SCIENCE & GLOBAL SECURITY
2020, VOL. 28, NO. 2, 80–109
https://doi.org/10.1080/08929882.2020.1789275

Geologic Analysis of the Democratic People's Republic of Korea's Uranium Resources and Mines

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ABSTRACT

The mining and milling of uranium ore is the first step in the production of fissile material and is a rate-limiting step for the indigenous production of nuclear weapons in the Democratic People's Republic of Korea (DPRK). This study reports a geologic analysis of uranium mines in the DPRK in order to bound the state's potential uranium production. The analysis suggests that the uranium deposits of the possible mines are of four types: (1) black shale (metamorphosed organic shale); (2) limestone; (3) granite/metasomatic; and (4) metamorphic deposits. Comparison with geologically-related, uranium-bearing host rocks in the Republic of Korea (ROK) indicate that DPRK uranium mines are associated with medium-to-high quantities of average low-grade ore (0.001–0.04 wt.% uranium). Using this low-grade ore, expansion of the state's nuclear arsenal would require the extraction of larger quantities of uranium ore than has been previously assumed. The DPRK's geology could, therefore, limit the future development of its nuclear weapons program.

ARTICLE HISTORY
Received 15 January 2020
Accepted 18 May 2020

Introduction

Efforts to determine and verify the fissile material and nuclear weapon production capacity of the Democratic People's Republic of Korea (DPRK) have been ongoing for decades. Study of its uranium production comprises a key element of these analyses, as the mining of natural uranium is the first step in the production of the two fissile materials from which weapons are made, high-enriched uranium and plutonium in irradiated reactor fuel. The international community currently estimates the quantities of enriched and natural uranium possessed by the DPRK using three primary

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sources: interviews of defectors;[1] documents from the Soviet Union and organizations such as the International Atomic Energy Agency (IAEA);[2] and persistent satellite observation of activities at various nuclear sites, such as the Pyongsan uranium mine and Yongbyon Nuclear Scientific Research Center (the center of the DPRK's nuclear program).[3] These sources provide valuable information regarding the DPRK's nuclear activities and fissile material production capabilities. Unfortunately, these open-source reports list varying numbers of suspected uranium mines and of uranium ore grade,[4] yielding large uncertainties in estimates of the available uranium resource in the DPRK. Thus, it is challenging to accurately estimate potential production rates or nuclear arsenal expansion timelines.

Present knowledge of North Korean mining activities

The DPRK began exploration of uranium and related rare earth elements as early as the 1940s—predating the Korean War. Its 1959 nuclear cooperation agreement with the Soviet Union accelerated the exploration for uranium deposits.[5] In 1964, with the aid of the Chinese government, the DPRK explored uranium deposits in Woonggi (or Unggi), Hamhung, Pyongsan, and Haegumgang cities.[6] The DPRK government declared the existence of two uranium mines and two milling facilities in 1992 after it became a party to the Treaty on the Nonproliferation of Nuclear Weapons (NPT) and submitted its mandatory initial report to the International Atomic Energy Agency (IAEA).[7] These included the Sunchŏn-Wolbisan mine and Pyongsan uranium mine, alongside the Pakchŏn milling facility –

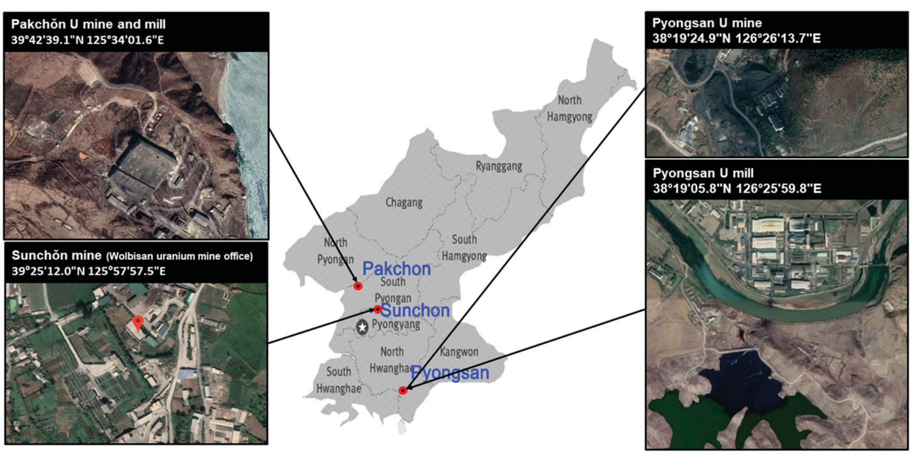

Figure 1. Locations of mines and mills reported by DPRK to IAEA in 1992 with documented satellite images. Images from Google Earth. Note that the location of Sunchŏn at Wolbisan mine is not well known (the google map marker points to what is reported as 'office building' for Sunchŏn uranium mine).[9]

Uranium Concentrate Pilot Plant, and the Pyongsan milling facility (Figure 1).[8]

The most significant uranium extraction and processing sites in the DPRK are the Pyongsan uranium mine and the milling facility in North Hwanghae Province. The mine has reportedly operated since the 1980s under the control of the People's Army Department, and the deposit contains an estimated total of 1.5 million tonnes or uranium ore.[10] However, reported values for the annual production of uranium ore vary widely, from 290 tonnes to 20,000 tonnes of uranium ore per year.[11] There also exist large discrepancies in the reported uranium ore grades. According to a report by the Korean Atomic Energy Research Institute (KAERI), the average grade of uranium ore collected in Pyongsan is as much as 0.08% uranium, in the form of uranium-bearing anthracite coal (due to error and mistranslation, some rock-type names are misinterpreted; in this case, anthracite coal is likely a metamorphosed organic shale) and its milling facility can process up to 200,000 tonnes of ore per year.[12] However, other sources assume a much higher ore grade of 0.26% uranium, based on a 1979 telegram memo from the Hungarian embassy in the DPRK to the Hungarian Foreign Ministry (quoting a Soviet source).[13]

Unlike the Pyongsan mine, there exist no open-source account of visits to the Sunchŏn mine and no available data provide specific coordinates for its location. Based on satellite images, the Sunchŏn city has a few mines but whether these mines host uranium or coal remains inconclusive. Defector accounts suggest that this mine may have been exhausted by now, and hence, no observable monitoring. The Pakchŏn mill is a pilot facility and satellite images show limited observable activities for the past decade. During 1982–1992, the facility processed 350 tonnes of sodium diuranate $Na_2U_2O_7$.[14] The ore processed at the Pakchŏn mill facility was collected from the Sunchŏn mine; it is believed to have had an average ore grade of 0.07% uranium.[15]

In addition to the two mines and two milling facilities declared by the DPRK government, there are several other alleged uranium mines and mills. These include Cholsan, Kusong, and Kujang mines in N. Pyongan Province; Hwangsan mine in S. Pyongan Province; Cheonmasan mill in N. Pyongan Province; Maebongsan mine (unknown location as there are multiple locations named Maebongsan); Kumchon mine in N. Hwanghae Province; Hamhung (or Hungnam), Musan, Sinpo, and Rajin (or Najin) mines in Hamgyong Province; Hyesan mine in Ryanggang Province; Wiwon mine in Chagang Province; and Woongi mine (possibly also be known as Sonbong or Rason/Nason) in N. Hamgyong Province.[16] Each of these possible mines contribute to the large discrepancies in reported uranium production capacities and ore grades. Various sources report statewide annual production capacities ranging from 190 to 200,000 tonnes of uranium ore and total recoverable uranium ore reserves up to 26 million tonnes.[17] There is also no consensus on the average grade of uranium ore, with reported amounts varying from 0.07% to 0.9%, even within a single mine.[18] Discrepancies in conclusions derived from defectors may be attributed to their imperfect knowledge of the sites and misinterpretations of their statements. An additional source of potential confusion is nomenclature, as there are many regions in DPRK with similar names and pronunciations, some of which have changed over time. Multiple names are often attributed to the same site (and *vice versa*). In terms of the reported uranium ore reserves, it is often unclear whether the quoted values reflect uranium ore within the deposits or the volumes of deposits themselves.[19] Similarly, sources are often unclear as to whether the units of reported figures are tonnes of ore or tonnes of elemental uranium. With respect to ore grade, it is usually unclear whether reported values refer to the average grade of uranium metal, U_3O_8, or UO_2. Together, these uncertainties result in considerable variation in estimates of the uranium resource.

In assessing uranium mining activities, satellite imagery analysis has recently proven to be an indispensable tool as it vastly enhances the ability to identify and characterize active uranium mines and mills. For example, observations of satellite imageries can inform that the mill tailings pond near the Pyongsan milling facility has expanded in past decades, reflecting

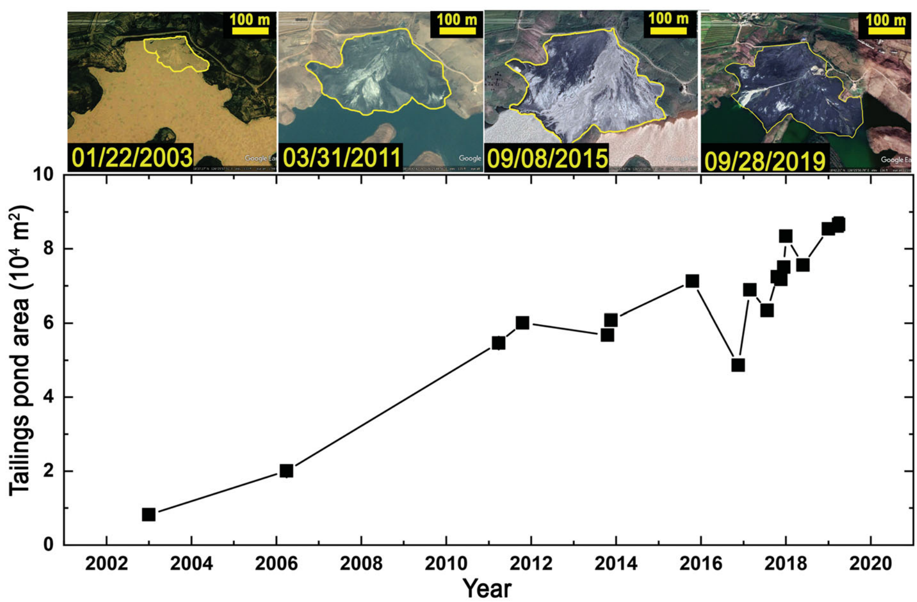

Figure 2. Satellite imagery analysis of increasing mill tailing pond area at Pyongsan milling facility from 2003 to 2019. Inset images are from Google Earth. The mill tailing pond areas shown here are subject to variations in size between intermittent observations based on annual rainfall patterns.

its continuing operation (Figure 2).[20] However, satellite imagery has limitations—the frequency of the collected images is often insufficient for detailed analysis of the rates of operation, as is image resolution. Furthermore, certain mining techniques such as *in situ* leaching yield minimal surface signature and are therefore difficult to detect by optical imaging. Satellite imagery studies should also be careful to account for the DPRK attempts to conceal fissile material production activities. And while imagery is crucial in forecasting the overall activity level of a site, it does not directly reveal the actual capacity of uranium production or the quality of the extracted uranium ore. Better estimates of the deposit production capacity and grade of uranium ores are therefore critical to accurately analyze the size of the DPRK's fissile material stockpile and the rate at which it might grow. New and complementary sources of information that might clarify these values are thus needed.

