailed analysis' (i.e., nuclear forensic characterization for isotopic, chemical, and physical signatures).

During a visit to INP in April, 2009 by GSEC managers and a national laboratory contract scientist provisionally agreed on elements of a five point program to initiate nuclear forensics engagement in Uzbekistan:

1) Exchange of nuclear forensic analytical techniques between Lawrence Livermore National Laboratory and INP to enhance technical capabilities

Lawrence Livermore National Laboratory will provide descriptions of analytical methodologies used for nuclear forensic analysis of uranium ores, uranium ore concentrates, and residual materials to INP. Techniques may include, but are not limited to, x-ray diffraction, optical and electron microscopy, and mass spectrometry. The INP will provide a similar list as well as written descriptions of analytical methods relative to symmetrical capabilities that exist in Uzbekistan.

2) Pursuit of comparative bilateral nuclear forensic analysis using a common sample exchanged between LLNL and INP

INP and LLNL will jointly select a representative sample of uranium ore or ore concentrate in common that will be analyzed for isotopic, chemical, and/or physical forensic signatures at both institutions. Similarities and discrepancies will be adjudicated through peer-review.

3) Collaboration with Uzbek scientific experts at their radiological laboratory to develop standard operating procedures in nuclear forensics

At the GSEC sponsored All-Central Asia Nuclear Safety Workshop held in Bishkek in November 2008, experts from Uzbekistan requested technical assistance in developing written standard operation procedures (SOP) for nuclear forensics. LLNL will provide input and peer-review leading to written standard operating procedures for the existing INP radiological laboratory. In order to develop the SOPs, LLNL will need access to experts and laboratories affiliated with the radiological facility. Once the SOPs are written, LLNL will revisit the laboratory to assist in their implementation.

4) Evaluation of access to samples of uranium ore and uranium ore concentrate in Uzbekistan for nuclear forensic analysis

Consistent with on-going regional work in Tajikistan and Kyrgyzstan, GSEC and national laboratory contract scientists will collaborate with experts from INP to identify 5 to 10 samples of representative uranium ore or ore concentrate with the highest promise for nuclear forensic analysis, both at LLNL and INP. Once identified, analytical plans can be devised and the samples fully documented relative to their provenance and process history.

5) Plan and technical feeds to increase public awareness in Uzbekistan to nuclear threats and hazards outside of administrative control

Awareness, orientation, and education regarding the threats from nuclear and radioactive materials promotes nuclear security objectives through prevention and improved response. Enhanced awareness enables the public and responders to fully protect the human health and the environment, as well as to gather complete forensic evidence from interdicted samples. LLNL will work with INP to assess the existing state of awareness as well as needs to augment the knowledge baseline through development of technical modules relating to radiation science, nuclear forensics, and/or national response.

Potential Kazakhstan Initiatives

Kazakhstan produced 6637 metric tons of $U_3O_8$ in 2006 and is presently the third largest producer of uranium ore concentrate in the world. Kazakhstan has a stated goal of becoming the world's largest producer of uranium ore concentrate by 2015. In addition, Kazakhstan is currently a large provider of commercial nuclear fuel pellets to international markets. Potential future engagement between GSEC and Kazakhstan involves signature development tasks as part of a continuing collaboration with KazAtomProm, the National Atomic Company of Kazakhstan. Technical collaboration will involve the ULBA Metallurgical Plant and their Institute for High Technology (IHT). The goal of continuing collaboration is to acquire high quality uranium materials beyond a set of uranium ore concentrates collected under agreement with KazAtomProm in 2006. Support for continued collaboration could accelerate access to high quality samples from various sources and significantly enhance a national nuclear forensic database. Furthermore, technical cooperation with ULBA allows GSEC to obtain process knowledge of the production of LEU fuel pellets and uranium ore concentrates traded internationally.

Future work in Kazakhstan focuses on promoting nuclear forensic best practice through development of morphological signatures of uranium nuclear fuel pellets and nuclear forensic analysis (using trace elements and uranium isotopes) of previously collected uranium ore concentrate to identify individual mines and processing sites. Cooperation with the Kazakhstan Atomic Energy Committee will also advance the development a national response plan to combat illicit nuclear trafficking based on nuclear forensics analysis and data exchanges and assist Kazakhstan in meeting its UNSCR 1540 obligation to address proliferation prevention.

## Recommendations

The GSEC has successfully utilized nuclear forensics as a means for regional security engagement in Tajikistan and Kyrgyzstan. Through regular presence in the region from 2006 to the present, GSEC successfully oriented regional partners to a nuclear forensics capability applied to counter the nuclear nonproliferation and counter-terrorism threat in Central Asia. The regional partners now apply nuclear forensics, when warranted, to suspect samples encountered outside of administrative control as well as have contacts to international expertise in the nuclear forensics discipline.

The most comprehensive reading of the nuclear security posture in Tajikistan, Kyrgyzstan, and Uzbekistan comes from country reports and technical discussions at the "All-Central Asia Nuclear Safety Workshop" held in Bishkek, Kyrgyzstan in November, 2008 and sponsored by GSEC (Smith, 2009). The workshop concluded that all governments in Central Asia recognize the global threat of radiological terrorism. This threat demands transboundary cooperation. Central Asia is a region of transit that is vulnerable to terrorist activities where local incidents involving authorized possession of nuclear or radiological materials can escalate quickly. Protecting human health and the environment from the almost 100 million tons of uranium mine tailings in Central Asia residual from the nuclear weapons enterprise of the former Soviet Union represents the priority challenge. All governments in the region are attracted to uranium legacy concerns. Cooperation and trust established through work on environmental issues builds a framework that can be used in time of emergency involving trafficking and proliferation of nuclear materials. Affected populations are not aware of the principles of radiation science nor security and safety threats associated with legacy production of uranium in Central Asia; there is real need for improved public awareness of the threats associated with this uranium legacy. In addition to credible outreach, there is the great need for next generation of experts trained in nuclear science that can address substantive security problems. The ability to respond to acts involving the unauthorized movement of radioactive materials by Kyrgyzstan, Tajikistan, and Uzbekistan has improved over the past four years. Responders are being trained and some capabilities now exist to respond to these threats. To better secure radiological materials, national registries of radioactive sources have been established. There is recognition of the importance of utilizing national response plans to respond to acts of illicit trafficking and proliferation. Nuclear forensics is a component of a comprehensive national response plan to address threats from nuclear proliferation and trafficking.

After the break-up of the former Soviet Union, there continues to be widespread disruption of basic infrastructure in Tajikistan and Kyrgyzstan including supplies of electricity, water supply, heat, and reliable means of communication by telephone and internet. Despite these challenges the Central Asian were consistent GSEC partners. Two developments are noteworthy. Uranium samples were successfully located and shipped to the United States for nuclear forensics analysis from sites in Tajikistan and Kyrgyzstan. These samples are derived from principal production areas for the atomic weapons enterprise of the former Soviet Union. Together with Kazakhstan, these two countries have distinguished themselves by providing nuclear forensic samples to the United States. Cooperation with other international forensic partners has often been more complicated without yielding the same results.

While collected for the purpose of nuclear forensic engagement, the uranium samples from Tajikistan and Kyrgyzstan were taken at heterogeneous mine dumps and tailing piles complicating subsequent nuclear forensic interpretation due to the inability to unequivocally trace these materials back to a unique source. As such,

these samples are of 'lower priority' as comparators. Throughout the 2006 to 2009 effort, there was a constant focus by the regional partners on the substantive environmental legacy and threats to human health and the environment from the production of uranium by the former Soviet Union throughout Central Asia. Only through continuing outreach on the nuclear security topic including the GSEC "All-Central Asia Nuclear Safety Workshop" held in Bishkek, Kyrgyzstan in November, 2008 were needs for nuclear forensics best practice elevated. Continued outreach and engagement is required to perpetuate nuclear security awareness.

The existing program is well positioned to pursue additional high value nuclear forensic work in the region should that is consistent with GSEC's nonproliferation objectives. Uzbekistan's Institute of Nuclear Physics is a mature and well-equipped scientific center that already is well oriented to nuclear forensics. The Uzbeks understand the utility of a well pedigreed nuclear forensic database that allows interdicted samples to be compared with unknowns enabling attribution and determination – or exclusion – of source. During the spring GSEC 2009 visit to Tashkent, INP stated that their republic law enforcement authorities already engage in nuclear forensics case work investigations. INP has been involved in analysis of purported "red mercury", $^{187}$Os, and other materials comprising common nuclear contraband scams. The opportunity to collect high quality uranium ore concentrate samples from the Navoi Mining and Metallurgy Combine is also compelling. Uzbekistan currently produces approximately 7% of the world's output of uranium or 2,350 metric tons of uranium ore concentrate per year.

Similar rational be can be applied to potential future nuclear forensic engagement with Kazakhstan. The civilian nuclear energy complex in Kazakhstan is large and supplies materials to global markets. Initial contracts have already been established with Kazatomprom for access to uranium ores, uranium ore concentrates, and nuclear fuels. The Institute of High Technology is well equipped for collaborative nuclear forensic studies. Nuclear forensics is also a piece of an emerging national response plan being developed by the Kazakhstan Atomic Energy Committee to address illicit trafficking involving a close partnership with the USG.

