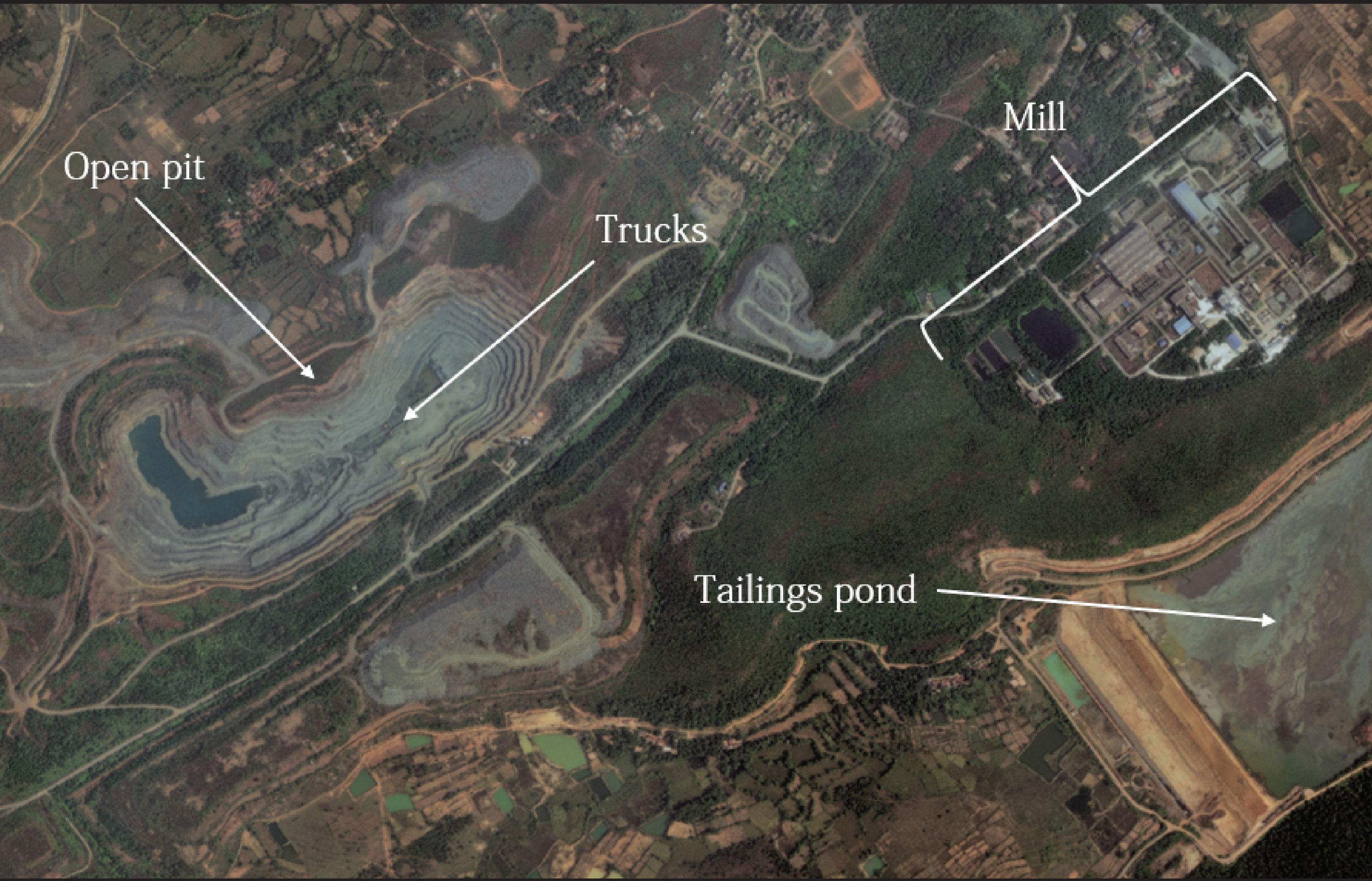

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Monitoring Uranium Mining and Milling in India and Pakistan through Remote Sensing Imagery

Melissa Hanham, Grace Liu, Joseph Rodgers, Ben McIntosh, Margaret Rowland, Mackenzie Best, Scott Milne, and Octave Lepinard

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Cover image: Turamidih Uranium Mill and Banduhurang Mine, India. Credit: WorldView-3, Digital Globe.