Geologic interpretations of uranium production pathway

The interpretation of geologic data provides a way to estimate the characteristics of uranium resources. Geology plays a significant role in all steps of the uranium production pathway, governing how and where resources will be explored and exploited, the design of mines and the mining techniques used, and the means of commissioning, operating, and decommissioning mines. Understanding of host rock characteristics enables an evaluation of the impact of weathering agents on the uranium ore deposit (*e.g.*, water content, oxygen, CO_2, and the related acidity), which can strongly influence its characteristics, including the type of uranium minerals present and the concentration of uranium metal within them. Identifying the depositional environment (*i.e.*, the processes by which uranium-bearing deposits form) thus provides insight into the grade of the ore along with qualitative estimates of the deposit volume at the time of exploitation.[21]

In modern mineral exploration, geologists typically combine satellite imagery, geophysical and geochemical techniques, and field sample collection to improve interpretation of ore grade and resources. If these preliminary findings indicate high potential for a mineral resource extraction, exploratory drilling is undertaken and the size, quality, and contents of the deposit are evaluated. The current political isolation of the DPRK precludes this manner of onsite investigations. However, many aspects of this geologic approach can still be used to obtain insight into the state's uranium resources through reliance on existing geologic datasets. This report demonstrates such an approach, using a variety of existing geologic maps to analyze and estimate the DPRK's potential uranium resources. The report begins by outlining the geology and geochemistry of uranium, focusing on the importance of redox reactions in precipitating varying amounts of uranium concentration in deposits. The report then summarizes the relevant geology of the Korean Peninsula, states the known uranium deposits in Republic of Korea (ROK), followed by more detailed DPRK geology, including analysis of the geologic settings of each reported and suspected uranium mine. These mines are then grouped based on the types of deposits corresponding to these geologic settings. Subsequent comparison with well-characterized uranium deposits in the nearby ROK allows for the estimation of parameters, such as ore grades, associated with these sites.

The geologic data used in this analysis are derived from 13 geologic/tectonic maps (Table 1), 3 explanatory texts, and numerous articles in the scientific literature. The geologic settings of each suspected uranium mine were compared among the different maps and texts to ensure accuracy and consistency. To compare the geology of the DPRK to that of analogous sites in the ROK, peer-reviewed articles on the ROK's uranium deposits, particularly the Okcheon metamorphic belt (OMB), were reviewed. The grades of the ore and the possible geologic origins of uranium in the Korean peninsula are extrapolated from geochemical analysis of the ROK's

Table 1. Geological maps used in this study.

	Title	Year	Information
1	Geological map of Chongjin (1:250,000)	1955	Geology compiled by Iwao Tateiwa and Osao Kadota, Tokyo Geographical Society, Japan
2	Geological map of Hun-Chun (1:250,000)	1955	Geology compiled by Shigeru Yabe, Tokyo Geographical Society, Japan
3	Geological map of Tung-Hsing-Chen (1:250,000)	1956	Geology compiled by Shigeru Yabe, Tokyo Geographical Society, Japan
4	Geological map of Yen-Chi (1:250,000)	1956	Geology compiled by Hiroshi Ozaki, Iwao Tateiwa, and Osao Kadota, Tokyo Geographical Society, Japan
5	Geological map of Fu-Sung (1:250,000)	1956	Geology compiled by Shigemitsu Okada, Tokyo Geographical Society, Japan
6	Geological map of Korea (1:1,000,000)	1956	Geological Survey of Korea and Geological Society of Korea
7	Geologic map of Daejeon (1:250,000)	1973	Geological and Mineral Institute of Korea, Hollym Corporation
8	Geological map of Korea (1:1,000,000)	1981	Korea Institute of Energy and Resources
9	Metallogenic map of Korea (1:1,000,000)	1983	Korea Institute of Energy and Resources
10	Geological map of Korean Peninsula and adjacent areas (1:1,500,000)	1990	Russian Academy of Sciences
11	Geological map of Korea (1:1,000,000)	1993	Geological Institute at the Academy of Sciences, Pyongyang, North Korea; Foreign Languages Publishing House
12	Tectonic map of Korea (1:1,000,000)	1994	Ministry of Natural Resources Development, Pyongyang, North Korea
13	World distribution of uranium deposits (1:35,000,000)	2018	IAEA Bulletin STI/PUB/1800 (ISBN 978-92-0-100118-4)

uranium deposits, which have been more exhaustively studied and reported on in the past decades. Through the lens of geologic settings, host rock ages, and mineralogical details, an estimated upper limit of production capacity and grade of uranium ore is provided for the suspected and known uranium mines of the DPRK.

Uranium geology

Uranium is a ubiquitous element in Earth's crust. It is found at conditions ranging from deep-Earth metamorphic rocks that have undergone alteration by extreme heat and pressure, to surficial sedimentary environments, with ages of these rocks and sediments varying from Neoarchean times (2800 Ma)[22] to the Quaternary Period (0.5 Ma).[23] While traces of uranium can be found in a variety of rock types, soils, rivers, and oceans, concentrated uranium ores—deposits with sufficiently high grades that make extraction economically viable—are relatively scarce. Depending on the geologic environment, uranium deposits differ in size, shape, host-rock type, and geochemical setting. The diversity and complexity govern the uranium concentrations in deposits.[24] For example, the concentration of uranium in ultramafic rocks is on average 4.8 ppm[25] or 0.0048% – this is about 5 mg of uranium per 1 kg of rock. In contrast, concentrations in marine phosphorites can be as high as 76 ppm on average.[26]

The key driver of uranium accumulation in all deposits and rock types is a redox process: a chemical reaction that affects the oxidation state of uranium, which governs its mobility and chemical reactivity in the environment. Uranium exists in nature primarily in two oxidation states: tetravalent (4^+) and hexavalent (6^+) uranium. Hexavalent uranyl ions are generally more soluble and consequently more mobile than are tetravalent uranium ions. The relative prevalence of each of these oxidation states depends on the redox conditions of the local geologic and geochemical environment. For example, in reducing conditions (lacking oxygen), tetravalent uranium exists primarily in the form of two minerals: dark-colored uraninite (UO_2), also known as pitchblende, and coffinite ($USiO_4$). Both can be oxidized into more mobile hexavalent species when exposed to oxygen. When these mobilized hexavalent uranium species are transported in a solution and meet a new reducing environment, they commonly precipitate out as bright yellow or orange-colored hydrated uranyl phosphate minerals, such as autunite ($Ca(UO_2)_2(PO_4)_2 10\text{-}12\,H_2O$) or uranyl oxyhydroxides, such as curite ($Pb_3(UO_2)_8O_8(OH)_6 \cdot 3H_2O$). While uranium is a major element in minerals like uraninite, it is a less abundant element in minerals such as autunite or curite and is therefore generally associated with lower uranium concentrations in the latter forms.

Hence, depending on the redox conditions, different uranium-bearing minerals are likely to form, yielding rocks of varying uranium content and, therefore, differing ore grades. Identifying the local geochemistry of a specific geologic setting provides a foundation for determining the origin of uranium in a deposit and the mineral formation process that was favored.

Characteristics of the deposit type and surrounding geology also govern the selection of mining and processing techniques. There are three primary means of extracting uranium resources: open pit mining, underground mining, and *in situ* leaching.[27] Each is suitable to particular depths and geologic settings. Open pit mining entails excavation of surficial soils and rocks and is employed for deposits in which uranium ore is relatively close to the surface (less than 150 m depth). Waste rock or overburden are stored near the pit while mining is ongoing. When the deposit is too deep for open-pit mining, either underground mining or *in situ* leaching is preferred. In underground mining, entry from the surface is made through a tunnel (known as a decline). Rock is removed through drilling and blasting to create smaller pieces of debris that are transported to the surface. The higher costs of underground mining, relative to open-pit mining, mean that the quantity or quality of uranium ore must be high enough to compensate. *In situ* leaching is a more recent and improved approach to uranium extraction that is less expensive and requires minimal excavation. Over half of the world's uranium is now mined by *in situ* leaching. Note that recently, *in situ* leaching is used at many sites that are shallow enough for open-pit mining because of its minimal environmental impact and surface disturbance. It involves pumping of a liquid with added oxidants or acidic solutions to mobilize uranium into solution, which is then carried through the ground and pumped to the surface at some prescribed distance from the injection wells. The uranium is then separated from the solution and recovered for processing.[28]

Because the types of uranium ore deposits vary and uranium geology can be complex, it is challenging to identify the exact origin, and thus the characteristics, of a deposit without extensive on-the-ground investigation. Nevertheless, by narrowing down the types of deposits likely to occur in the DPRK through evaluation of its geologic history and depositional environments, factors like ore grade and volume can be inferred.