Finally, the opportunity to potentially access high purity uranium ore concentrate samples for nuclear forensic analysis from 10 metric tons secured at the State Enterprise Vostokredemet facility in Tajikistan potentially yields data important to nuclear forensic databases developed for the region. This opportunity offers key data for a likely modest investment of programmatic funding. Should further engagement with Tajikistan be a priority for GSEC, both State Enterprise Vostokredemet and the Nuclear Radiation and Safety Agency of Tajikistan are positioned to provide these samples and have indicated their support for a joint nuclear forensics investigation.

**Acknowledgements**

A program of regional security engagement in Central Asia is the result of the dedication of sponsors in the National Nuclear Security Administration (NNSA), Nuclear Nonproliferation and International Security (NA-24), Office of Global Security Engagement and Cooperation (NA-242), scientists and managers of the Global Security Principal Directorate at Lawrence Livermore National Laboratory, and regional partners in Central Asia.

At NNSA and GSEC, Christina Andersson, Anne Phillips, Joy Patrick, and Lauren Lafaro all managed aspects of this work over the past years and were unyielding in their recognition of strong regional partnerships that rely upon technical engagement. Their direction defined the program. At the Lawrence Livermore National Laboratory, Richard Knapp established an institutional presence in Central Asia in the late 1990's and this work would not have been possible without his path-finding and early credibility with our Central Asian partners. Michael Kristo, David Herr, Timothy Horgan, Gerald Kiernan, and Rachel Lindvall were important scientific collaborators both in the analytical laboratory as well as in the development of complex task orders necessary to execute this work in the region. Justin Reed provided valuable critiques of the final report. Over the years, Margie Altenbach and Karen Roland executed all the complex logistics and foreign travel arrangements required to sustain a lasting engagement program in Central Asia. Eileen Vergino continues to serve as strong liaison with GSEC.

In Central Asia, there are too many scientists to thank individually for their selfless contributions. However, several deserve mention for their long-standing partnership with Lawrence Livermore National Laboratory. In Tajkistan, Muzafar Yunusov and Leonid Pavlyuk of State Enterprise Vostokredment and Ilkhom Mirsaidov of the Nuclear Radiation and Safety Agency are superb senior scientists and proud technical representatives of their country. In Kyrgyzstan, the talent and enthusiasm of Amanbai Sarnagoev, Emilbek Toichubekov, and Nataliya Spectorenko from the Ministry of Emergency Situations were essential to meeting program objectives. In Uzbekistan, Vitali Petrenko, Anvar Avezov, and Bekhzod Yuldashev from the Institute of Nuclear Physics and the Uzbekistan Academy of Sciences embraced the science to further the nuclear security posture throughout the region. These personal relationships underscore the necessity of engagement as a key component of an effective nuclear security program in Central Asia.

## References

American Physical Society / American Association for the Advancement of Science Joint Working Group, 2008, Nuclear Forensics – Role, State of the Art, and Program Needs, 54 p.

Buckley, P.B., J. Ranville, B.D. Honeyman, D.K. Smith, N. Rosenberg, R.B. Knapp, 2003, Progress Toward Remediation of Uranium Tailings in Mailuu-Suu, Kyrgyzstan, Lawrence Livermore National Laboratory, UCRL-JC-153644, 7p.

Chivers, D.H., B.F. Lyles, B.H. Isselhardt, and J.S. Snider, 2008, Before the Day After: Using Pre-detonation Nuclear Forensics to Improve Fissile Material Security, Arms Control Today, v. 38, n. 6, p. 22-28.

Dreicer, M., I.D. Hutcheon, M.J. Kristo, D.K. Smith, E.S. Vergino, and R.W. Williams, 2009, International Nuclear Forensics Cooperation – Future Opportunities, Lawrence Livermore National Laboratory, LLNL-CONF-413601, 8p.

Dunlop, W. and H. Smith, 2006, Who Did It? Using International Forensics to Detect and Deter Nuclear Terrorism, Arms Control Today, v. 36, n. 8.

Fyodorov, G.V., 2001, Industrial Types of Uranium Deposits in Kazakhstan, in Assessment of Uranium Deposit Types and Resources – a Worldwide Perspective, International Atomic Energy Agency, IAEA-TECDOC-1258, 253p.

International Science and Technology Center, 2007, "International Workshop Coordinating Efforts to Combat the Illicit Trafficking of Nuclear and Other Radioactive Materials in Central Asia", Dushanbe, Tajikistan 7-9 November 2007.

International Atomic Energy Agency, 2006, "Nuclear Forensics Support", Nuclear Security Series No. 2, 67p.

Keegan, E., Z. Varga, M. Wallenius, K. Mayer, G. Rasmussen, 2009, Nuclear Forensic Signatures in Uranium Ore Concentrates, Proceedings of the Institute of Materials Management (INMM) 50th Annual Meeting, www.inmm.org.

Knapp, R.B., J.H. Richardson, N. Rosenberg, D.K. Smith, A.F.B. Tompson, A. Sarnogoev, B. Duisebayev, D. Janeck, 2002, Radioactive Tailings Issues in Kyrgyzstan and Kazakhstan, Lawrence Livermore National Laboratory, UCRL-JC-144915, 9p.

Kozak, G., 2006, "Illicit Nuclear Trafficking" Thesis, The International University, Vienna, 29p.

Moody, K.J., I.D. Hutcheon, and P.M. Grant, 2005, Nuclear Forensics Analysis, CRC Press, Taylor and Francis Group, 485p.

Niemeyer, S., and D.K. Smith, 2007, Following the Clues: the Role of Forensics in Preventing Nuclear Terrorism, Arms Control Today, v. 37, n. 6, p. 14-15.

Nuclear Threat Initiative, 2009, "Central Asian Nations to Reduce "Dirty Bomb" Threat", Tuesday, June 30, http://gsn.nti.org/

Organization for Economic Co-Operation and Development (OECD) Nuclear Energy Agency and the International Atomic Energy Agency (IAEA), 2001, Uranium 2001: Resources, Production, and Demand, 348p.

Petrenko, V.D., B.S. Yuldashev, U. Ismailov, N.N. Shiplov, A.D. Avezov, 2008, Using Radiation Monitors to Prevent Illicit Nuclear Trafficking, Illicit Nuclear Trafficking: Collective Experience and the Way Forward, Edinburgh, 19-22 November 2007, International Atomic Energy Agency, p. 753-761.

Podvig, P. (ed.), 2001, Russian Strategic Nuclear Forces, MIT Press, Cambridge, Massachusetts, 692p.

Radio Free Europe, 2008, "Kyrgyzstan: IAEA Seeks Answers to Radioactive Seizure", Wednesday, January 16, http://www.frerl.org/

Robinson, J.W., E.M. Skelly-Frame, and G.M. Frame, 2005, Undergraduate Instrumental Analysis, Sixth Edition, Marcel Dekker, 1051p.

Sevcik, M., 2003, Uranium Tailings in Kyrgyzstan: Catalyst for Cooperation and Confidence Building?, The Nonproliferation Review, Spring 2003, p. 147 – 154.

Smith, D.K., M.J. Kristo, S. Niemeyer, G.B. Dudder, 2008, Documentation of a model action plan to deter illicit nuclear trafficking, Jour. Radioanalytical and Nuclear Chemistry, v. 276, no. 2, p. 415-419.

Smith, D.K., 2009, "Report on the 2008 All-Central Asia Nuclear Safety Workshop, November 12-14, 2008, Bishkek, Kyrgyzstan" Lawrence Livermore National Laboratory, unpublished Foreign Trip Report, 19p.

United Nations in Kyrgyzstan, 2009, "The High-Level International Forum 'Uranium Tailings: Local Problems, Regional Consequences, Global Solution' took place in Geneva on 29 June 2009", http://un.org.kg/

United Nations Scientific Committee of the Effects of Atomic Radiation (2000) UNSCEAR 2000 Report to the United Nations General Assembly, with scientific annexes.

## Appendix I
## Nuclear Forensic Analysis of Central Asia Uranium Silicates and Oxides at Lawrence Livermore National Laboratory

### Conduct of Analysis

The goal of nuclear forensics analysis is to link nuclear and radiological materials to people, places, and events. As nuclear and radiological material is produced and transferred, it often incorporates isotopes as well as geological contaminants that may be exploited by nuclear forensic analysis. Nuclear forensics interpretation – and the resulting attribution - requires the ability to either compare or predict isotopic, chemical, or other physical signatures from nuclear or radioactive materials relative to signatures that are indicative of the process origin of these materials.

Analytical protocols for samples of uranium ore, ore dumps, ore concentrates, and ore tailings return data on the physical characteristics of the sample including the mineralogy or molecular form, trace element impurities at levels of a part per million or less, and isotope ratios of uranium including ratios of $^{235}U/^{234}U$ and $^{238}U/^{235}U$.

The distribution of these isotopes and elements is related to physical, chemical, and environmental properties that vary systematically across the earth's continents. Assuming the signatures are transferred from the geology to the samples, the regular variation in isotopic and chemical composition in a sample can provide information that enables geolocation. As well, processes associated with manufacturing of nuclear fuels may also perturb isotopic and chemical compositions.