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Introduction

New and advancing geospatial technologies hold great potential for aiding analysts. The use of tools such as hyperspectral analysis, change-detection algorithms, and the advancement of machine learning have the potential to reveal a more comprehensive view of the nuclear activities at the front end of the fuel cycle within states of concern.

This Occasional Paper details existing and potential uranium mines and mills in India and Pakistan as part of an ongoing project at the James Martin Center for Nonproliferation Studies (CNS) to track uranium production in Asian states that possess nuclear weapons.[1] As non-signatories to the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), India and Pakistan face challenges procuring fissile material from foreign sources. Both countries have ongoing nuclear-weapon programs, clear and increasing demands to supply their nuclear-energy programs, and domestic production deficits. The continuing and increasing demand for uranium in India and Pakistan indicates that domestic uranium production is likely to grow significantly in the near future. This paper explores remote sensing techniques that can allow open-source analysts to monitor and track front-end uranium production activity in these countries.

Locating and monitoring uranium mines is possible through a variety of open-source means. Many governments voluntarily report their operational uranium mines and mills to the International Atomic Energy Agency (IAEA), which is then published biannually in what is colloquially known as the "Red Books."[2] Scientists working at certain mines periodically publish research papers on uranium-extraction technologies, and uranium-mining companies track trends in mining production and investment, adding to the available data. Satellite imagery can also provide invaluable baseline information about the operational status, production, and capacity of a given facility.

Uranium is generally mined using one of three different approaches: open-pit mining, underground mining, and in-situ leaching (ISL).[3] Open-pit mining is best used when the ore body is close to or at the surface, and is commonly employed for mining metals such as copper and iron. The open-pit method is most commonly used for mining large, high-grade uranium deposits. Underground mining is performed in many different contexts depending on the quality and structure of the ore deposits, but normally employs vertical shafts, horizontal adits, or ramped declines to reach the ore, which is then brought to the surface by large conveyor belt systems or trucks. Lastly, ISL allows for uranium extraction in deposits and beds that are too thin or too deep for open-pit underground mining. Deposits that are contained in permeable material above an impermeable strata are also prime candidates for ISL. The method injects a dissolvent into the ore, suspending the uranium in a liquid solution. The solution is then pumped to a processing plant and extracted in the form of solid uranium oxide, or yellowcake.

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[1] See Melissa Hanham, Grace Liu, Joseph Rodgers, Mackenzie Best, Scott Milne, and Octave Lepinard, "Monitoring Uranium Mining and Milling in China and North Korea through Remote Sensing Imagery," CNS Occasional Paper #40, James Martin Center for Nonproliferation Studies, October, 2018, www.nonproliferation.org/op40-monitoring-uranium-mining-and-milling-in-china-and-north-korea-through-remote-sensing-imagery.

[2] The Indian government regularly reports data on its uranium-mining operations, but Pakistan does not. The biannual Red Books are published jointly by the IAEA and the Organisation for Economic Cooperation and Development (OECD).

[3] Hanham et al., "Monitoring Uranium Mining and Milling in China and North Korea," p. 2.

Each of the three mining techniques presents different optical signatures that can be detected via satellite imagery. However, determining if the site's primary purpose is uranium extraction can be difficult. Mining operations for other metals, especially copper, utilize much of the same technology and equipment as uranium mining. Of the three methods, open-pit mining leaves the most prominent signature in the form of a large cavity, exposing the ore to be extracted. Underground mining is more difficult to detect in optical imagery, but clues such as processing equipment and waste-material piles located near the mine entrance can tip off analysts about the presence of mining activity. ISL is the most challenging mining method for analysts to identify as it provides few optical signatures, and necessary materials can be easily hidden or moved away from the sites. However, the ISL method still requires a large processing plant, which can be seen from satellite imagery.[4]

A simple way to distinguish between a uranium- and a copper-milling facility is to confirm or rule out the presence of an electrowinning plant. Electrowinning, the electric disposition of metals from their ores after leaching, is rarely used in uranium mining and milling operations. An electrowinning plant, as pictured in Figure 1 below, can help analysts distinguish the type of milling activity.

Figure 1. Olympic Dam Electrowinning Plant, SA, Australia. Source: Google Earth.