The report now turns to the geology of the Korean Peninsula, followed by descriptions of well-characterized ROK uranium deposits, from which some characteristics can be extrapolated to the DPRK's nearby uranium deposits. Following the overall geology of the Korean Peninsula, a more detailed summary of the DPRK geology is provided. The DPRK geology is grouped into three principle chronologic eras and rock types: (1) Precambrian metamorphic basement rocks of ~1.6–2.6 Ga[29]; (2) Meso-Neoproterozoic rocks of 541–1600 Ma; and (3) Paleozoic sediments and magmatic rocks of ~251–66 Ma—alongside their relevance to the suspected mines. By comparing the depositional environments of the ROK's uranium deposits and the suspected uranium mines in the DPRK, this study provides a constraining analysis of the most likely ore grades of the deposits in the DPRK and provides a case study of how this bounded ore grade prediction can be used to estimate the DPRK's fissile material production capability.

Geology of Korean Peninsula

The Korean Peninsula is composed of heavily deformed Precambrian crystalline basement rock and successive sedimentary rocks with a ~3600 Ma history of crustal deformation.[30] The Peninsula can be divided into three major continental rock masses, known as massifs: (1) Rangnim (or Nangrim) massif in the North, (2) Gyunggi massif in the central peninsula, and (3) Yeongnam massif in the South. These massifs are separated by two main structural belts, or series of foothills formed from contractional tectonic movements: Imjingang belt in the north and Okcheon belt in the south. The current geopolitical division of the Korean Peninsula leaves the Rangnim massif predominantly in the DPRK, separated from the Gyunggi massif of the ROK by the Imjingang belt. The Rangnim massif is further subdivided into two submassifs, the Rangnim submassif in the western-middle parts that include the Phyungnam basin (PB) covering ~32,561 km^2, and the smaller Kwanmo submassif in the northeastern part. To the very east of the DPRK, there is another small massif, the Hambuk, bounded by the Seungchon fault next to the Kwanmo submassif.

Figure 3 shows a simplified map of Korean Peninsula with the distribution of the main geologic units of massifs and basins. Overlaid onto this simplified map is a list of reported and alleged uranium mines/mills of the DPRK, as well as the known ROK's uranium deposits. In some cases, the existence of a mine in DPRK can be confirmed by satellite imagery, but this method can be inaccurate, since the footprint of a mine can be very small.

Uranium deposits in the Republic of Korea

Uranium ore deposits have been explored on the Korean Peninsula since the mid-1950s when local radioactivity anomalies were first detected. In regions where such uranium signal is found, mineralization is related primarily to sedimentary, hydrothermal, or metamorphic rocks. Today, deposits associated with black shale in the OMB are the primary source of the ROK's uranium reserves. Okcheon (or Ogcheon or Okchon) is located in Chung-Cheong-do Province, in central-western Korea. Bounded by the

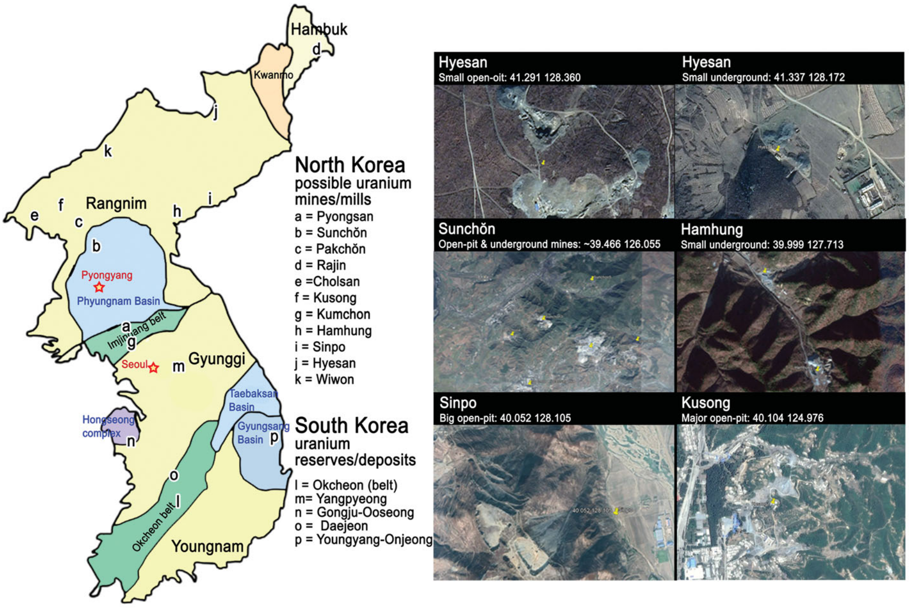

Figure 3. Simplified map of Korean Peninsula with major geologic units overlaid with reported and purported uranium mines/mills in the DPRK and documented uranium reserves in the ROK. This map is modified after Zhai et al. (2016).[31] The locations shown on the map are based on reported names of mining site and therefore may not be accurate. Some of the alleged mines were documented using satellite images (Images Google Earth).

Precambrian Yongnam Massif to the southeast and Gyonggi Massif to the northwest, the OMB is a NE-trending fold-and-thrust belt.[32] The site has been explored through conventional drilling and tunneling methods and reportedly contains ~34,000 tonnes of uranium.[33]

The OMB is composed mainly of fossil-poor metamorphosed fine-grained siltstone and sandstone of late Proterozoic (2500–541 Ma) to possibly early Paleozoic (~540–480 Ma) Okcheon system.[34] There are pockets of locally occurring calcareous (calcium carbonate-bearing) silicate, limestones, conglomerates, quartzites, and felsic metavolcanic rocks of Proterozoic age, as well as Jurassic and Cretaceous (145–66 Ma)) granitoids that intrude the metasedimentary rocks.[35] The complex geology here arises from the multiple geotectonic events that have deformed the Korean Peninsula. Geologists divide the OMB unit into more than 10 formations, among which is the Munjuri unit, composed of metamorphosed clays, which are associated with uraniferous black slates.[36]

Black slate is a term that includes carbonaceous black metasedimentary rocks that have been subjected to high pressures and high temperatures. The black slate is widespread in the OMB. Metalliferous black slates with high organic content extend for over 100 km and are interbedded with coaly slates, forming a 20–40 km thick layer.[37] In this black slate layer, the bulk of the uranium is adsorbed onto clay minerals, with the exception of rare cubes of uraninite that are often several micrometers in size.[38] Uranium primarily exists in the tetravalent form in uraninite (UO_2) within the coaly slates, and as uranothorite ($(Th, U)SiO_4$) in black slates.[39] To a lesser degree, it is also found in hexavalent form.[40] Geologists have also reported that various sulfide minerals, such as pyrite (FeS_2), are readily associated with uraninite in the coaly slate layers, along with barite ($BaSO_4$).[41] Uranium is commonly accompanied by redox-sensitive trace elements, such as vanadium, molybdenum, and nickel. Independent geochemical analyses of various studies indicate a consensus on very low-grade uranium in the OMB, on average ~0.023–0.036 wt.% uranium metal or less.[42] There is currently no uranium being mined from the OMB.

Apart from the well-investigated OMB, there are three minor uranium occurrences in the ROK. First, there is the metamorphic terrane of Gyunggi massif, encompassing the Jungwonsan, Yunmuyngsan, and Bonapsan prospects, located 50 km northeast of Seoul.[43] According to Dahlkamp, these are small, fracture-controlled uranium concentrations at the contact of highly deformed quartzite and gneiss or schist of Proterozoic age. Uranium in this metamorphic terrane is in the form of pitchblende (UO_2). While the ore concentration is not reported by Dahlkamp, underground water evaluation by the Korea Institute of Geosciences and Mineral Resources report uranium concentration up to 242 µg/L.[44] Another minor occurrence is related to sandstone-type uranium mineralization of the Cretaceous Gyungsang system in Youngyang Basin—Onjeong to the east coast and Gonggju-Ooseong in central Chungcheongnam-do, western Korea.[45] The third minor uranium occurrence is related to the Jurassic aged granite rocks near Daejeon Province near the central OMB, first reported by Hwang and Moon in 2018.[46] The uranium-bearing minerals found here are associated with pegmatite bodies and hydrothermally-altered parts of granite of the late Jurassic and early Cretaceous age.[47] Geochemical analyses of these studies indicate low $CaO + Na_2O$ and high K_2O contents in the uraniferous rocks with an intense alteration index from potassium-metasomatism.[48] None of the above reserves have sufficient uranium contents or ore grades to be considered economically viable. For example, the average uranium grade in hydrothermally altered granites in Daejeon area is less than 0.001% or 10 ppm uranium.[49]

Detailed geology of the DPRK and relevance to alleged and reported uranium mines

To better understand the type of uranium deposits that may occur in the DPRK, it is useful to identify the state's major geologic features. In general, the relevant features can be delineated into three groups: Precambrian metamorphic rocks, Meso-Neoproterozoic rocks, and Paleozoic sediments and Mesozoic magmatic rocks.

1. **Precambrian rocks (Hadean Eon to Paleoproterozoic Era – >4000–1600 Ma):** Underlying the Rangnim Massif of DPRK are two ancient Precambrian complexes,[50] the Archean and Paleoproterozoic complexes.
   i. The Archean (4000–2500 Ma) complex in the Rangnim submassif consists of metamorphosed igneous rocks such as orthogneisses,[51] and supracrustal rocks[52] made up of mica-quartzite, hypersthene ($(Mg,Fe)SiO_3$) plagioclase[53] and 2.5–2.58 Ga gneisses. Archean rocks in the Kwanmo submassif comprise the supracrustal sequence known as the Musan group, along with orthogneisses and granites. The Musan group consist of biotite gneiss, amphibolite, bi-mica schist,[54] and quartzite.[55]
   ii. Paleoproterozoic (2500–1600 Ma)) metamorphic rocks in the Rangnim massif have two distinct metamorphic grades[56]—a low-grade volcanic sedimentary sequence of the Macheollyung group and high-grade granulite facies[57] referred to as the Jungsan group. The Macheollyung group is particularly dominant in the Kwanmo submassif. The Jungsan group, composed mostly of Paleoproterozoic granites, is well-developed in the southwestern part of Rangnim submassif. There are also pockets of igneous rocks that solidified from a melt at great depth, known as the plutonic rocks, which intrude into the Rangnim massif.