The mineralogy identifies whether the matrix is geologic or anthropogenic as well as whether it is a pure phase or a mixture. The color, trace elements and isotope ratios will reflect heterogeneities imparted by the geochemical origin of the sample or by subsequent industrial processing. Together these signatures allow for discrimination of samples as well as provide information on their origin or subsequent processing history.

The sequence of nuclear forensic analysis dictates that a destructive test – which consumes the sample – follows a nondestructive test. In general the sample is first categorized for it physical attributes, analyzed for molecular form by x-ray diffraction, and then chemical purified for analysis of trace elements or uranium isotopes. The exact sequence is contingent on the size of the sample, its constituent radioactivity, and collateral information on the sample's origin and/or history.

## X-Ray Diffraction

Uranium ore, ore concentrate, and residual materials are analyzed by x-ray diffraction (XRD) spectrometry using Cu $K_\alpha$ radiation and Bragg-Brentano focusing via a Scintag PADV diffractometer. Incident beam divergence and scatter slits are 1 and 2 degrees, respectively, while detector scatter and registration slits are 0.3 and 0.2 mm, respectively. The x-ray tube is operated at 45kV and 35mA, and specimens are scanned from $2\Theta$ = 10 - 90° in 0.02° steps, with integration times of 2 - 3 seconds per step.

## Mass Spectrometry

Aliquots of the samples analyzed by mass spectrometry (MS) are dissolved in nitric acid in sealed Teflon PFA vials on a hotplate. The digestions are done in a clean-room. The solutions are analyzed for U isotopes ($^{234}U$, $^{235}U$, $^{236}U$, and $^{238}U$) using a GV IsoProbe multi-collector ICP-MS (MC-ICPMS), and for trace-element abundances with a Thermo-X7 quadrupole ICP-MS. The U isotope data are collected using the conventional sample-standard bracketing technique. NIST U500 and SRM-948 are used as primary standards, and NIST U900 is used for QC validation. Trace-element concentrations are measured in these same aliquots by external calibration against standard solutions. Error estimates are based on statistics of individual analyses and results from matrix-matched uranium trace element studies. The 1-sigma error of the trace element analysis (including sample preparation and instrumental error) is less than 20%.

## Appendix II
## Sampling at Central Asian Uranium Mine Dumps and Tailings Piles

Sampling of uranium ores, ore dumps and tailings in Central Asia was conducted by experts from State Enterprise Vostokredmet in Tajikistan and from the Ministry of Emergency Situations in Kyrgyzstan in consultation with a Lawrence Livermore National Laboratory scientist who visited many, but not all, of the sampling sites. The ability to work with regional experts cannot be understated; the regional experts have process knowledge of the history of uranium production at the sampling sites that is essential to identifying optimal sampling sites. As well, the regional experts are uniquely positioned to secure permissions for site access at active and defunct sites that are contaminated to collect samples.

Sampling involved visiting uranium mine dumps and tailing piles and breaching protective radiation caps approximately one meter thick with a backhoe or auger to access samples of interest at each sampling station. Handheld alpha and gamma radiation meters were used to categorize samples to protect workers and categorize the samples. Several loose sediment samples were collected at each sampling station and were combined to form a representative sample using the 'cone and quarter" technique (Robinson et al., 2005).

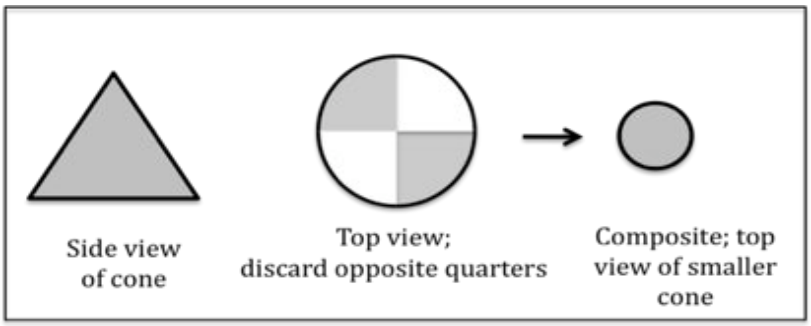
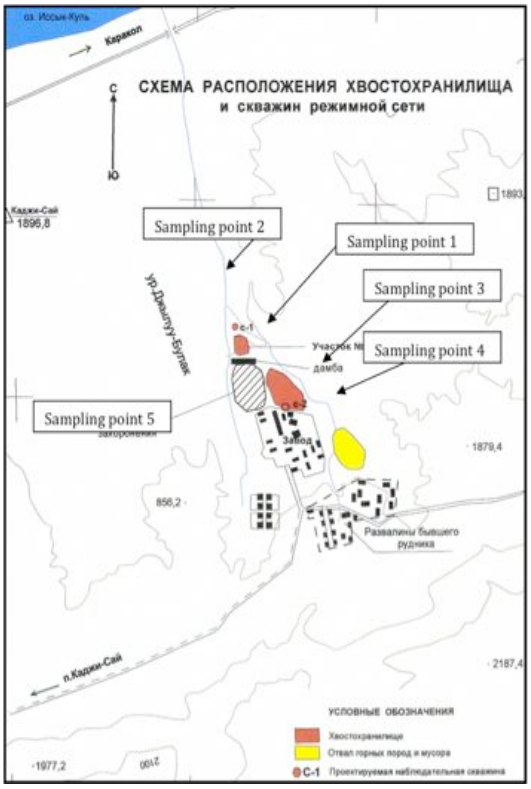



Figure 6. "Cone and quarter" sample splitting technique for loose sediments used to produce representative samples from Central Asian uranium ore dumps and tailings.

Samples were returned to the institutes where 10 gram aliquots from each station were prepared for international air freight shipment to Lawrence Livermore National Laboratory. An illustration of sampling stations from the Kaji-Say uranium mine and mill in Kyrgyzstan follows.




Sampling stations at the Kaji-Say uranium mine and mill in Kyrgyzstan


Details of sampling station 5 near Kaji-Say uranium mill plant

Using power auger drill to excavate surficial containment cap for sampling at Kaji-Say

Using hollow sampling tube to collect samples from open excavation

Recovery of uranium sediments on plastic sheets from sampling tube at Kaji Say prior to sample splitting

## Appendix III
## Central Asia Nuclear Forensic Data Tables and Geochemical Variation Diagrams

Mineralogical Signatures

The samples are a mixture of clays and sands (grain size is approximately 0.1mm to 3 mm). X-ray diffraction was used to determine the mineralogy of the samples. The results from samples collected at the Kaji-Say mine and mill indicate the samples are comprise quartz, calcium-alumina silicates, clays, micas, and uranium oxides.

| Material | Phases |
|---|---|
| SOIL | Quartz, clay, calc-aluminum silicates, aluminum silicates, and iron oxides |
| SOIL | Quartz, calc-aluminum silicates, minor uranium oxides, and possibly other metals |
| SOIL | Quartz, clay, mica |
| SOIL | Quartz, clay, mica, birnessite (Na-Mn oxide) |
| SOIL | Quartz, clay, mica, birnessite, small amount of uranium bearing oxides |

Table V. X-ray diffraction results for samples from Kaji-Say, Kyrgyzstan.

The radiation profile of these samples has been described above in the description of sampling locations in Tajikistan and Kyrgyzstan. The samples contain naturally occurring radionuclides including $^{226}$Ra, $^{232}$Th, and $^{40}$K that are measurably above background (to 25,000 Bq/kg for $^{226}$Ra relative to a background level of 35 Bq/kg).

Nuclear Forensic Uranium Isotope and Elemental Signatures

Isotopic measurements of $^{238}U/^{235}U$ and $^{235}U/^{234}U$ and 59 major and trace elements (reported as parts per million or micrograms per gram) are provided in the following tables. The samples are tabulated by sampling location (i.e., Karta 1-9, Taboshar I-II, Taboshar I-V, Adrasman in Tajkistan and Kaji-Say and Ming Kush in Kyrgyzstan). Due to constraints in the analytical laboratory, for a few samples, not all analytes were measured. Where analytes were not measured they are so designated in the tables. Samples measured below detection limits are also identified.

Variation diagrams plotting uranium and calcium concentrations by sample, uranium isotopes by sample, and cobalt and nickel plotted against each other are also included, with explanatory captions, after the data tables.