India and Pakistan both have plans to expand their nuclear-energy industries, increasing both countries' demands for uranium. However, as non-signatories to the NPT, both countries face a multitude of challenges to importing uranium. They are not entitled to receive nuclear-related technologies from nuclear-weapon states, nor are they allowed to trade nuclear materials with any NPT states parties.[5] This leaves only non-signatory countries as possible trading partners: Israel, North Korea, and South Sudan. Pakistan has a history of trade with North Korea through the now-defunct A.Q. Khan network.

Both countries have applied for membership in the Nuclear Suppliers Group (NSG) in order to legitimately satisfy their demand for uranium. In 2008, after a multiyear negotiation process and

[4] A state pursuing a covert uranium-mining operation, though, would not likely place an ISL processing plant near a nearly invisible mining operation.
[5] As of this writing, the NPT currently features 191 states parties to the treaty.

sustained US lobbying, the NSG granted India a waiver but not membership to the group, allowing access to the forty-eight member states' nuclear technology and fuel resources.[6] Subsequently, Australia entered an agreement to supply India with uranium under strict safeguards in 2014.[7] Pakistan has not received either membership or a waiver.

India's access to NSG resources has alleviated a portion of their uranium supply stress but has not fully eliminated it. Both India and Pakistan are expanding existing uranium mines and mills and funding exploratory research into new sites for uranium-resource exploitation. Both countries still rely heavily on domestic production of uranium resources, which allows analysts to gain significant insight into their nuclear capabilities by monitoring domestic uranium-production sites. The operational output of a mine or processing plant can be gauged by weighing numerous factors, including the amounts of vehicle traffic, construction on the site, tailings and waste piles, and changes in the surrounding environment. The Narwapahar Underground Uranium Mine of the Uranium Corporation of India Ltd. (UCIL), shown below, exhibits signatures of ongoing activity such as vehicle traffic and changes in waste ponds.

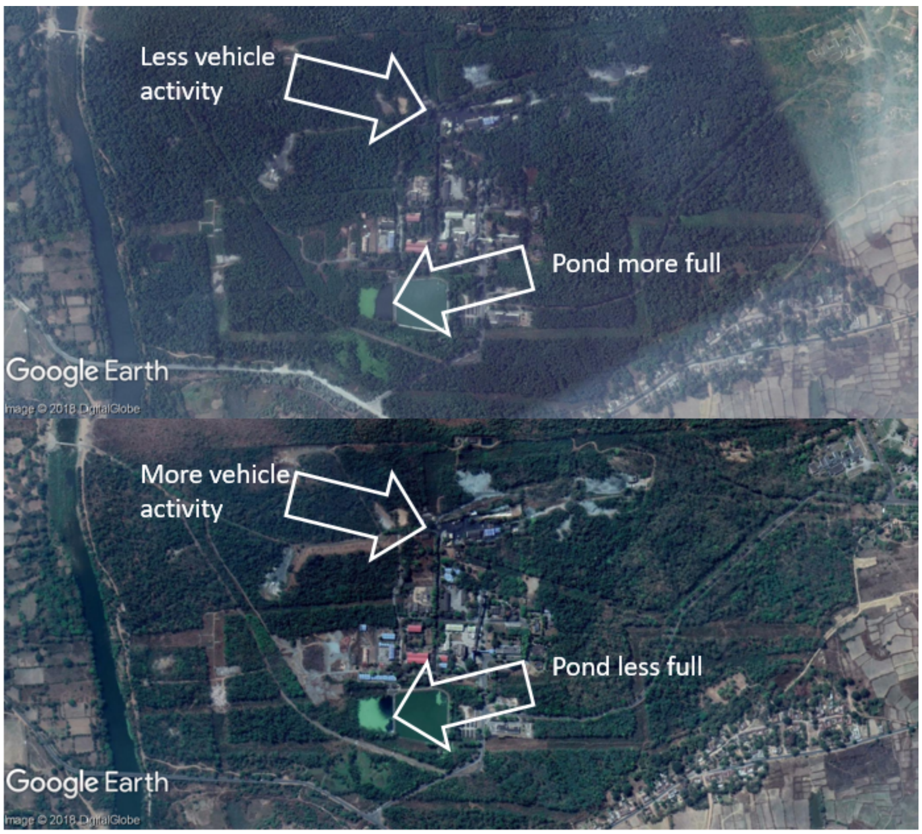

Fig. 2: Narwapahar Underground Uranium Mine of UCIL. Source: Google Earth

[6] The NSG's unique offer to India to waive requirements of full-scope IAEA safeguards as a condition for nuclear supply falls short of membership. The benefits to India of full NSG membership are comprehensively discussed in Mark Hibbs, "Eyes on the prize: India's pursuit of membership in the Nuclear Suppliers Group," *Nonproliferation Review*, Vol. 24, Nos. 3–4 (June–July 2017), https://www.tandfonline.com/doi/pdf/10.1080/10736700.2018.1436253?needAccess=true.