Hadean-Archean rocks rarely host large uranium ore deposits, while Proterozoic metamorphic rocks do. The concentration of uranium resulting from metamorphic processes that developed in the Precambrian rocks of the DPRK is similar to the minor uranium occurrence in Proterozoic metamorphic terrane of South Korea's Guynggi Province, as reported by Dahlkamp,[58] or perhaps comparable with the Lianshanguan uranium deposit in Northeast China.[59] The abundance of uranium can vary depending on the grades and constituent minerals of the metamorphic rocks. Granulite facies (high-grade metamorphism at medium pressure and higher temperature) are relatively depleted in uranium as compared with the equivalent rocks of amphibolite facies (medium-grade metamorphism at medium pressure and lower temperature).[60]

Geologic analysis indicates the occurrence of Proterozoic metamorphic rocks at several alleged mines. Sinpo mine is located near the Lower Proterozoic Machollyung group. This is important as the presence of Precambrian metamorphic rocks implies the possibility of metamorphite-type uranium deposits in this alleged mine. If this mine is extant and its ore is of metamorphic origin, its approximate ore grade may be inferred from that of the ROK's metamorphic terrane-based uranium resource, or the Lianshanguan uranium deposit, based on regional proximity and rock type similarity. The average grade of uranium in the ROK's metamorphic terrane-based uranium resources is very low (less than 0.005% uranium).[61] The Lianshanguan uranium deposit has formations that are comparable to those of the DPRK in terms of age and lithology. The average uranium contents of the main host rocks range from 6.65 ppm (0.000665% uranium) in schist to 14.36 ppm (0.0014% uranium) in alkaline metamosomatite rocks.[62] However, their viability as a resource remains uncertain at this stage without detailed, on-the-ground geochemical and mineralogical analysis.

2. **Meso-Neoproterozoic rocks (1600–541 Ma):** Meso-neoproterozoic rocks are heavily concentrated in the Phyungnam Basin (PB) of the DPRK. There are two notable groups within the Meso-neoproterozoic rocks that are of interest: (1) the Mesoproterozoic (1.6–1.0 Ga) Sangwon group, which is further divided into four subgroups, mostly of sedimentary compositions; and (2) the Neoproterozoic (100–541 Ma) Kuhyon group.

The Pyongsan, Kumchon, and Hyesan mines are located near the sedimentary Mesoproterozoic Sangwon group, as well as the Neoproterozoic Kuhyon. To expand on the characteristics of their rock types, the sedimentary Sangwon group is discussed in detail below:

a) Jikuhyun, with 2.5–2.1 Ga conglomerates, sandstone, pelitic siltstone, and carbonate schist
b) Sandangu composed of dolomite and limestone; and
c) Mukchon and Myoraksan consisting of limestone, dolomite, phyllite, calcareous conglomerate, and quartz sandstone.

These four subgroups are overlain unconformably by the Yontan group, composed of dolomite, shale, and fine sandstone, which marks the youngest layer of the Proterozoic eon underlain by the Cambrian Hwangju system.[63] The Hwangju system begins with the Pyongsan group, which is composed of a phosphorus and sulfide-bearing black slate, along with dolomite, limestone, pelite, and argillaceous limestone.[64]

Another notable formation is the upper Riphean-Vendian (1600–541 Ma) Kuhyon suite, which is primarily composed of phyllites, sedimentary clay shales, and calcareous shales with pebbles. The rock compositions are like those of the Mesoproterozoic Sangwon group, but the age of Kuhyon suite is slightly younger. The Kuhyon suite outcrops substantially at multiple geological faults surrounding the PB, including near the Pyongsan and Kumchon uranium mines.

The sedimentary Meso-Neoproterozoic rocks found here are closely related to those of the OMB in the ROK. The geologic settings of both regions are dominated by sedimentary rocks, among which the carbonaceous black shale unit is key to uranium mineralization.[65] While mineralogical details for each of the suspected or reported DPRK uranium mines are unavailable, an IAEA report identifies the presence of "black shale" at a uranium mine in the DPRK, a fact also mentioned by Sozinov and later repeated in a Nautilus Institute report in 2004.[66] This is consistent with the available geologic maps. Sozinov identified "high carbonaceous deposits (black shale)" located between the upper Cambrian Mukchon[67] and lower Cambrian Yongdeok formation, as well as the lower Paleozoic zones.[68] The correlation of coffinite, a uranium silicate, and pyrite, an iron sulfide, in carbonaceous shales made by Sozinov, agrees with the geochemical features found in the OMB, in that the uranium occurrence is related to phosphorus, vanadium, chromium, nitrogen, barium, and lead, along with some of rare earth elements (REE), which also commonly occur in the OMB of the ROK.[69]

Based on their comparable geological settings, host rock age, and mineralogical details, this study hypothesizes that the following suspected and reported mines in the DPRK are probably metamorphosed organic shale deposits similar to those found in the OMB: Pyongsan, Kumchon, and Hyesan, with an average ore grade of 0.03% uranium. These siliceous, carbon-rich shales are dense and reminiscent of "anthracite." However, these metamorphic organic shales differ from anthracite in their higher degree of metamorphism and the consequent increased non-carbon content. While some spatial variation in ore grade will occur throughout these deposits, grades will rarely exceed 0.2% uranium. This approximate upper bound is derived from the hypothesized hydrothermal venting origin of uranium mineralization, which typically yields low-grade uranium ore, below 0.1–0.2% uranium.

Mines associated with these settings likely represent the DPRK's most abundant sources of natural uranium. As such, more detailed assessment is warranted. While the majority of recent assessments claim a much higher ore grade for the DPRK uranium mines—up to 0.9%—several reports project uranium ore quality ranges consistent with the geologic interpretations here. A notable description comes from Sozinov, who had access to the ground prior to the early 1990s.[70] The author collected sets of sedimentary rocks from the Upper Cambrian Mukchon and Lower Cambrian Yongdeok formations. Geochemical analysis showed uranium contents from 21.8 to 323.9 ppm, equivalent to ∼0.002–0.03 wt.% uranium in carbonaceous-siliceous schist within carboniferous shales.[71] Sozinov also noted that ∼0.1–0.2 wt.% or higher-grade uranium was found in exceptional cases of carbon-siliceous shale.[72] In the case of these higher uranium concentrations, superimposed processes involving successive stages of deformation and recrystallization enhanced the local concentration of uranium, such that these values do not reflect the typical concentration of primary uranium distribution.[73] The values reported by Sozinov represent the sole source of on-the-ground investigations that exists in the open-source literature. As far as the average grades are concerned, the overall ore grade given by Sozinov is substantially lower than that mentioned in a telegram from the Hungarian ambassador to the DPRK in 1979, who described the average ore grade at that time as "0.26 and 0.086%" for the two main uranium mines (believed to be Pyongsan = 0.26% and Pakchon = 0.086%).[74]

To further refine estimates of uranium ore grades in metamorphosed organic shale deposits, comparison with geologically similar sites outside the DPRK proves instructive. Typical uranium contents of black shale deposits worldwide range from 3 to 250 ppm (0.0003–0.025%), with an average around 8 ppm.[75] Two particular black shale deposits, the Niutitang Formation of the Guizhou Province in South China and a lower unit of the Peltura zone (Alum Shale Formation) of the Närke region in Sweden, exhibit geologic similarity with DPRK deposits, allowing for a better comparison. As in the DPRK case described by Sozinov, the Niutitang and Alum Shale Formations feature coffinite and uraninite as some of the primary uranium-bearing minerals, and both are associated with metal sulfides, phosphates, limestones, and abundant organic substances.[76] They are also comparable in age, since all are Cambrian (541–485.4 Ma) formations. The uranium content ranges from 20 to 600 ppm (0.002–0.06% uranium) with an average of 0.0024–0.006% uranium in the Niutitang Formation; and it ranges from 100–300 ppm (0.01–0.03% uranium) with an average of 0.02% uranium in the Alum Shale Formation.[77] These ore concentrations are within the anticipated range for uranium metamorphosed organic shale deposits from a geochemical perspective, and agree well with the estimated uranium ore grades determined here for the Pyongsan, Kumchon, and Hyesan DPRK uranium mines.