Table VI. Uranium isotope and 59 major and trace elements measured in 33 samples collected from Tajikistan and Kyrgyzstan

| | Karta 1-9 1 | Karta 1-9 2 | Karta 1-9 3 | Karta 1-9 4 | Karta 1-9 5 |
|---|---|---|---|---|---|
| U-238/U-235 | 137.28 | 136.49 | 136.42 | 136.61 | 136.85 |
| U-235/U-234 | 120.48 | 133.69 | 123.76 | 125.47 | 123.46 |
| Be | 3.9 | < 3.9 | < 2.1 | 3.6 | < 2.4 |
| Na | 17000 | 10500 | 7510 | 16100 | 8500 |
| Mg | 6440 | 10300 | 6840 | 8560 | 12900 |
| Al | 65900 | 59300 | 30800 | 58700 | 48800 |
| K | 34300 | 25100 | 11900 | 24600 | 17200 |
| Ca | 39800 | 63000 | 60000 | 74300 | 122000 |
| Ti | 1960 | 2580 | 1260 | 1896 | 2130 |
| V | 50.5 | 70.1 | 64 | 84 | 60.6 |
| Cr | 471 | 83.6 | 88 | 53.1 | 116 |
| Mn | 3410 | 2038 | 2570 | 10350 | 1380 |
| Fe | 31900 | 43700 | 31800 | 32300 | 29400 |
| Co | 12.47 | 22.2 | 11.5 | 14.5 | 12.6 |
| Ni | 26.2 | 46.6 | 27.9 | 36.1 | 30 |
| Cu | 297 | 388 | 184 | 317 | 285 |
| Zn | 502 | 592 | 251 | 452 | 371 |
| Ga | 131.2 | 181 | 73.5 | 112 | 127 |
| Ge | 2.8 | 2.5 | < 1.5 | 2.1 | < 2.1 |
| Rb | 158.9 | 126.5 | 57.2 | 132.9 | 83 |
| As | NM | NM | NM | NM | NM |
| Sr | 201 | 237 | 171.3 | 237 | 280 |
| Y | 18.4 | 18.1 | 13.19 | 20.5 | 15.6 |
| Zr | 114 | 104 | 56.6 | 96 | 57.5 |
| Nb | < 2.1 | < 0.9 | < 0.9 | < 1.5 | < 1.2 |
| Mo | 40 | 111 | 84.4 | 80 | 44 |
| Ru | < 0.27 | < 0.15 | < 0.33 | < 0.21 | < 0.15 |
| Rh | 0.65 | 0.53 | 0.53 | 0.34 | 0.29 |
| Pd | 0.75 | 0.69 | 0.52 | 0.74 | < 0.6 |
| Ag | 4.7 | 18 | 4.5 | 16 | 4.7 |
| Cd | 4 | 5.6 | < 2.1 | 3.5 | 3.2 |
| Sn | 5.7 | 4.4 | 3 | 5.1 | 1.34 |
| Sb | 22.2 | 22.6 | 11.8 | 18 | 15.1 |
| Te | < 6 | < 6 | < 2.1 | < 2.7 | < 1.8 |
| Cs | 6.32 | 8 | 3.01 | 5.2 | 4.6 |
| Ba | 2740 | 3870 | 1530 | 2300 | 2690 |
| La | 29 | 28.7 | 19.9 | 28.1 | 23.7 |
| Ce | 56.7 | 57 | 40.1 | 56 | 46.2 |
| Pr | 5.93 | 6.06 | 4.38 | 5.99 | 5.18 |
| Nd | 21.28 | 22.6 | 16.3 | 21.4 | 18.9 |
| Sm | 4.1 | 4.34 | 3.3 | 4.2 | 3.58 |
| Eu | 0.91 | 1.24 | 0.68 | 0.87 | 0.99 |
| Gd | 3.9 | 4.5 | 3.1 | 4.2 | 3.5 |
| Tb | 0.59 | 0.58 | 0.44 | 0.61 | 0.49 |
| Dy | 3.09 | 3.2 | 2.42 | 3.35 | 2.6 |
| Ho | 0.69 | 0.63 | 0.46 | 0.7 | 0.51 |
| Er | 2.1 | 1.86 | 1.4 | 2.21 | 1.6 |
| Tm | 0.37 | 0.25 | 0.2 | 0.33 | 0.232 |
| Yb | 2.2 | 1.72 | 1.34 | 2.17 | 1.5 |
| Lu | 0.34 | 0.26 | 0.19 | 0.32 | 0.221 |

| | | | | | |
|---|---|---|---|---|---|
| **Hf** | < 2.1 | < 0.6 | < 0.45 | < 1.2 | < 0.42 |
| **Ta** | < 3.6 | < 1.2 | < 0.42 | < 0.36 | < 0.6 |
| **W** | 3 | 7 | < 1.8 | 4.5 | < 0.6 |
| **Re** | < 0.09 | < 0.051 | < 0.09 | < 0.09 | < 0.06 |
| **Ir** | 1.4 | 1.02 | 0.67 | 0.45 | < 0.36 |
| **Pt** | < 0.27 | < 0.24 | < 0.24 | < 0.12 | < 0.09 |
| **Au** | < 1.2 | < 0.9 | < 0.9 | < 0.57 | < 0.51 |
| **Tl** | 2.07 | 1.65 | 1.11 | 1.86 | 1.16 |
| **Pb** | 955 | 900 | 644 | 1180 | 673 |
| **Th** | 13.2 | 11.94 | 8.18 | 13.7 | 7.9 |
| **U** | 98.3 | 954 | 241 | 327 | 119 |

Measurement errors for analysis of uranium isotopes and major and trace elements are described in Appendix I. All elements reported as parts per million (microgram/gram). NM = not measured. "<" denotes detection limit.

| | Taboshar I-II-1 | Taboshar I-II-2 | Taboshar I-II-3 | Taboshar I-II-4 | Taboshar I-II-5 |
|---|---|---|---|---|---|
| **U-238/U-235** | 136.63 | 137.13 | 136.92 | 136.75 | 137.45 |
| **U-235/U-234** | 117.65 | 116.96 | 113.64 | 114.29 | 114.94 |
| **Be** | 2.9 | 7.1 | 6.4 | 6 | 3 |
| **Na** | 17700 | 12400 | 9800 | 10570 | 10870 |
| **Mg** | 2136 | 7600 | 7230 | 6470 | 3200 |
| **Al** | 69400 | 96000 | 97000 | 86000 | 65200 |
| **K** | 38800 | 42200 | 43400 | 40500 | 35700 |
| **Ca** | 5850 | 40400 | 39000 | 27900 | 8570 |
| **Ti** | 1350 | 2020 | 1840 | 1780 | 1327 |
| **V** | 12.4 | 39 | 38.2 | 34.2 | 21.4 |
| **Cr** | 15.5 | 50.6 | 48.5 | 31.9 | 14.1 |
| **Mn** | 592 | 3560 | 3490 | 2870 | 1460 |
| **Fe** | 15300 | 62800 | 64100 | 52800 | 32100 |
| **Co** | 5.44 | 35.1 | 36 | 27.5 | 10.4 |
| **Ni** | 4 | 27.4 | 34.4 | 20.7 | 6.9 |
| **Cu** | 179 | 400 | 422 | 317 | 298 |
| **Zn** | 515 | 1240 | 1161 | 924 | 640 |
| **Ga** | 75 | 106 | 82.7 | 101 | 74.2 |
| **Ge** | < 1.2 | 3.1 | 3.5 | 3.1 | 2 |
| **Rb** | 163.2 | 223 | 232 | 210 | 164 |
| **As** | NM | NM | NM | NM | NM |
| **Sr** | 105.8 | 185 | 146 | 148 | 94.3 |
| **Y** | 19.8 | 60.3 | 56.3 | 46.8 | 19.4 |
| **Zr** | 138 | 188 | 172 | 154.1 | 123.6 |
| **Nb** | < 0.39 | 8.6 | 3.8 | < 1.2 | < 0.36 |
| **Mo** | 89.2 | 177 | 570 | 69.1 | 66.1 |
| **Ru** | < 0.21 | < 0.09 | < 0.15 | < 0.09 | < 0.18 |
| **Rh** | < 0.3 | 0.22 | < 0.18 | < 0.09 | < 0.09 |
| **Pd** | 0.6 | 1.7 | 1.7 | 1.25 | 0.53 |
| **Ag** | 2.15 | < 6 | 4.3 | < 9 | 3.4 |
| **Cd** | 3.6 | 9.4 | 9.5 | 7.1 | 5 |
| **Sn** | 1.8 | 8.6 | 3.4 | 8.5 | 5.2 |
| **Sb** | 10.32 | 60.6 | 27.7 | 24.7 | 26.9 |
| **Te** | < 1.2 | < 3.3 | < 1.8 | < 1.2 | < 0.9 |
| **Cs** | 4.82 | 15.2 | 16.4 | 13.29 | 6.49 |
| **Ba** | 1377 | 1780 | 1270 | 1760 | 1370 |
| **La** | 40.1 | 113 | 105 | 86.7 | 42.7 |
| **Ce** | 76.7 | 223 | 207 | 171.9 | 82.1 |
| **Pr** | 7.8 | 23.7 | 22.2 | 18.2 | 8.47 |
| **Nd** | 27 | 85 | 80 | 65.4 | 29.91 |
| **Sm** | 4.7 | 15.9 | 15.5 | 12.4 | 5.31 |
| **Eu** | 0.66 | 1.72 | 1.65 | 1.4 | 0.76 |
| **Gd** | 4.43 | 15.5 | 14.9 | 11.9 | 5 |
| **Tb** | 0.63 | 2.15 | 2.09 | 1.65 | 0.67 |
| **Dy** | 3.4 | 11.3 | 10.7 | 8.6 | 3.6 |
| **Ho** | 0.745 | 2.09 | < 2.4 | 1.7 | 0.725 |
| **Er** | 2.43 | 6.1 | 5.9 | 4.7 | 2.21 |
| **Tm** | 0.36 | 0.81 | 0.75 | 0.61 | 0.32 |
| **Yb** | 2.53 | 5.2 | 5.1 | 4.03 | 2.22 |
| **Lu** | 0.36 | 0.71 | 0.7 | 0.57 | 0.329 |
| **Hf** | 1.5 | 2 | 1.9 | 1.13 | 0.9 |
| **Ta** | < 0.42 | < 0.9 | < 0.9 | < 0.21 | < 0.24 |
| **W** | < 0.33 | < 3.9 | < 3 | < 0.45 | < 0.54 |
| **Re** | < 0.042 | < 0.09 | < 0.06 | < 0.045 | < 0.021 |

| | | | | | |
|---|---|---|---|---|---|
| **Ir** | < 0.15 | < 0.6 | < 0.51 | < 0.09 | < 0.06 |
| **Pt** | < 0.21 | < 0.15 | < 0.18 | < 0.21 | < 0.09 |
| **Au** | < 0.45 | < 0.57 | < 0.3 | < 0.42 | < 0.18 |
| **Tl** | 2.25 | 5 | 5.1 | 3.89 | 2.4 |
| **Pb** | 554 | 3400 | 2900 | 2390 | 1000 |
| **Th** | 16 | 37 | 39 | 28.6 | 16.8 |
| **U** | 104 | 320 | 270 | 212.6 | 93.3 |