[7] Nuclear Energy Agency and International Atomic Energy Agency, "Uranium 2016: Resources, Production and Demand," (OECD, 2016), p. 156.

India

Uranium Supply and Demand

As of January 1, 2015, India operates twenty-one reactors: eighteen pressurized heavy-water reactors, two boiling-water reactors and one light-water reactor, generating a total of 5.3 gigawatts (Gwe) per year.[8] Construction is underway for four pressurized heavy-water reactors, one light-water reactor (of the VVER-type) and one prototype fast-breeder reactor.[9] Uranium requirements for the pressurized heavy-water reactors are currently met by a combination of indigenous and imported sources, while the two boiling-water reactors and light-water reactor require enriched uranium, which is currently imported.[10] Light-water reactors built in the future will likely be fueled by imported enriched uranium.

India's 2013 uranium demand totaled 1,400 tons (tU), with forecasts of installed capacity and demand continuing to grow as projects under construction are progressively completed.[11] The most recent estimates put annual production levels range from 200–50 tU, indicating a severe domestic supply shortfall.[12]

Uranium Resources and Production

India's known uranium resources (reasonably assured resources, or RAR, plus inferred) are estimated at 181,606 tU hosted in the following deposit types:

Carbonate deposits	42.24%
Metamorphite	31.55%
Sandstone-type	10.33%
Unconformity-type	9.95%
Metasomatite	3.74%
Granite-related	1.99%
Quartz pebble conglomerate	0.19%

As of January 1, 2015, the known conventional resources established so far include 160,033 tU of RAR and an additional 21,573 tU of inferred resources.[13]

India's Department of Atomic Energy controls uranium-related activities in the country. The Atomic Mineral Directorate for Exploration and Research performs uranium exploration, and the UCIL performs mining and production activities. The UCIL currently operates seven underground uranium mines—Jaduguda, Bhatin, Narwapahar, Turamdih, Bagjata, Mohuldih, and Tummalapalle—and one open-pit mine (Banduhurang). All except Tummalapalle are located within 30 km of Jamshedpur, the most populous city in the northeastern state of Jharkhand. UCIL

[8] NEA and IAEA, "Uranium 2016," p. 76.
[9] IAEA, "Uranium 2016," p. 157.
[10] Ibid, p. 263.
[11] Ibid, p. 263.
[12] Franz J. Dahlkamp, "Uranium Deposits of the World: Asia," (Springer, 2009).
[13] IAEA, "Uranium 2016," p. 257.

operations are directed from Jaduguda, about 25 km south of Jamshedpur. The ore procured from these mines is processed at mills located at the Jaduguda and Turamdih sites, while Tummalapalle has a dedicated mill due to its relative isolation in the southeastern province of Andhra Pradesh over 1,200 km away.[14]