Interestingly, underneath the plan view, regions nearby Pyongsan may also have uranium-bearing siliceous phosphate spheroids–small, irregular knots of minerals composed of silica and phosphate (Figure 4). Sozinov indicated a "scattered or clotted form of spheroids that contain uranium" in which the content of uranium was found to correlate with organic

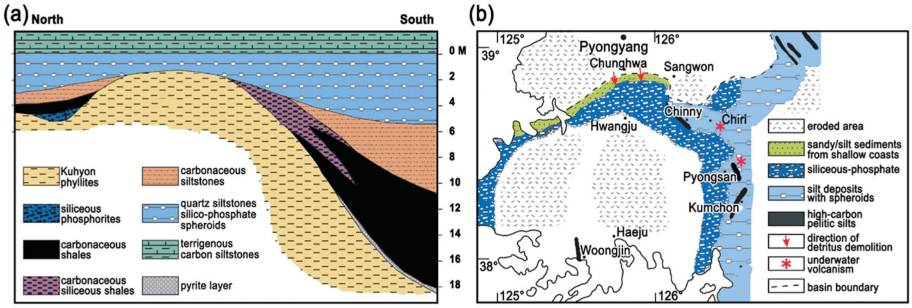

Figure 4. (a) Cross-sectional stratigraphy of the Chinny-Chiri region. (b) Geological map near Pyongyang. Both figures are from Sozinov (2008).[83] Translation and color-codes were added by Park.

matter and phosphates.[78] The uranium content of phosphate siltstone samples from the Hwangju syncline near Chiri district[79] was measured to be up to 1,000 ppm (or 0.1% uranium), with an average of 388.4 ppm (or 0.0388% uranium), signifying a slightly higher average uranium grade in phosphate–bearing formations as compared with that of the organic shale.[80] A partial stratigraphic unit included in the study (Figure 4(a)) exhibits a layer of ~3.7 m long, 1.25 m thick siliceous phosphorites, as well as a layer of 32 m long, ~4 m thick quartz-siltstones silico-phosphate spheroids. While descriptive chemical compositional analysis is unavailable, some areas with a higher uranium ore grade (up to 0.1% uranium) may be expected in Pyongsan uranium mine and nearby areas. Curiously enough, ROK previously extracted uranium metal from imported phosphate fertilizers, perhaps comparable to those obtained in phosphorite deposits of the DPRK, for use in its nuclear research activities.[81] The average uranium concentration in the imported phosphate fertilizers ranged up to ~0.014% uranium.[82]

3. **Paleozoic (541–251.9 Ma) sediments and Mesozoic (251.9–66 Ma) magmatic rocks**: Paleozoic sediments are found throughout the PB. These sediments are of two main groups: (1) the Joseon supergroup of Cambrian (541–485.4 Ma) and Ordovician (485.4–445.2 Ma) carbonate series and; (2) the Pyungan supergroup of Carboniferous–Permian (358.9–251.9 Ma) and Triassic (251.9–201.3 Ma)) coal seams, shale, and limestone. Mesozoic magmatic rocks include the following: (1) Triassic magmatic rocks that are ~220 Ma composed of syenite, calc-alkalintie and kimberlite from post-orogenic settings[84]; (2) a Jurassic group of ~190–170 Ma, including biotite, granites, and granodiorites and; (3) late upper Cretaceous granites of ~110 Ma.

The Paleozoic sediments distributed between the southern and northern Korean peninsula are quite comparable.[85] Ordovician limestones are particularly well exposed in the Northern part of the PB, near the Sunchŏn mine; and in northern Chagang province, near the Wiwon mine. The two mines can be characterized as limestone deposit. In many of the suspected and recognized uranium mines, patches (plan view of 400–600 m^2) of Mesozoic granites are readily observed from geological maps. This is especially true in Kusong, where granites of Jurassic, Triassic, and Cretaceous age are dominant. In Kusong, there are also small patches of Cretaceous sedimentary rocks, composed of sandstone, shales, and limestones that are exposed. The regional geology here suggests that if extant, the uranium deposit is most likely granite related. Thus, uranium mineralization at these sites might be comparable to that of the pegmatitic and hydrothermally altered granite in the Daejeon area near the central OMB of the ROK. Uranium concentration near the Daejeon area is attributed to the post-magmatic hydrothermal alteration of potassium-metasomatism during the Jurassic-Cretaceous period. The uranium ore quality in Jurassic granites of the Daejeon area is $\sim$ 0.001%.[86] If they are of comparable origin, the granite-related uranium deposits in Kusong would likely be of very low grade.

Summary of uranium ore grade in the DPRK

A brief synopsis of the geology and host rocks found in each suspected mine in the DPRK and the OMB in the ROK is illustrated in Figure 5, accompanied by Table 2. Based on the geologic analysis presented here, it is estimated that average uranium ore grades are roughly 0.001–0.04% at the majority of known and alleged DPRK mines. It is important to stress that local heterogeneity in ore grade will exist within a deposit, a formation, and among their constituent rocks; some mines might therefore overlie relatively high-grade ores within a heterogeneously distributed ore body. For example, based on comparison with the OMB, variations in ore grade of metamorphosed organic shale deposits in the DPRK are expected to yield local concentrations ranging, at most, from roughly 0.0001 wt.% to 0.4 wt.%. The minimum and maximum bound here are deduced from a study on the OMB, in which the uranium concentration in a single grain ranged from $\sim$38 ppm to $\sim$4,500 ppm.[87] However, the extreme uranium concentration in a single grain reflects the resuspension of sediment in an anoxic environment that amplified the diffusive exchange between particles and water at the time the grain was formed. While the concentration is observed among constituent grains, it is not necessarily related to the uranium content of the bulk rock concentration, which, in the case of the OMB, is no greater than 0.036% uranium on average.[88] Given the overall

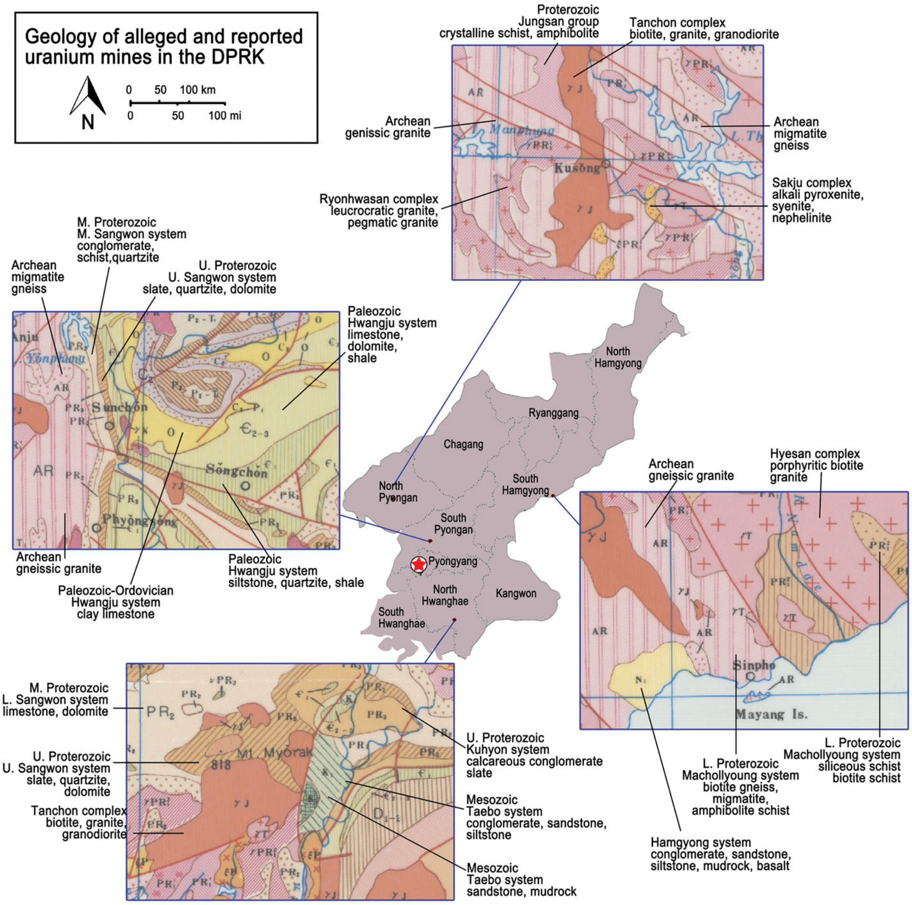

Figure 5. Geology of the most re-occurring alleged and reported uranium mines in DPRK. Geologic details were taken from the "Geological map of Korea, produced by Geological Institute Academy of Sciences, DPRK (Ministry of Natural Resources Development, Pyongyang, 1993)", scale: 1:1,000,000.

geology of the ore deposits and drawing from comparison with ore grades of nearby shale deposits with commensurate geochemistry, there is reason to believe that substantial quantities of ore with average grades above 0.2% are unlikely. As stated above, the 0.2% is derived from an expectation that uranium mineralization resulted from hydrothermal processes, which typically yield ore grades of 0.1–0.2% at most. This average ore grade and the corresponding predicted ore grade range are significantly lower than those commonly used in analysis of the DPRK fissile materials production.

It is also worth noting that the uranium resources remaining in the known and alleged deposits in the DPRK today are high grade. In an ordinary case, a cost-benefit analysis determines the minimum ore grade and production quantity of commercially mined resources. In other words, resource extraction practices are governed by economic concerns. However,

Table 2. Name of reported and suspected uranium mines with predicted deposit type and ore grade.

	Name	Predicted deposit type	Predicted ore grade (%U metal)
DPRK	Cholsan	Monazite from pegmatite deposit or granite related	Average of ~0.001%, with an upper bound of ~0.05%.
	Hamhung	Possibly granite-related or metasomatite	Average of ~0.001%, with an upper bound of ~0.05%.
	Hyesan	Metamorphosed organic shale or anthracite coal mines	Average of ~0.03%, with an upper bound of ~0.2%.
	Kumchon	Metamorphosed organic shale	Average of ~0.03%, with an upper bound of ~0.2%.
	Kusong	Monazite from pegmatite deposit or granite related	Average of 0.001%, with an upper bound of ~0.05%.
	Pyongsan	Metamorphosed organic shale	Average of ~0.03%, with an upper bound of ~0.2%.
	Rajin (Najin or Sonbong, or Woonggi-Ungki)	Granite related	Average of ~0.001%, with an upper bound of ~0.05%.
	Sinpo	Metamorphic terrane	Average of ~0.005%, with an upper bound of ~0.01%.
	Sunchŏn (Wolbisan)	Limestone	Average of ~0.04%, with an upper bound of ~0.2%.
	Wiwon	Limestone	Average of ~0.04%, with an upper bound of ~0.2%.
ROK	Daejeon, central OMB	K-metasomatite	Average of ~ 0.001%, and locally up to 0.0024%
	Gongju-Ooseong	Sandstone-type	Average of ~0.005% or less
	Okcheon	Metamorphosed organic shale (black shale)	Average of ~ 0.02–0.036%
	Yangpyeong	Metamorphic terrane	Average of ~0.005% or less
	Youngyang-Onjeong	Sandstone-type	Average of ~0.005% or less

in the extraordinary case of the DPRK, conventional cost-benefit analyses are likely not used, and uranium may be mined regardless of the quality and cost, most likely in the order of the deposits' ore grades. Given the history of uranium production in the DPRK—both the possible export of higher-grade uranium ore and continuous demand for uranium for weapons production activities—the uranium resources remaining today might be of lower-than-average grade due to the depletion of high-grade resources. The DPRK is likely to have first mined specific portions of the available deposits with ore grades at the higher end of the predicted range in order to reduce production costs and increase production rates. The average ore grade of the deposit, and thus of mined ore, would therefore be reduced. Hence, it is argued that the 0.001–0.04% range deduced from geological maps and literature review should generally match to what would be mined today.