Measurement errors for analysis of uranium isotopes and major and trace elements are described in Appendix I. All elements reported as parts per million (microgram/gram). NM = not measured. "<" denotes detection limit.

| | Taboshar I-V 1 | Taboshar I-V 2 | Taboshar I-V 3 | Taboshar I-V 4 | Taboshar I-V 5 |
|---|---|---|---|---|---|
| **U-238/U-235** | 137.11 | 137.60 | 136.94 | 137.68 | 136.50 |
| **U-235/U-234** | 126.58 | 126.42 | 121.95 | 129.87 | 125.00 |
| **Be** | < 2.7 | 3.4 | 2.2 | 2.4 | 4.4 |
| **Na** | 1500 | 403 | 652 | 450 | 1260 |
| **Mg** | 7210 | 6070 | 6920 | 5560 | 6150 |
| **Al** | 56300 | 44500 | 50500 | 35600 | 53900 |
| **K** | 33300 | 17600 | 31510 | 17700 | 21600 |
| **Ca** | 141800 | 170000 | 135500 | 141000 | 147700 |
| **Ti** | 1361 | 694 | 1351 | 839 | 780 |
| **V** | 32.8 | 36.3 | 29.3 | 25.16 | 42 |
| **Cr** | 18 | 24.4 | 14.4 | 18.4 | 31.4 |
| **Mn** | 1660 | 1378 | 1197 | 1420 | 2300 |
| **Fe** | 34300 | 46600 | 35700 | 36500 | 66900 |
| **Co** | 8.41 | 5.6 | 9.7 | 7.25 | 9.13 |
| **Ni** | 8.1 | 7.1 | 7.7 | 6.9 | 9.8 |
| **Cu** | 257 | 414 | 253 | 241 | 462 |
| **Zn** | 531 | 436 | 514 | 541 | 639 |
| **Ga** | 22.3 | 16.7 | 18 | 10.8 | 40.1 |
| **Ge** | < 1.5 | 1.4 | 1.13 | 1.25 | < 1.5 |
| **Rb** | 167.9 | 96 | 158 | 86.2 | 120 |
| **As** | NM | NM | NM | NM | NM |
| **Sr** | 158 | 155 | 141.3 | 138.3 | 159 |
| **Y** | 13.06 | 18.5 | 10.7 | 13.8 | 24.8 |
| **Zr** | 67.5 | 46.4 | 59.9 | 24.9 | 53.5 |
| **Nb** | < 0.45 | < 0.36 | < 0.48 | < 0.36 | < 0.9 |
| **Mo** | 10.8 | 63.5 | 23.5 | 8.1 | 14.9 |
| **Ru** | < 0.09 | < 0.12 | < 0.09 | < 0.06 | < 0.18 |
| **Rh** | < 0.12 | < 0.06 | < 0.09 | < 0.06 | < 0.12 |
| **Pd** | 0.36 | < 0.9 | 0.33 | 0.41 | 0.7 |
| **Ag** | 0.8 | < 4.2 | 1.1 | < 1.2 | < 0.6 |
| **Cd** | 5.1 | 4.3 | 5.1 | 4.3 | 5.5 |
| **Sn** | 1.3 | < 0.3 | < 0.36 | 0.57 | < 0.3 |
| **Sb** | 12 | 8.5 | 14 | 12.5 | 13.4 |
| **Te** | < 0.6 | < 0.6 | < 0.54 | < 0.9 | < 0.9 |
| **Cs** | 8.9 | 7.42 | 7.62 | 5.9 | 9.1 |
| **Ba** | 250 | 145 | 168 | 59.4 | 657 |
| **La** | 27.6 | 15.1 | 14.5 | 10 | 18 |
| **Ce** | 54.9 | 32.4 | 29.6 | 15.1 | 36.4 |
| **Pr** | 5.89 | 3.95 | 3.27 | 2.92 | 4.24 |
| **Nd** | 21.2 | 16.1 | 12.17 | 12.2 | 17 |
| **Sm** | 3.9 | 3.8 | 2.34 | 2.9 | 4.1 |
| **Eu** | 0.62 | 0.48 | 0.41 | 0.35 | 0.61 |
| **Gd** | 3.6 | 3.68 | 2.23 | 3 | 4.56 |
| **Tb** | 0.45 | 0.57 | 0.3 | 0.457 | 0.68 |
| **Dy** | 2.28 | 3.17 | 1.63 | 2.43 | 4 |
| **Ho** | 0.46 | 0.64 | 0.324 | 0.49 | 0.806 |
| **Er** | 1.38 | 1.87 | 1.01 | 1.49 | 2.54 |
| **Tm** | 0.1841 | 0.27 | 0.146 | 0.202 | 0.36 |
| **Yb** | 1.3 | 1.82 | 1.02 | 1.42 | 2.46 |
| **Lu** | 0.19 | 0.26 | 0.15 | 0.204 | 0.371 |
| **Hf** | < 0.48 | < 0.45 | < 0.36 | < 0.36 | < 0.45 |
| **Ta** | < 0.18 | < 0.3 | < 0.12 | < 0.18 | < 0.18 |
| **W** | < 0.9 | < 0.9 | < 0.33 | < 0.42 | < 0.6 |
| **Re** | < 0.036 | < 0.048 | < 0.039 | < 0.033 | < 0.036 |
| **Ir** | < 0.18 | < 0.12 | < 0.048 | < 0.12 | < 0.27 |

| | | | | | |
|---|---|---|---|---|---|
| **Pt** | < 0.15 | < 0.12 | < 0.042 | < 0.039 | < 0.12 |
| **Au** | < 0.36 | < 0.12 | < 0.15 | < 0.12 | < 0.21 |
| **Tl** | 1.66 | 0.89 | 1.55 | 0.9 | 1.11 |
| **Pb** | 230 | 440 | 393 | 263 | 596 |
| **Th** | 12.77 | 15.2 | 8.8 | 1.1 | 18.3 |
| **U** | 38.6 | 101.7 | 30.7 | 58.4 | 106 |

Measurement errors for analysis of uranium isotopes and major and trace elements are described in Appendix I. All elements reported as parts per million (microgram/gram). NM = not measured. "<" denotes detection limit.