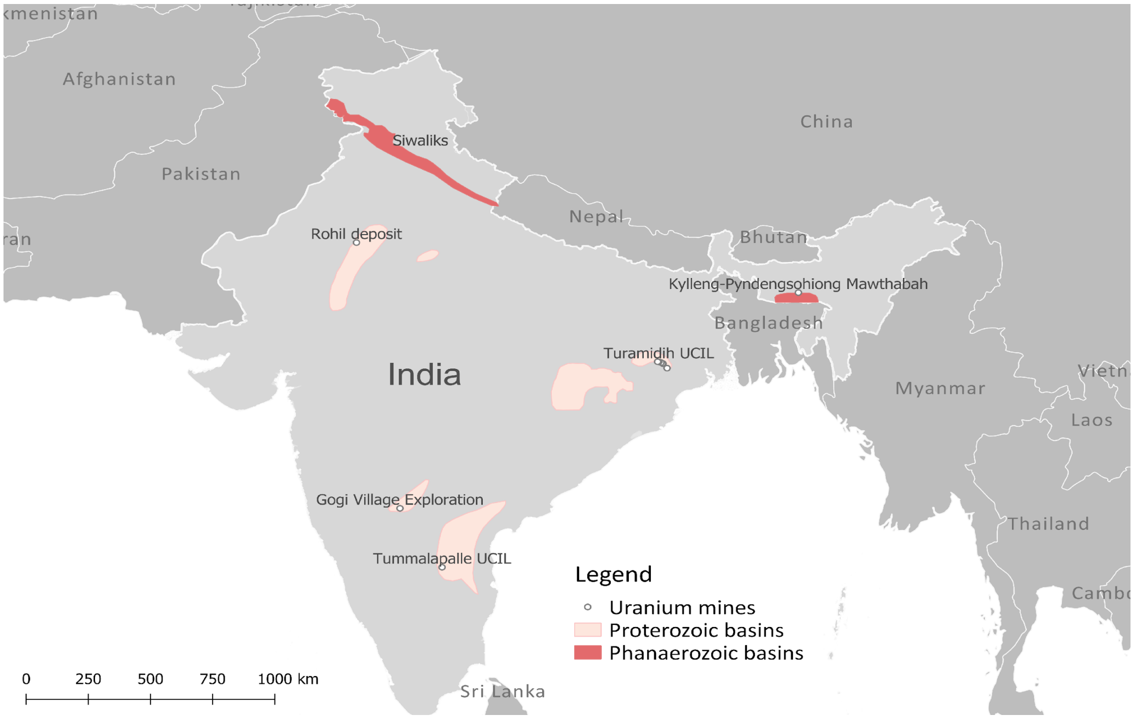

Fig. 3: Map created by Mackenzie Best and Joseph Rodgers using Tableau Software.

Globally, most uranium ore features an average grade just above 0.1% uranium.[15] India's eight operational mines produce large tonnage of mostly low-grade uranium ore consisting of less than 0.1% uranium. India utilizes a combination of open-pit and underground mining; although ISL is being explored as a potential extraction method for future projects, it is generally not practiced in India at this time.[16] This benefits imagery analysts, as these methods are more easily analyzed via satellite imagery than the ISL method.

Hyperspectral analysis of known uranium-mining sites offers many potential benefits, but is hampered by current limitations. Significant variability exists in the deposit types of India's uranium resources, as noted in the table above. This variability, combined with the low average grade of uranium ore, complicates attempts to create a hyperspectral signature of locations containing uranium. In addition, hyperspectral imagery from the now-decommissioned Hyperion (EO-1) satellite, which was the sole space-based hyperspectral sensor producing publicly available images, only featured a resolution of 30 m^2. This is insufficient for the analysis of ore with such a low grade.

[14] Ibid, p. 156.
[15] World Nuclear Association, "Uranium Mining Overview," updated July 2018, http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/uranium-mining-overview.aspx.
[16] A.K. Sarangi and K. K. Beri, "Uranium Mining By In-Situ Leaching," paper presented at the conference "Technology Management for Mining, Processing and Environment," Indian Institute of Technology, Kharagpur, December 1–3, 2000, http://www.ucil.gov.in/pdf/myth/Uranium%20mining%20by%20in-situ%20leaching.pdf.

A much higher resolution would be needed to isolate uranium's hyperspectral signature from that of the ore within which it is contained.

Figure 4 shows two annotated satellite images of activity at the Turamdih mill and Banduhurang open-pit mine, respectively. One can see tracks and a bulldozer bringing ore into the milling facility. Likewise, a truck filled with ore can be seen pulling away from a loading crane, with two empty trucks waiting side-by-side to be filled with ore from the mine.

Fig. 4: Banduhurang Mine and Turamdih Mill, Jharkhand, India. Source: DigitalGlobe.

Prospective Mines and Projects

In light of the growing demand for uranium, the Indian government and UCIL are currently developing three additional uranium-production sites: the Lambapur-Peddagattu project outside of Nalgonda, Telangana; the Kylleng-Pyndengsohiong Mawthabah project in Domiasiat, Meghalaya;[17] and the Gogi project in Gogi, Karnataka. All three projects face stiff resistance from local interests on the basis of potential health and environmental impacts.[18] A fourth underground mining project of the Rohil deposit in the Sikar district of Rajasthan is in an advanced stage of exploration.