Understanding production capacity based on the ore grade estimates

Commonly, the production capacity of a deposit is evaluated by estimating quantity and quality of ore, of which the former value is dependent on the

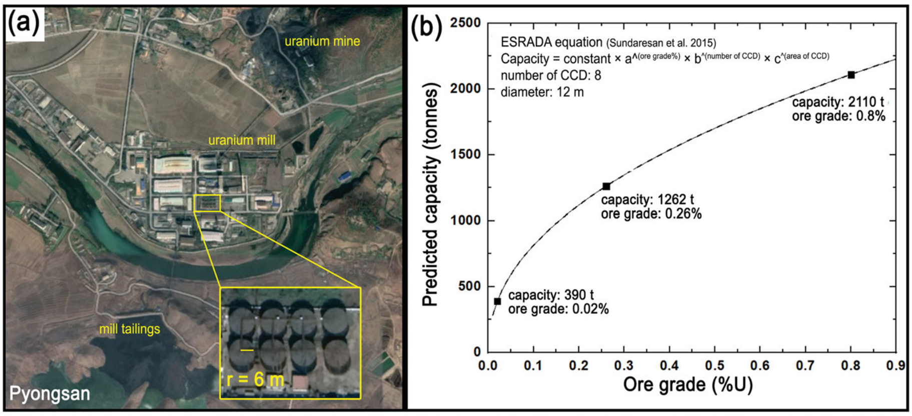

Figure 6. (a) Optical satellite image of Pyongsan uranium mine and mill. The inset shows what appear to be eight CCD units in the Pyongsan ore processing plant. Satellite image is from Google Earth. (b) Predicted uranium production capacity (tonnes/year) as a function of increasing ore grade (%uranium) based on the model developed by Sundaresan et al. (2015).[92] When ore grades higher than those determined here (~0.02% uranium) are assumed, the predicted mill production capacity increases severalfold.

thickness and length of the subsurface metal-bearing horizon. However, the lack of available detailed regional cross-sectional stratigraphy of each alleged and reported uranium mine in the DPRK severely hinders any attempt to accurately determine ore volume. Given the lack of necessary data, one relies primarily on ore grade as an indicator of DPRK uranium resource characteristics. This section demonstrates how ore grade estimates based on geological analysis (0.02–0.2% uranium) influence DPRK uranium and fissile material production models.

A number of studies have used satellite imagery in an attempt to estimate the processing capacity of known uranium mills, which may indicate the annual U_3O_8 (triuranium octoxide) production rate for which the mill was designed.[89] One such method entails measurement of the counter current decantation (CCD) units, also known as thickeners, that are used to separate dissolved uranium-bearing minerals from the gangue ore (Figure 6(a)) in uranium mills. The annual mill production capacity is estimated as a function of assumed ore grade and the size and number of CCD units.[90] Figure 6(b) illustrates that the predicted production capacity is quite sensitive to the ore grade value assumed, such that geologically-informed ore grade determinations serve as a critical prerequisite to any such modeling.

It should be noted that while the concept of utilizing the visible signatures from satellite imagery to calculate the production capacity has an attractive simplicity, such an analysis could yield specious results. Critically, there is no theoretical correlation between the CCD size and production capacity, as mill design criteria are driven mainly by the clay content of the ore and by the uranium losses a producer is willing to endure at this processing stage. Hence, CCD sizes and counts alone are of limited utility in assessing production capacity.[91]

An alternative approach, used by von Hippel, involves calculation of annual uranium ore extraction requirements based on the DPRK's esimated 2018 inventories of fissile material and low-enriched uranium, assuming ore grades of 0.15–0.9%.[93] These calculations take into account myriad factors, such as conversion losses at each processing step. Assuming that uranium hexafluoride conversion and enrichment technology used by the DPRK are comparable to advanced systems used elsewhere, the resulting model reasonably relates the quantity of uranium metal mined to the resulting fissile material and low-enriched uranium inventories.[94] As with the former approach, the results of these calulations are highly dependent on the assumed uranium ore grade, which determines the quantity of uranium metal contained in extracted ore. Using the same conversion factors as von Hippel, this study illustrates in Figure 7 how the predicted annual uranium ore requirements change when the ore grades determined via geologic analysis (0.02–0.2%) are used. The predicted ore requirements, and the related production capacity, differ by an order of magnitude due to the use of different uranium ore grades in each scenario. This analysis may

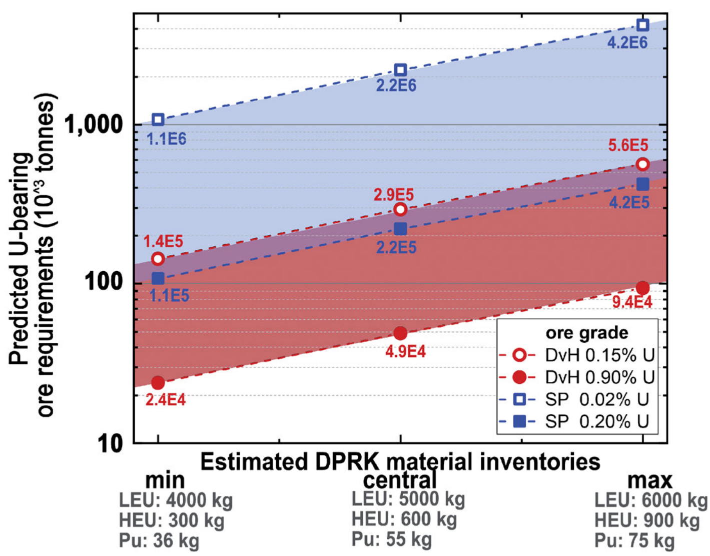

Figure 7. Estimates of annual uranium ore requirements (tonnes) for plutonium, highly-enriched uranium and low-enriched uranium. Calculations using the ore grades assumed by David F. von Hippel (DvH, 0.15–0.9% uranium) are compared with those using the ore grades determined via geologic analysis in this study (SP, 0.02–0.2% uranium). Following von Hippel, three sets of estminated material inventory sizes are used (min, central, and max) to account for uncertainty in the precise DPRK stockpile size.[95]

serve as an important data point for future assessment of the DPRK's fissile material production capacity.

Conclusions and future outlook

There remain many uncertainties with respect to the DPRK's uranium resources; without onsite access for direct sampling, these uncertainties cannot be resolved. New, complementary methods for the estimation of resource characteristics and fissile material production capacities are therefore necessary to better bound predictions. This study reports the results of one such method, a detailed analysis of the available geologic data.

By evaluating the overall and regional surfacial geology of the reported and suspected uranium mines in the DPRK, and correlating these features to those of known uranium deposits in the ROK, China, and elsewhere, the type of deposits that that are likely to be encountered and their corresponding uranium ore grade have been inferred. This study infers that the dominant rock-type of the uranium deposits at four DPRK uranium mines (Pyongsan, Kumchon, Sinpo, and Hyesan) is metamorphosed organic shale, with an average ore grade of approximately 0.03% uranium and a likely upper bound of approximately 0.2% uranium. Some higher grade uranium deposits may be found in Pyongsan, specifically within phosphate-bearing formations below the organic shale. The Hamhung, Kusong, Cholsan, and Rajin mines are likely granite/metasomatite-related, all with very low grade uranium (<0.01% uranium).[96] Sunchŏn and Wiwon mines may be associated with a limestone deposit, in which the average ore grade is estimated to be ~0.04% uranium, perhaps similar to uranium-bearing phosphate rocks in China.[97] Of course, this analysis assumes that these alleged mines do exist, which is not clearly established for a number of the locations.

In quantifying the ore volume and correponding production capacity of inaccessible regions like the DPRK, satellite imagery has the potential to identify visible features that can further clarify the processes of uranium production. For example, an accurate volume estimation of mill tailings over time can aid in determination of the rate at which it processes ore, assuming ore characteristics are understood. Similarly, observation of railcar movements in and out of the milling facility can aid in the bounding of ore volume processing rates. Tracking of the movements, type, and size of railcars might elucidate the plausible amount of yellowcake production onsite. Future studies should focus on determining and correlating these and other physical variables at mining and milling sites, in order to better explain the general scope of uranium production. In all cases, insight from rigorous geologic analysis will prove invaluable as inputs into production models.

Acknowledgements

This work is supported by the Nuclear Threat Initiative (NTI), under a Grant ID 5145. S.G.Y. Park thanks Terence P. McNulty for his immense help on analyzing uranium milling processes, Professor Moon-Sup Cho and Director Sang-Mo Koh for their valuable input and intellectual discussions that made this manuscript possible.