| | Adrasman-1 | Adrasman-2 | Adrasman-3 | Adrasman-4 | Adrasman-5 | Adrasman-6 |
|---|---|---|---|---|---|---|
| **U-238/U-235** | 137.94 | 137.83 | 138.01 | 138.76 | 138.76 | 137.87 |
| **U-235/U-234** | 120.50 | 121.67 | 127.57 | 95.47 | 101.35 | 127.01 |
| **Be** | 1.2 | 1.17 | 1.3 | 2.4 | 1.14 | 1.2 |
| **Na** | 5500 | 4300 | 4580 | 24000 | 5430 | 2950 |
| **Mg** | 2370 | 1550 | 2260 | 2720 | 3470 | 2460 |
| **Al** | 47000 | 38400 | 46200 | 57000 | 49200 | 42000 |
| **K** | 31000 | 35700 | 39100 | 26600 | 33100 | 31000 |
| **Ca** | 12900 | 6160 | 6700 | 9200 | 11000 | 5800 |
| **Ti** | 1230 | 950 | 1310 | 1540 | 1290 | 930 |
| **V** | 134 | 106 | 111 | 520 | 113 | 93 |
| **Cr** | 10.6 | 7.3 | 8.7 | 22.7 | 11.5 | 8.2 |
| **Mn** | 900 | 650 | 750 | 690 | 864 | 800 |
| **Fe** | 79000 | 54000 | 67000 | 15300 | 47700 | 58000 |
| **Co** | 13.3 | 8.3 | 10.4 | 6.92 | 7.57 | 6.9 |
| **Ni** | 12.8 | 2.32 | 3.36 | 9.2 | 5.1 | 5.4 |
| **Cu** | 380 | 347 | 460 | 503 | 523 | 950 |
| **Zn** | 189 | 100 | 148 | 207 | 163 | 88 |
| **Ga** | 14.6 | 14.1 | 16.2 | 16.12 | 16 | 16.5 |
| **Ge** | 7.3 | 5.6 | 6.6 | 3.7 | 5.3 | 6.3 |
| **Rb** | 158 | 132 | 151 | 131 | 134 | 153 |
| **As** | 159 | 121 | 95 | 96 | 87 | 106 |
| **Sr** | 112 | 76 | 88 | 102.9 | 117.8 | 56 |
| **Y** | 8.2 | 4.48 | 6.3 | 14.8 | 8 | 8.3 |
| **Zr** | NM | NM | NM | NM | NM | NM |
| **Nb** | 8.6 | 6.9 | 8.1 | 17.4 | 7.6 | 6.5 |
| **Mo** | 37.1 | 24.8 | 24.6 | 48.5 | 12.3 | 13.2 |
| **Ru** | < 0.05 | < 0.05 | < 0.05 | < 0.05 | < 0.05 | < 0.05 |
| **Rh** | < 0.02 | < 0.02 | < 0.02 | < 0.02 | < 0.02 | < 0.02 |
| **Pd** | 0.217 | 0.13 | 0.18 | 0.36 | 0.22 | 0.19 |
| **Ag** | 16.2 | 18.6 | 15.3 | 7 | 19.1 | 25.3 |
| **Cd** | 1.23 | 0.43 | 0.86 | 0.72 | 0.92 | 0.52 |
| **Sn** | 30 | 9.6 | 15.7 | 4.9 | 5.62 | 8.7 |
| **Sb** | 43 | 20.3 | 17.4 | 16.6 | 37.3 | 26.5 |
| **Te** | 0.63 | 0.65 | 0.49 | < 0.15 | 0.35 | 0.39 |
| **Cs** | 6 | 5.5 | 14.2 | 3.71 | 6.6 | 6.9 |
| **Ba** | 2590 | 2630 | 2550 | 406 | 2420 | 1390 |
| **La** | 20.5 | 8.3 | 10.1 | 12.5 | 12.9 | 13.5 |
| **Ce** | 39.4 | 24.3 | 29.1 | 30.1 | 30.7 | 24.2 |
| **Pr** | 4.3 | 1.96 | 2.51 | 2.96 | 3.1 | 2.88 |
| **Nd** | 14.9 | 6.75 | 9 | 10.5 | 11.1 | 9.8 |
| **Sm** | 2.59 | 1.29 | 1.79 | 2.4 | 2.07 | 1.77 |
| **Eu** | 0.55 | 0.35 | 0.42 | 0.263 | 0.51 | 0.352 |
| **Gd** | 2.64 | 1.47 | 1.96 | 2.5 | 2.3 | 1.75 |
| **Tb** | 0.32 | 0.163 | 0.243 | 0.455 | 0.28 | 0.237 |
| **Dy** | 1.76 | 1 | 1.46 | 3.03 | 1.67 | 1.45 |
| **Ho** | 0.37 | 0.211 | 0.289 | 0.636 | 0.346 | 0.31 |
| **Er** | 1.12 | 0.7 | 0.92 | 1.98 | 1.1 | 1.01 |
| **Tm** | 0.165 | 0.111 | 0.144 | 0.306 | 0.172 | 0.162 |
| **Yb** | 1.16 | 0.82 | 1.06 | 2.09 | 1.23 | 1.15 |
| **Lu** | 0.183 | 0.136 | 0.166 | 0.317 | 0.196 | 0.184 |
| **Hf** | NM | NM | NM | NM | NM | NM |
| **Ta** | < 3 | < 3 | < 3 | < 3 | < 3 | < 3 |
| **W** | 123 | 62 | 94 | 9 | 33 | 60 |
| **Re** | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Ir** | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| **Pt** | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 |
| **Au** | NM | NM | NM | NM | NM | NM |
| **Tl** | 1.51 | 1.39 | 1.53 | 1.4 | 1.44 | 1.26 |
| **Pb** | 1230 | 930 | 760 | 860 | 890 | 770 |
| **Th** | 8.5 | 7.3 | 8.1 | 7.6 | 9.2 | 9.7 |
| **U** | 27.3 | 18.8 | 29.4 | 100 | 31 | 33.5 |

Measurement errors for analysis of uranium isotopes and major and trace elements are described in Appendix I. All elements reported as parts per million (microgram/gram). NM = not measured. "<" denotes detection limit.

| | Kaji-Say SP1 | Kaji-Say SP2 | Kaji-Say SP3 | Kaji-Say SP4 | Kaji-Say SP5 |
|---|---|---|---|---|---|
| **U-238/U-235** | 137.51 | 138.62 | 137.92 | 138.05 | 137.08 |
| **U-235/U-234** | 131.31 | 134.26 | 130.45 | 129.36 | 135.14 |
| **Be** | NM | NM | NM | NM | NM |
| **Na** | 23800 | 25200 | 4900 | 1310 | 850 |
| **Mg** | NM | NM | NM | NM | NM |
| **Al** | 51300 | 75000 | 36700 | 30900 | 43900 |
| **K** | 7300 | 9200 | 11300 | 12100 | 11100 |
| **Ca** | 42200 | 54500 | 20700 | 3180 | 5200 |
| **Ti** | 3180 | 4040 | 1800 | 3890 | 3270 |
| **V** | 68 | 109 | 65 | 103 | 68 |
| **Cr** | 880 | 798 | 750 | 139 | 244 |
| **Mn** | NM | NM | NM | NM | NM |
| **Fe** | 49400 | 49900 | 29100 | 12900 | 13000 |
| **Co** | 37.4 | 41.1 | 9.6 | 9.4 | 9.7 |
| **Ni** | 56 | 65.5 | 24.7 | 22.9 | 20 |
| **Cu** | 75 | 85 | 76 | 22.7 | 21.1 |
| **Zn** | 151 | 157 | 158 | 74 | 62 |
| **Ga** | 21 | 26.9 | 10.3 | 19.7 | 15.8 |
| **Ge** | NM | NM | NM | NM | NM |
| **Rb** | NM | NM | NM | NM | NM |
| **As** | 40 | 33 | < 9 | < 21 | < 18 |
| **Sr** | 690 | 800 | 128 | 46 | 68 |
| **Y** | NM | NM | NM | NM | NM |
| **Zr** | NM | NM | NM | NM | NM |
| **Nb** | 12.3 | 17.5 | 6.1 | 13.5 | 13.2 |
| **Mo** | 138 | 95 | 4.6 | 2.4 | 2.5 |
| **Ru** | < 0.025 | < 0.025 | < 0.025 | < 0.025 | < 0.025 |
| **Rh** | < 0.048 | < 0.012 | < 0.027 | < 0.015 | < 0.018 |
| **Pd** | NM | NM | NM | NM | NM |
| **Ag** | < 0.39 | 0.43 | < 0.18 | < 0.33 | < 0.25 |
| **Cd** | 1.76 | 1.67 | 1.42 | 0.24 | 0.33 |
| **Sn** | 3.7 | 4.5 | 2.5 | 3.3 | 2.8 |
| **Sb** | 2.45 | 3.3 | 1.44 | 1.17 | 2.62 |
| **Te** | < 0.54 | < 0.42 | < 0.45 | < 0.9 | < 0.51 |
| **Cs** | NM | NM | NM | NM | NM |
| **Ba** | 1150 | 1340 | 870 | 227 | 282 |
| **La** | NM | NM | NM | NM | NM |
| **Ce** | NM | NM | NM | NM | NM |
| **Pr** | NM | NM | NM | NM | NM |
| **Nd** | NM | NM | NM | NM | NM |
| **Sm** | NM | NM | NM | NM | NM |
| **Eu** | NM | NM | NM | NM | NM |
| **Gd** | NM | NM | NM | NM | NM |
| **Tb** | NM | NM | NM | NM | NM |
| **Dy** | NM | NM | NM | NM | NM |
| **Ho** | NM | NM | NM | NM | NM |
| **Er** | NM | NM | NM | NM | NM |
| **Tm** | NM | NM | NM | NM | NM |
| **Yb** | NM | NM | NM | NM | NM |
| **Lu** | NM | NM | NM | NM | NM |
| **Hf** | NM | NM | NM | NM | NM |
| **Ta** | < 3 | < 3 | < 3 | < 3 | < 3 |
| **W** | 5.7 | 6.4 | 15.6 | 3.5 | 3.2 |
| **Re** | 0.52 | 0.27 | < 0.015 | < 0.012 | < 0.005 |