These planned mines feature desirable attributes such as ore in close proximity to the surface and higher-grade ore than is typically found in India.

[17] Formerly known as the Domiasiat mine.
[18] IAEA, "Uranium 2016," p. 72.

Pakistan

Uranium Supply and Demand

The Pakistan Atomic Energy Commission (PAEC) currently operates five nuclear reactors: four 325-megawatt Khushab pressurized water reactors of Chinese origin and a 125-megawatt pressurized heavy-water reactor of Canadian origin. Three additional 1,000-megawatt Chinese-origin Hualong One reactors are currently under construction, two of which are scheduled to come online in the early 2020s, bringing Pakistan's total number of operating reactors to seven in the next few years.

Pakistan appears to face a significant uranium shortfall. Previous analysis of Pakistan's Khushab reactors suggests that four reactors operating at roughly 70 percent efficiency may require 70 tU per year in total.[19] The IAEA/OECD "Red Book" estimates that Pakistan is mining roughly 45 tU per year. Pakistan appears to already operate at a uranium deficit with its four Khushab reactors. The construction of the three Hualong reactors will further increase Pakistan's demand for uranium.

Uranium Resources and Production

Pakistan's uranium is mined from the Tertiary Siwalik Group deposit, which also spans across Northern India.[20] Pakistan operates four uranium mines located near the cities of Qabul Khel, Nanganai, Taunsa, and Baghalchore. The Baghalchore site ceased uranium production in the late 1990s and is now a low-level radioactive-waste storage facility.

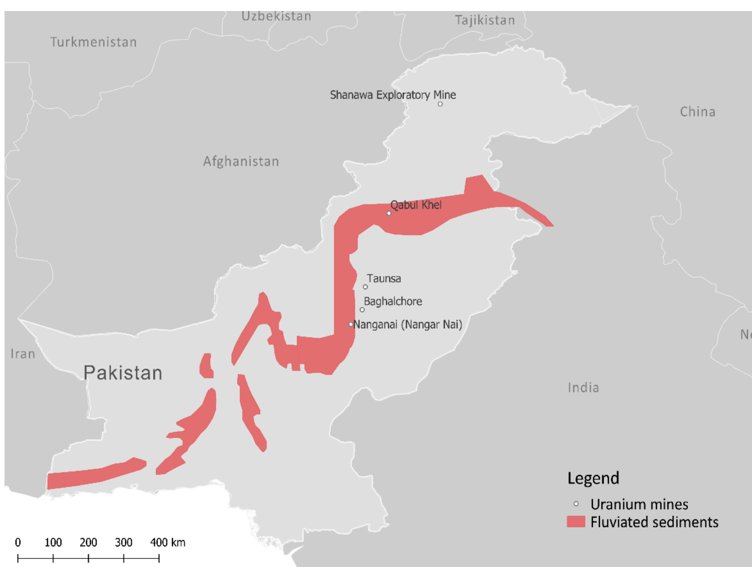

Fig. 5: Map created by Mackenzie Best and Joseph Rodgers using Tableau Software.

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[19] Tamara Patton, "Uranium Fuel Constraints for Pakistan's Nuclear Weapon Complex," December 2012, Arms Control Wonk, https://www.armscontrolwonk.com/archive/205928/patton-on-pakistans-u-supply/.
[20] Franz Dahlkamp, "Uranium Deposits of the World: Asia."

Pakistan currently operates two uranium mills: the Issa Khel uranium mill and a site known as BC-1.[21] Uranium mined at the Qabul Khel mine is transported directly by rail to the Issa Khel uranium mill for processing. The Issa Khel uranium mill can process an estimated one ton of mined uranium ore per year.[22] Officials from the Pakistani government have claimed that the BC-1 site is no longer operational. However, satellite imagery appears to show activity at the site, as seen in Figure 6's image comparison. Due to the mill's close proximity to the Nanganai and Taunsa uranium mines, BC-1 may serve as a mill for these mines.