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[24]Ibid.; Peter C. Burns and Robert Finch, Uranium: Mineralogy, Geochemistry and the Environment.
[25]ppm is parts per million, equivalent to 0.0001%.
[26]Rock type and corresponding uranium content is from W. L Lasseter, "Uranium Occurrence and Distribution in Virginia," Presentation to the National Research Council Committee on Uranium Mining, 13 December 2010, Danville Virginia, and references therein. Uranium deposit types are from International Atomic Energy Agency and the OECD Nuclear Energy Agency, "Uranium Resources, Production and Demand," (1997), https://www-pub.iaea.org/MTCD/Publications/PDF/te_1258_prn.pdf, and https://www.oecd-nea.org/ndd/pubs/2018/7413-uranium-2018.pdf; International Atomic Energy Agency. Geological Classification of Uranium Deposits and Description of Selected Examples. 2018, available at https://www.oecd-nea.org/ndd/pubs/2018/7413-uranium-2018.pdf.
[27]See for example, *International Atomic Energy Agency, Uranium Extraction Technology*, (Vienna: International Atomic Energy Agency, 1993).
[28]Maxim Seredkin, Alexander Zabolotsky, and Graham Jeffress, "In Situ Recovery, an Alternative to Conventional Methods of Mining: Exploration, Resources Estimation, Environmental Issues, Project Evaluation, and Economics," *Ore Geology Reviews* 79 (2016): 500–514, https://www-pub.iaea.org/MTCD/Publications/PDF/trs359_web.pdf.
[29]Ga is giga-annum or billion years ago.
[30]See for example, Sung Kwun Chough, *Geology and Sedimentology of the Korean Peninsula* (Elsevier-Health Science, 2014), ISBN 978-0-12-405518-6, http://doi.org/10.1016/C2012-0-02847-5.
[31]Mingguo Zhai et al., "The Geology of North Korea: An Overview," *Earth Science Reviews* 194 (2019): 57, https://www.sciencedirect.com/science/article/pii/S0012825219300509?via%3Dihub

[32]Gi Young Jeong, "Mineralogy and Geochemistry of Metalliferous Black Slates in the Okcheon Metamorphic Belt, Korea: A Metamorphic Analogue of Black Shales in South China block," *Mineralium Deposita* 41 (2006): 469–481, https://link.springer.com/article/10.1007/s00126-006-0067-5.
[33]The uranium potential for South Korea is category 2 – 1,000-10,000 tons uranium; it has a large source of low grades in black shales of the country – category 6: 500,000 to 1,000,000 tons of uranium," from M. V. Hansen, "Republic of Korea" (IUREP N.F.S No. 154, IAEA, Vienna, 1977), 15.
[34]See for example, Inkyu Shin, Sunghyun Kim, Dongbok Shin, "Mineralogy and Sulfur Isotope Compositions of the Uraniferous Black Slates in the Ogcheon Metamorphic Belt, South Korea," *Journal of Geochemical Exploration* 169 (2016): 1–12, https://doi.org/10.1016/j.gexplo.2016.07.008; Chang Whan Oh, Sung Won Kim, In-chang Ryu, et al., "Tectono-metamorphic Evolution of the Okcheon Metamorphic Belt, South Korea: Tectonic Implications in East Asia," *The Island Arc* 13 (2004): 387–402, https://doi.org/10.1111/j.1440-1738.2004.00433.x; YoungJae Kim, Jieun Seo, et al., "Geochemistry and Uranium Mineralogy of the Black Slate in the Okcheon Metamorphic Belt, South Korea," *Geochemical Journal* 49 (2015): 443–452, https://doi.org/10.2343/geochemj.2.0369; Moonsup Cho, Wonseok Cheong, W.G. Ernst, Keewok Yi, Jeongmin Kim, "SHRIMP U-Pb Ages of Detrital Zircons in Metasedimentary Rocks of the Central Ogcheon Fold-Thrust Belt, Korea: Evidence for Tectonic Assembly of Paleozoic Sedimentary Protoliths," *Journal of Asian Earth Sciences* 63 (2013): 234–249, https://doi.org/10.1016/j.jseaes.2012.08.020.
[35]Ibid.
[36]Jeong, "Mineralogy and Geochemistry of Metalliferous Black Slates in the Okcheon Metamorphic Belt: Korea: A Metamorphic Analogue of Black Shales in South China block."
[37]Shin et al., "Mineralogy and Sulfur Isotope Compositions of the Uraniferous Black Slates in the Ogcheon Metamorphic Belt, South Korea"; Oh et al., "Tectono-metamorphic Evolution of the Okcheon Metamorphic Belt, South Korea: Tectonic Implications in East Asia"; Kim et al., "Geochemistry and Uranium Mineralogy of the Black Slate in the Okcheon Metamorphic Belt, South Korea"; Cho et al., "SHRIMP U-Pb Ages of Detrital Zircons in Metasedimentary Rocks of the Central Ogcheon Fold-Thrust Belt Korea: Evidence for Tectonic Assembly of Paleozoic Sedimentary Protoliths."
[38]Kim et al., "Geochemistry and Uranium Mineralogy of the Black Slate in the Okcheon Metamorphic Belt, South Korea."
[39]Shin et al., "Mineralogy and Sulfur Isotope Compositions of the Uraniferous Black Slates in the Ogcheon Metamorphic Belt, South Korea."
[40]Shin et al., "Mineralogy and Sulfur Isotope Compositions of the Uraniferous Black Slates in the Ogcheon Metamorphic Belt, South Korea"; Oh et al., "Tectono-metamorphic Evolution of the Okcheon Metamorphic Belt, South Korea: Tectonic Implications in East Asia"; Kim et al., "Geochemistry and Uranium Mineralogy of the Black Slate in the Okcheon Metamorphic Belt, South Korea"; Cho et al., "SHRIMP U-Pb Ages of Detrital Zircons in Metasedimentary Rocks of the Central Ogcheon Fold-Thrust Belt Korea: Evidence for Tectonic Assembly of Paleozoic Sedimentary Protoliths."
[41]Kim et al., "Geochemistry and Uranium Mineralogy of the Black Slate in the Okcheon Metamorphic Belt, South Korea."
[42]Shin et al., "Mineralogy and Sulfur Isotope Compositions of the Uraniferous Black Slates in the Ogcheon Metamorphic Belt, South Korea"; Oh et al., "Tectono-metamorphic Evolution of the Okcheon Metamorphic Belt, South Korea: Tectonic Implications in East Asia"; Kim et al., "Geochemistry and Uranium Mineralogy of the Black Slate in the

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[43]Franz J. Dahlkamp, *Uranium Deposits of the World: Asia* (Berlin, Heidelberg: Springer Berlin Heidelberg, 2009), 321–390, http://dx.doi.org/10.1007/978-3-540-78558-3.

[44]242 microgram per liter is equivalent to 0.242 ppm. Byong-Wook Jo, Jeong-Chan Ho, Han-In Sup et al., "Investigation of natural radioactive materials in groundwater (II)" (Final Report, Korea Institute of Geoscience and Mineral Resources, Korean National Academy of Sciences, 2009), in Korean.

[45]Dahlkamp, "*Uranium deposits of the world – Asia*"; M. Matolin and M. Tauchid, Report to the Government of the Democratic People's Republic of Korea, Uranium Prospecting, DRK/3/003 Evaluation Mission, 1987.

[46]Jeong Hwang and Sang-Ho Moon, "Geochemical Evidence for K-metasomatism Related to Uranium Enrichment in Daejeon Granitic Rocks near the Central Ogcheon Metamorphic Belt, Korea," *Geosciences Journal* 22 (2018): 1001–1013, https://link.springer.com/article/10.1007/s12303-018-0053-9.

[47]Ibid.

[48]Index of alteration is used as a means to measure the role of chemical weathering in the production of clastic sediments, see for example, Karin Goldberg and Munir Humayun, "The Applicability of the Chemical Index of Alteration as a Paleoclimatic Indicator: An Example from the Permian of the Parana Basin, Brazil," *Paleogeography, Paleoclimatology, Paleoecology* 293 (2010):175–183, https://doi.org/10.1016/j.palaeo.2010.05.015.

[49]Hwang and Moon, "Geochemical Evidence for K-metasomatism Related to Uranium Enrichment in Daejeon Granitic Rocks near the Central Ogcheon Metamorphic Belt, Korea"; Jeong Hwang "Occurrence of U-minerals and Source of Uranium in Groundwater in Daebo Granite Daejeon Area," *The Journal of Engineering Geology* 23 (2013): 399–407, in Korean, with partial English, https://doi.org/10.9720/kseg.2013.4.399.

[50]Complexes refer to units of rocks composed of multiple rock types.

[51]Orthogneiss is a type of gneiss derived from igneous rocks, where gneiss refers to metamorphic rock that is formed by high temperature and pressure.

[52]Supra-(above) crustal refers to rocks deposited on top of the basement complex.

[53]Plagioclase is a feldspar mineral group (NaAlSi3O8 – CaAl2Si2O8).

[54]Schist is a type of metamorphic rock exhibiting complex folding patterns.

[55]Mingguo Zhai et al., "The Geology of North Korea: An Overview."

[56]Grades of metamorphism refer to the pressure and temperature condition under which the metamorphic rocks formed. The greater the pressure and temperature the rock body is exposed to, the higher the grade it becomes.

[57]Granulite is granular metamorphic rock primarily composed of quartz and feldspar. Facies, a distinctive characteristic for that area and reflect the depositional environment.

[58]Franz J. Dahlkamp, "*Uranium deposits of the world – Asia*", 321–390.

[59]Jiarong Zhong and Zhitian Guo, "The Geological Characteristics and Metallogenetic Control Factors of the Lianshanguan Uranium Deposit, Northeast China," *Precambrian Research* 39 (1988): 51–64, https://doi.org/10.1016/0301-9268(88)90050-2. This deposit occurs in a transitional zone lying between an Archean craton and Lower Proterozoic

sequences – the approximate age is similar to the that of Precambrian metamorphic rocks in the DPRK.

[60]Ibid.

[61]Franz J. Dahlkamp, "*Uranium deposits of the world – Asia*", 321–390; Byungwook Jo et al., *Investigation of Natural Radioactive Materials in Groundwater*, in Korean.

[62]Zhong and Guo, "The Geological Characteristics and Metallogenetic Control Factors of the Lianshanguan Uranium Deposit, Northeast China."

[63]Unconformity is a geologic term that describes the absence of rocks that record the time period between two formations in direct contact. From a geologic perspective, this is important because one can correlate an unconformity surface from region to another.

[64]Zhai et al., "The Geology of North Korea: An Overview."