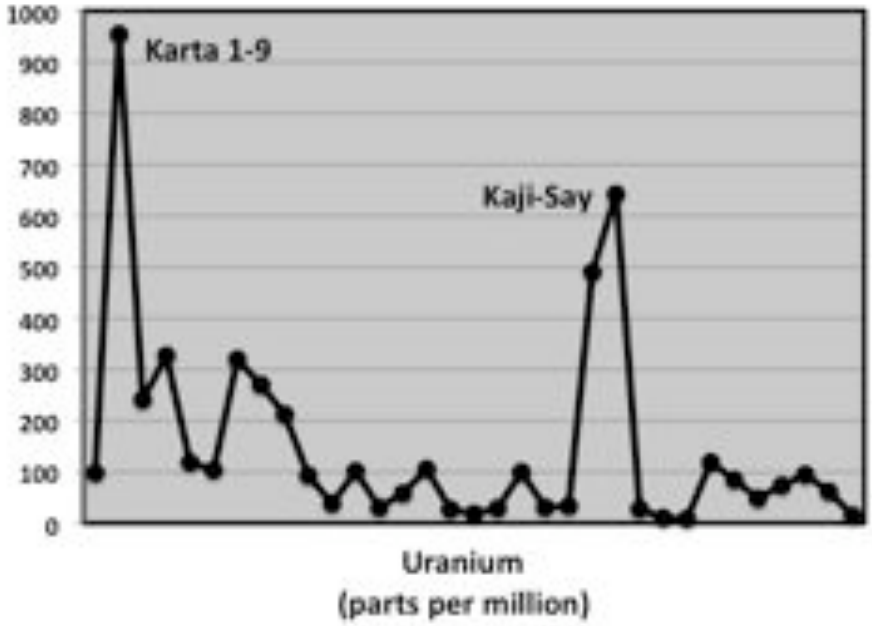
| | | | | | |
|---|---|---|---|---|---|
| **Ir** | <0.04 | <0.04 | <0.04 | <0.04 | <0.04 |
| **Pt** | < 0.09 | < 0.12 | < 0.036 | < 0.047 | < 0.031 |
| **Au** | NM | NM | NM | NM | NM |
| **Tl** | NM | NM | NM | NM | NM |
| **Pb** | NM | NM | NM | NM | NM |
| **Th** | NM | NM | NM | NM | NM |
| **U** | 490 | 642 | 28.3 | 10.5 | 8.8 |

Measurement errors for analysis of uranium isotopes and major and trace elements are described in Appendix I. All elements reported as parts per million (microgram/gram). NM = not measured. "<" denotes detection limit.

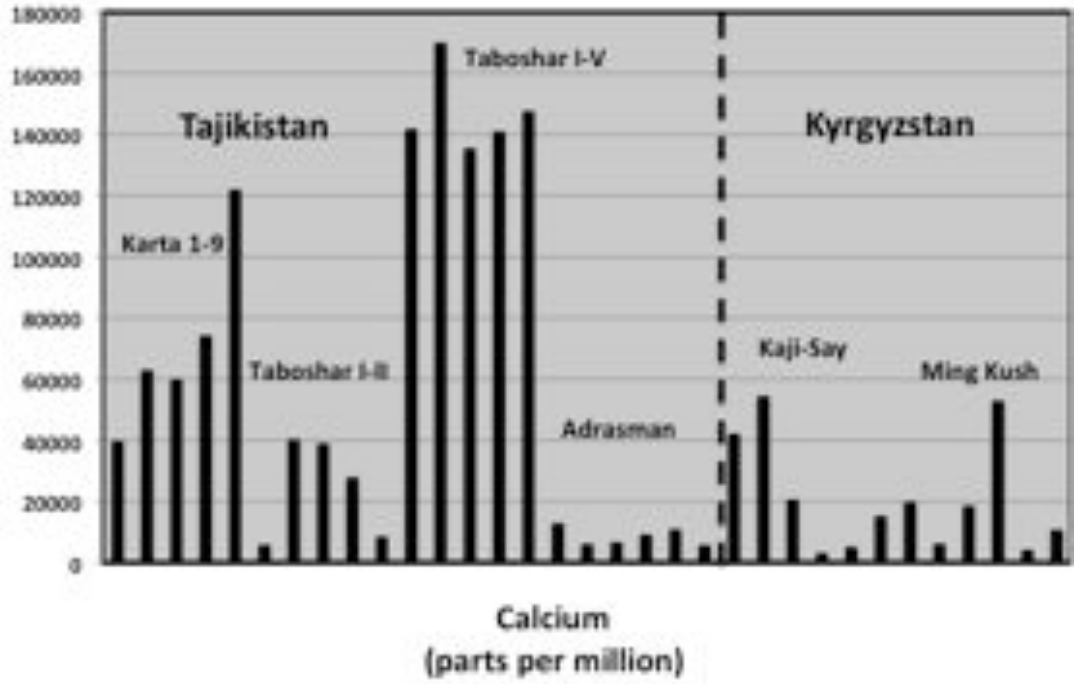
| | Ming Kush1 | Ming Kush2 | Ming Kush3 | Ming Kush4 | Ming Kush5 | Ming Kush6 | Ming Kush7 |
|---|---|---|---|---|---|---|---|
| **U-238/U-235** | 138.23 | 138.66 | 138.36 | 138.62 | 137.72 | 137.92 | 137.93 |
| **U-235/U-234** | 120.23 | 111.05 | 116.21 | 103.82 | 110.64 | 128.14 | 129.57 |
| **Be** | 1.6 | 1.44 | 0.5 | 1.6 | 2.8 | 0.67 | 2.2 |
| **Na** | 970 | 376 | 357 | 292 | 277 | 233 | 452 |
| **Mg** | 760 | 687 | 430 | 483 | 1610 | 730 | 1340 |
| **Al** | 25600 | 25100 | 17900 | 21800 | 41800 | 35100 | 60000 |
| **K** | 3210 | 4890 | 4140 | 1230 | 6600 | 5050 | 7200 |
| **Ca** | 15300 | 19900 | 6220 | 18600 | 53000 | 4180 | 10800 |
| **Ti** | 2000 | 1460 | 1090 | 2660 | 2700 | 1240 | 3200 |
| **V** | 28.8 | 22.9 | 7.2 | 26.4 | 61 | 14.1 | 47 |
| **Cr** | 20.6 | 18 | 10.3 | 19.3 | 36.8 | 15.1 | 36 |
| **Mn** | 39.2 | 27.6 | 32 | 31 | 98 | 50.1 | 47 |
| **Fe** | 10900 | 8140 | 5500 | 9000 | 9700 | 6880 | 11200 |
| **Co** | 9 | 5.31 | 1.89 | 5.13 | 11 | 3.36 | 6.7 |
| **Ni** | 22.9 | 14.5 | 5.51 | 17.2 | 29.4 | 6.28 | 12.6 |
| **Cu** | 25.6 | 17 | 16.1 | 21.4 | 22 | 10.4 | 19.8 |
| **Zn** | 34.9 | 35.2 | 15.6 | 27.3 | 100 | 16.1 | 43 |
| **Ga** | 7.4 | 6.38 | 4.61 | 6.2 | 10.6 | 8.1 | 18.3 |
| **Ge** | 4.4 | 1.86 | 2.18 | 1.8 | 1.77 | 1.64 | 3.1 |
| **Rb** | 19.6 | 28.4 | 22.5 | 8.4 | 44.3 | 31.6 | 57 |
| **As** | 12 | 8.9 | 8.1 | 18 | 9.1 | 3 | 7.8 |
| **Sr** | 137 | 137 | 74.5 | 117.1 | 274 | 104 | 141 |
| **Y** | 10.36 | 9.9 | 5.6 | 9.67 | 18.6 | 10.9 | 15.8 |
| **Zr** | NM | NM | NM | NM | NM | NM | NM |
| **Nb** | 9.5 | 7.1 | 6.29 | 13.4 | 12.7 | 7.5 | 16.6 |
| **Mo** | 121 | 21.9 | 22.7 | 141 | 13.5 | 1.4 | 9.8 |
| **Ru** | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| **Rh** | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| **Pd** | 0.32 | 0.32 | 0.33 | 0.29 | 0.61 | 0.32 | 0.45 |
| **Ag** | 0.205 | 0.18 | 0.145 | 0.26 | 0.24 | 0.163 | 0.35 |
| **Cd** | 0.35 | 0.23 | < 0.068 | 0.45 | 0.45 | < 0.027 | < 0.12 |
| **Sn** | 2.09 | 1.38 | 1.07 | 2.5 | 2.49 | 1.41 | 4.8 |
| **Sb** | 0.82 | 0.56 | 0.58 | 0.88 | 0.63 | 0.39 | 1.51 |
| **Te** | < 0.15 | < 0.15 | < 0.15 | < 0.15 | < 0.15 | < 0.15 | < 0.15 |
| **Cs** | 1.97 | 2.38 | 1.56 | 1.01 | 4.83 | 2.6 | 7.8 |
| **Ba** | 268 | 238 | 153 | 97 | 370 | 276 | 329 |
| **La** | 14.56 | 14.1 | 8.4 | 17.3 | 22.6 | 17.9 | 26.7 |
| **Ce** | 26.2 | 26.8 | 14.8 | 26.2 | 43.5 | 35.4 | 49 |
| **Pr** | 2.87 | 3.03 | 1.58 | 2.59 | 5 | 3.93 | 5.8 |
| **Nd** | 10.01 | 10.7 | 5.44 | 8.3 | 17.8 | 13.8 | 20.1 |
| **Sm** | 1.89 | 2.07 | 0.98 | 1.43 | 3.6 | 2.52 | 3.74 |
| **Eu** | 0.38 | 0.421 | 0.195 | 0.27 | 0.76 | 0.43 | 0.61 |
| **Gd** | 1.91 | 2.03 | 1 | 1.54 | 3.54 | 2.35 | 3.48 |
| **Tb** | 0.284 | 0.294 | 0.152 | 0.235 | 0.55 | 0.327 | 0.51 |
| **Dy** | 1.71 | 1.75 | 0.95 | 1.51 | 3.32 | 1.85 | 2.97 |
| **Ho** | 0.352 | 0.353 | 0.2 | 0.322 | 0.67 | 0.388 | 0.6 |
| **Er** | 1.1 | 1.09 | 0.63 | 1.04 | 2.04 | 1.22 | 1.84 |
| **Tm** | 0.165 | 0.165 | 0.097 | 0.161 | 0.31 | 0.191 | 0.282 |
| **Yb** | 1.152 | 1.1 | 0.67 | 1.14 | 2.08 | 1.36 | 1.96 |
| **Lu** | 0.174 | 0.171 | 0.1035 | 0.181 | 0.33 | 0.213 | 0.298 |
| **Hf** | NM | NM | NM | NM | NM | NM | NM |
| **Ta** | < 3 | < 3 | < 3 | < 3 | < 3 | < 3 | < 3 |
| **W** | 2.12 | 1.56 | 1.15 | 3.78 | 2.68 | 1.28 | 2.81 |
| **Re** | 0.306 | 0.077 | 0.148 | 0.115 | 0.087 | < 0.005 | < 0.005 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Ir** | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| **Pt** | < 0.05 | < 0.05 | < 0.05 | < 0.05 | < 0.05 | < 0.05 | < 0.05 |
| **Au** | NM | NM | NM | NM | NM | NM | NM |
| **Tl** | 1.67 | 1.43 | 1.51 | 1.98 | 1.34 | 0.273 | 1.8 |
| **Pb** | 21.3 | 19.7 | 19.6 | 23.7 | 27 | 22.4 | 55 |
| **Th** | 6.6 | 6 | 3.41 | 6.2 | 10.8 | 8.1 | 16 |
| **U** | 119 | 85 | 48.6 | 74 | 95 | 62 | 15.4 |