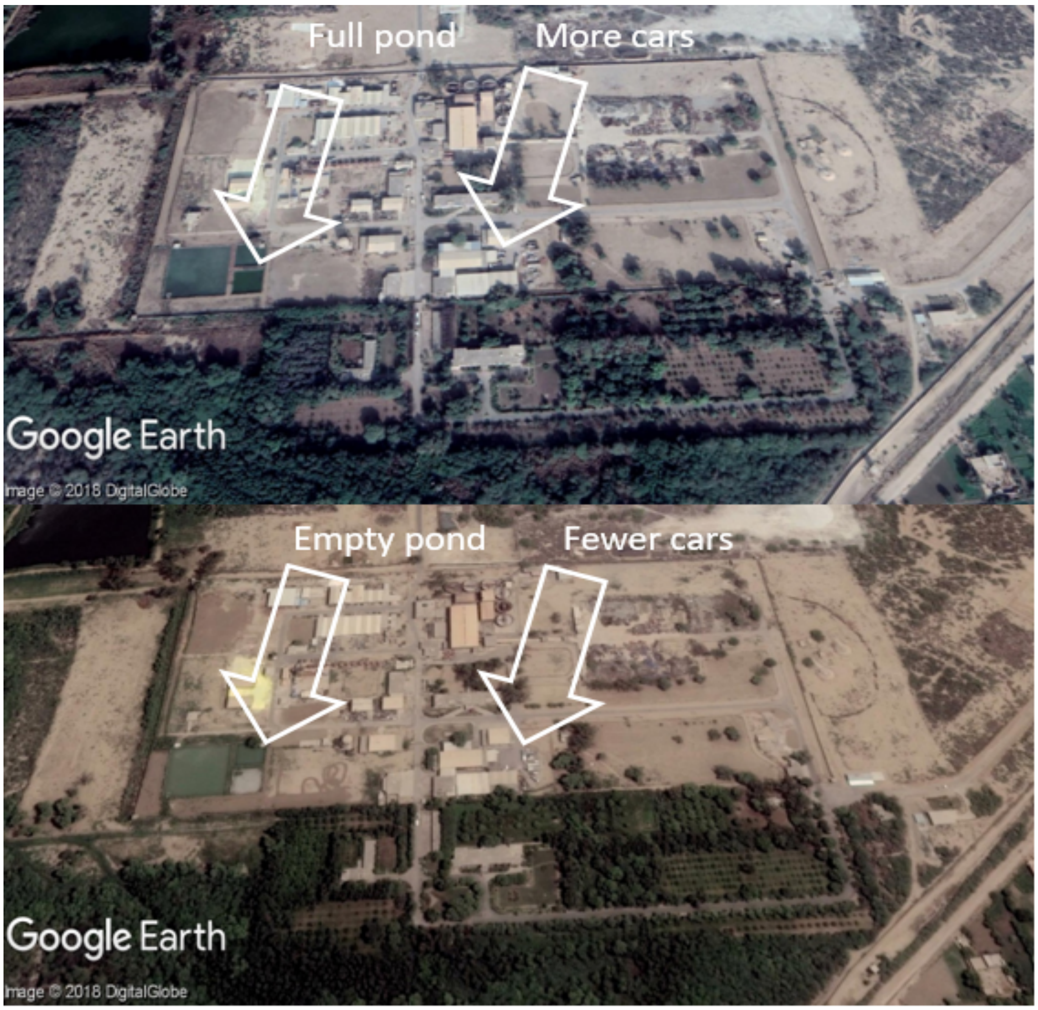

Fig. 6: BC-1 Uranium Mill, Punjab, Pakistan. Source: Google Earth.

The average grade of Pakistan's uranium ore ranges between .02 and .03 percent,[23] similar in grade to the ore found in India. Unlike India, Pakistan utilizes ISL technology for its three operational mines.

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21 International Atomic Energy Agency, "Country Nuclear Fuel Cycle Profiles," 2nd ed., IAEA Technical Reports Series No. 425, 2005, pp. 63–65.
22 Ibid.
23 "Pakistan," Chapter 10 in *Global Fissile Material Report 2010: Balancing the Books: Production and Stocks*, International Panel on Fissile Materials, December 2010.

Unfortunately, as aforementioned, the ISL method is much more difficult to monitor via satellite imagery than open-pit or underground mining.[24] As most ISL activity takes place below ground, ISL leaves few visible signatures, such as rubble or waste piles, from which extraction volumes, ore grade estimations, or operational efficiency can be estimated.