[65]Shin et al., "Mineralogy and Sulfur Isotope Compositions of the Uraniferous Black Slates in the Ogcheon Metamorphic Belt, South Korea"; Oh et al., "Tectono-Metamorphic Evolution of the Okcheon Metamorphic Belt, South Korea: Tectonic Implications in East Asia"; Kim et al., "Geochemistry and Uranium Mineralogy of the Black Slate in the Okcheon Metamorphic Belt, South Korea"; Cho et al., "SHRIMP U-Pb Ages of Detrital Zircons in Metasedimentary Rocks of the Central Ogcheon Fold-Thrust Belt Korea: Evidence for Tectonic Assembly of Paleozoic Sedimentary Protoliths"; Jeong, "Mineralogy and Geochemistry of Metalliferous Black Slates in the Okcheon Metamorphic Belt: Korea."

[66]N.A. Sozinov, "Metalliferous Carbonaceous Deposits of the Pkhennam Trough of the Sino-Korean Shield," Transactions of the Geological Institute, Russian Academy of Sciences Geological Institute, 579, (2008), in Russian. http://www.ginras.ru/library/pdf/579_2008_sozinov.pdf; Matolin and M. Tauchid, Report to the Government of the Democratic People's Republic of Korea, Uranium Prospecting, DRK/3/003 Evaluation Mission Hayes, "North Korea's Uranium exports: much ado about something."

[67]More specifically, the Sulhwasan group of Mukchon Series is where one might find comparable geology of uranium-bearing black slates.

[68]Sozinov, "Metalliferous Carbonaceous Deposits of the Pkhennam Trough of the Sino-Korean Shield."

[69]Ibid; V.M Gapsin and N.A. Sozinov, "Geochemistry of Black Shale in the Upper Cambrian and Lower Cambrian in the Phyungnam Basin, 1991 (journal unidentified, partial pages provided in Russian).

[70]Sozinov, "Metalliferous Carbonaceous Deposits of the Pkhennam Trough of the Sino-Korean Shield,"

[71]Sozinov, in his collected sample lists of sedimentary rocks from upper Cambrian Mukchon formation and lower Cambrian Yongdeok formation. The higher uranium content was found in the Yongdeok formation, in thuringite. Gapsin & Sozinov, 1991 (journal unidentified, partial pages provided in Russian).

[72]Sozinov, "Metalliferous Carbonaceous Deposits of the Pkhennam Trough of the Sino-Korean Shield."

[73]Ibid.

[74]Szalontai and Radchenko, "North Korea's Efforts to Acquire Nuclear Technology and Nuclear Weapons: Evidence from Russian and Hungarian archies"; Jeffrey Lewis, "Recent Imagery Suggests Increased Uranium Production in North Korea, Probably for Expanding Nuclear Weapons Stockpile and Reactor Fuel" 38 North (14 August 2015), https://www.38north.org/2015/08/jlewis081215/.

[75]Vernon E. Swanson, "Geology and Geochemistry of Uranium in Marine Black Shales – A Review," Geological Survey Professional Paper 356-C, United States Atomic Energy Commission (1961), https://pubs.usgs.gov/pp/0356c/report.pdf.

[76]Sozinov, "Metalliferous Carbonaceous Deposits of the Pkhennam Trough of the Sino-Korean Shield"; Gapsin and Sozinov, "Geochemistry of Black Shale in the Upper Cambrian and Lower Cambrian in the Phyungnam Basin"; Xu Jun, San-Yuan Zhu, Tai-Yi Luo, Wen Zhou, and Yi-Liang Li, "Uranium Mineralization and Its Radioactive Decay-Induced Carbonization in a Black Shale-Hosted Polymetallic Sulfide Ore Layer, Southwest China," *Economic Geology* 110 (2015): 1643–1652, https://doi.org/10.2113/econgeo.110.6.1643; Guangchi Tu, *Geochemistry of Strata Bound Deposits in China* (Beijing, China: Science Press, 1996), 519; Z. H Liu et al., "The Lower Cambrian Niutitang Formation at Yangtiao (Guizhou, SW China): Organic Matter Enrichment, Source Rock Potential, and Hydrothermal Influences," *Journal of Petroleum Geology* 38 (2015): 411–432, https://doi.org/10.1111/jpg.12619; V. E. Mckelvey, "Uranium in the Upper Cambrian Black Shale of Sweden," Trace Elements Investigation Report 495, United States Department of the Interior Geological Survey, 1955, http://pubs.usgs.gov/tei/0495/report; Niels H. Schovsbo, "Uranium Enrichment Shorewards in Black Shales: A Case Study from the Scandinavian Alum Shale," *GFF* 124 (2002): 107–116, https://doi.org/10.1080/11035890201242107; Andrei Lecomte et al., "Uranium Mineralization in the Alum Shale Formation (Sweden): Evolution of a U-rich Marine Black Shale from Sedimentation to Metamorphism," *Ore Geology Reviews* 88 (2017): 71–98, https://doi.org/10.1016/j.oregeorev.2017.04.021.
[77]Jun et al., "Uranium Mineralization and Its Radioactive Decay-Induced Carbonization in a Black Shale-Hosted Polymetallic Sulfide Ore Layer, Southwest China"; Mckelvey, "Uranium in the Upper Cambrian Black Shale of Sweden"; Schovsbo, "Uranium Enrichment Shorewards in Black Shales: A Case Study from the Scandinavian Alum Shale."
[78]Sozinov, "Metalliferous Carbonaceous Deposits of the Pkhennam Trough of the Sino-Korean Shield."
[79]Chiri district does not exist anymore under the changed district names in North Korea.
[80]Sozinov, "Metalliferous Carbonaceous Deposits of the Pkhennam Trough of the Sino-Korean Shield."
[81]Jungmin Kang, Peter Hayes, Li Bin, Tatsujiro Suzuki, and Richard Tanter, "South Korea's Nuclear Surprise," *Bulletin of the Atomic Scientists* 61 (2015): 40–49, https://doi.org/10.1080/00963402.2005.11460853.
[82]In discussion with the Korea Institute of Geoscience and Mineral Resources.
[83]Sozinov, "Metalliferous Carbonaceous Deposits of the Pkhennam Trough of the Sino-Korean Shield."
[84]Post-orogenic means following the events of orogenesis – a geological event when a continental plate collides and forms a mountain.
[85]Mun Gi Kim and Yong Il Lee, "The Pyeongan Supergroup (Upper Paleozoic-Lower Triassic) in the Okcheon Belt, Korea: A Review of Stratigraphy and Detrital Zircon Provenance, and Its Implications for the Tectonic Setting on the Eastern Sino-Korean Block," *Earth-Science Reviews* 185 (August 2018): 1170–1886, https://doi.org/10.1016/j.earscirev.2018.09.006.
[86]Franz J. Dahlkamp, "*Uranium deposits of the world – Asia*," 321–390; Hwang and Moon, "Geochemical Evidence for K-Metasomatism Related to Uranium Enrichment in Daejeon Granitic Rocks near the Central Ogcheon Metamorphic Belt, Korea", Hwang "Occurrence of U-minerals and Source of Uranium in Groundwater in Daebo Granite, Daejeon Area".
[87]Cho et al., "SHRIMP U-Pb Ages of Detrital Zircons in Metasedimentary Rocks of the Central Ogcheon Fold-Thrust Belt Korea: Evidence for Tectonic Assembly of Paleozoic Sedimentary Protoliths"; Jeong, "Mineralogy and Geochemistry of Metalliferous Black Slates in the Okcheon Metamorphic Belt: Korea."

[88]Shin et al., "Mineralogy and Sulfur Isotope Compositions of the Uraniferous Black Slates in the Ogcheon Metamorphic Belt, South Korea"; Oh et al., "Tectono-Metamorphic Evolution of the Okcheon Metamorphic Belt, South Korea: Tectonic Implications in East Asia"; Kim et al., "Geochemistry and Uranium Mineralogy of the Black Slate in the Okcheon Metamorphic Belt, South Korea"; Cho et al., "SHRIMP U-Pb Ages of Detrital Zircons in Metasedimentary Rocks of the Central Ogcheon Fold-Thrust Belt Korea: Evidence for Tectonic Assembly of Paleozoic Sedimentary Protoliths"; Jeong, "Mineralogy and Geochemistry of Metalliferous Black Slates in the Okcheon Metamorphic Belt: Korea."

[89]Lalitha Sundaresan, Srinivasan Chandrasheka, and Bhupendra Jasani, "Monitoring Uranium Mining and Milling using Commercial Observation Satellites," *ESARDA Bulletin* 53 (2015): 73–82, https://publications.jrc.ec.europa.eu/repository/bitstream/JRC99038/esarda_bulletin_issue_53_-_2015.pdf; Srinivasan Chandrasheka, Lalitha Sundaresan, and Bhupendra Jasani, "Estimating Uranium Mill Capacity using Satellite Pictures," ISSSP National Institute of Advanced Studies, R35-2015 (November 2015).

[90]Ibid.

[91]The use of mill equipment as identification factor is limited to milling capacity, as opposed to mining capacity. While Pyongsan appears to be unusual in that the mill is located next to the mine, ore from other purported mines, extant and active, might have been sent to places like the Pyongsan mill. This would skew an estimate of mining capacity based on milling capacity. Improved or complementary data sources are needed for a better assessment of the throughput.

[92]Sundaresan et al., "Monitoring Uranium Mining and Milling using Commercial Observation Satellites"; Chandrasheka et al., "Estimating Uranium Mill Capacity using Satellite Pictures."

[93]von Hippel, "Methods for Refining Estimates of Cumulative DRPK Uranium Production."

[94]Ibid.

[95]Ibid.

[96]The World Nuclear Association (WNA) differentiates between (1) very high-grade uranium ores (>200,000 ppm), (2) high-grade uranium ores (20,000–200,000 ppm), (3) low-grade uranium ores (1,000–20,000 ppm), and (4) very low-grade uranium ores (<1000 ppm), from: "Supply of Uranium," World Nuclear Association, last modified May 2020, https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/uranium-resources/supply-of-uranium.aspx.

[97]Yiyang Ye, Nahlar Al-Khaledi, and Lee Barker et al. "Uranium Resources in China's Phosphate Rocks-Identifying Low-Hanging Fruits," *Earth and Environmental Sciences* 227 (2019): 052033, doi: 10.1088/1755-1315/227/5/052033.