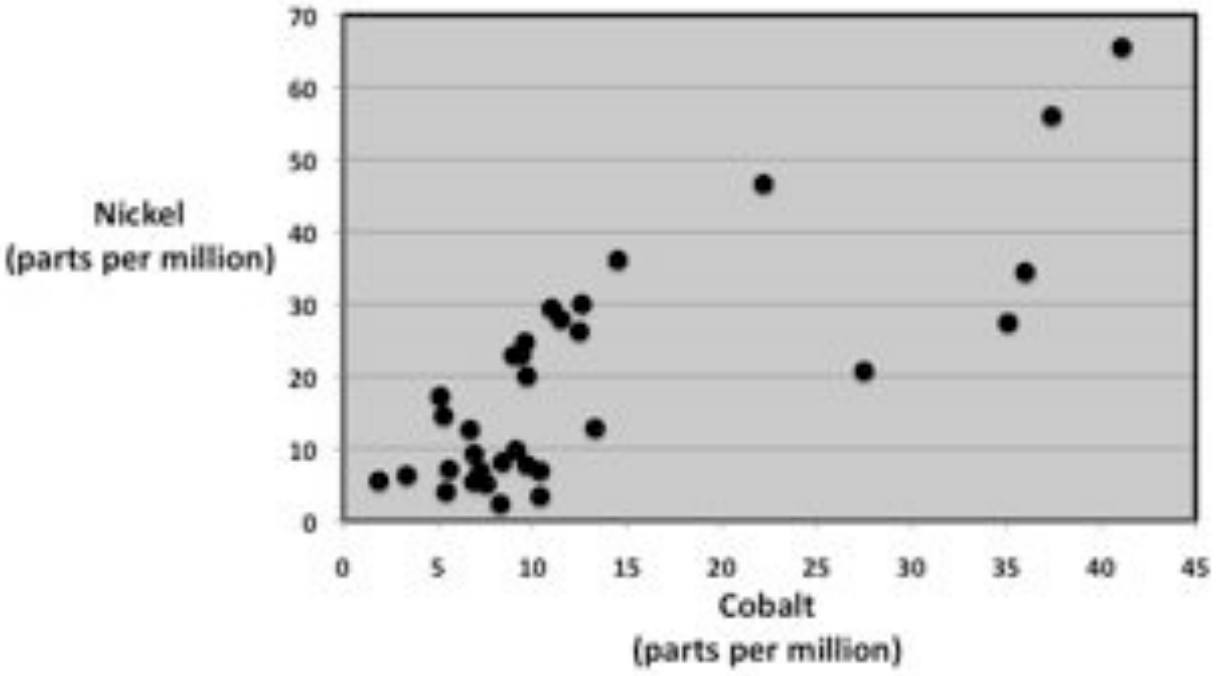
Measurement errors for analysis of uranium isotopes and major and trace elements are described in Appendix I. All elements reported as parts per million (microgram/gram). NM = not measured. "<" denotes detection limit.



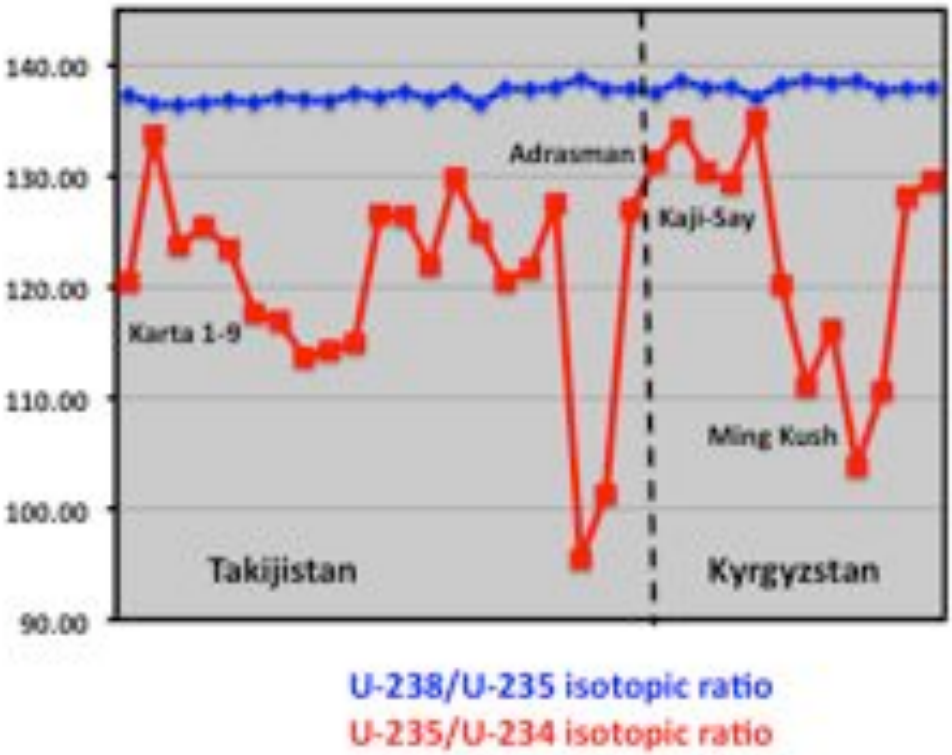

Uranium concentration (in parts per million) for 33 Central Asian samples. Samples are enriched in uranium (up to 100 to 200 parts per million) above natural background. Specific samples from Karta 1-9 in Tajikistan and Kaji-Say in Kyrgyzstan exhibit local enrichments in uranium concentration with an upper limit in excess of 900 parts per million.




Calcium concentrations (in parts per million) for 33 Central Asian samples. Calcium (and other major and trace elements) can be used to distinguish distinct source locations. These data indicate the samples from the Karta 1-9 and Taboshar IV locales in Tajikistan have higher calcium concentrations than the Kaji-Say and Ming Kush sites in Kyrgyzstan.




Nickel verses cobalt variation diagram (in parts per million) for 33 Central Asian samples. Nickel and cobalt are 'compatible elements' and show similar geochemical behavior in these samples indicted by the (approximately) linear trend on the diagram. A similar variation is seen plotting vanadium. The signature variation acts systematically and aids in the identification of unique sample locations. The highest concentration samples are from the Kaji-Say locale in Kyrgyzstan.




Variation in major uranium isotope ratios for 33 Central Asian samples. Plot of $^{238}U/^{235}U$ in blue and $^{235}U/^{234}U$ in red. The data clearly indicate the nearly invariant ratio of $^{238}U/^{235}U$ that is fixed in nature at 137.88. In contrast the $^{235}U/^{234}U$ ratio varies considerably due to radioactive decay and subsequent 'disequilbrium' partitioning of U-234 in the presence of aqueous fluids (see discussion in text). The variation in $^{235}U/^{234}U$ isotope ratio provides an additional indicator of the source location of the samples (i.e., note difference in Kaji-Say verses Ming Kush samples in Kyrgyzstan). Processing of the uranium ores may also affect the $^{235}U/^{234}U$ ratio. Of note, differences are also seen from sources within a single sampling location (mine or mill, e.g., Karta 1-9 and Adrasman in Tajikistan).