The annotated imagery of the Qabul Khel mine in Figure 7 demonstrates this difficulty. The structures and developed area visible in the center of the image are the processing plant for the ISL mines. The in-situ wells, located in the top left and middle right of the image, do not reveal obvious optical signatures, making their identification difficult. Although the in-situ wells are very close to the processing facility at Qabul Khel, it should be noted that this is not necessary for an ISL operation. The ISL solution taken from a well site can be transported over longer distances or hidden fairly easily if desired. In this case, one can infer that the placement of these wells in proximity to the processing facility is likely an attempt to reduce transportation costs.

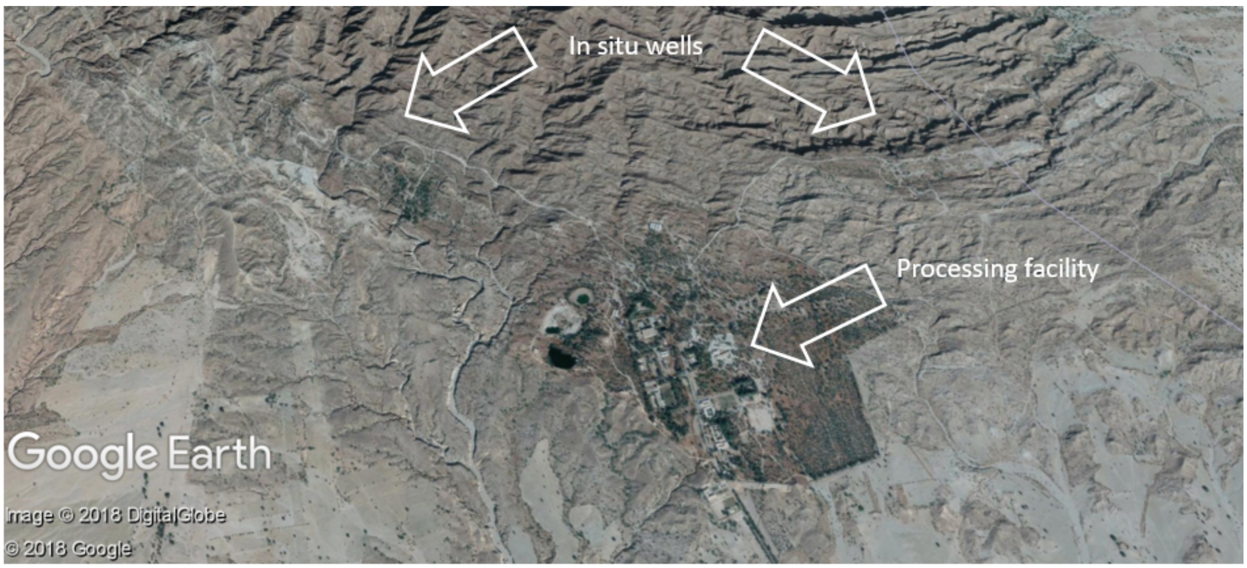

Fig. 7: Qabul Khel Uranium Mine and Processing Plant, Punjab, Pakistan. Source: Google Earth.

Prospective Mines and Projects

Pakistan planned to produce uranium at a fifth mine located near the city of Shanawa by 2014. The mine underwent construction from 2009 until 2011, but construction was suspended due to insufficient funds.[25]

As a result of Pakistan's consistent deficit of uranium, the PAEC has launched expensive uranium-exploration drilling projects in the Kirthar mountain range, the Kohat plateau, and the Potwar

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24 Hanham et al., "Monitoring Uranium Mining and Milling in China and North Korea."
25 Samim Akhtar, Yang XiaoYong, and Wang Fang Yue, "Uranium Deposits and Resources Potential in Pakistan: A Review," *Science International*, Vol. 27., No. 2, pp. 1293–96 (2015), https://www.tib.eu/en/search/id/BLSE%3ARN602648677/URANIUM-DEPOSITS-AND-RESOURCES-POTENTIAL-IN-PAKISTAN/.

plateau.[26] In July of 2017, the China National Nuclear Corporation (CNNC) signed a contract with the PAEC to begin technical cooperation in the exploration and development of uranium resources. The Aerial Survey and Remote Sensing Center of the CNNC will assist in locating potential mines in Pakistan by looking for heat signatures using radiometric imaging.[27]

Conclusion

India and Pakistan's uranium mining and milling operations pose challenges for nonproliferation monitors and analysts, but deserve attention. Both countries have clear and increasing demands for uranium to supply the needs of their energy programs, and both currently have domestic production deficits. These factors would lead both India and Pakistan to increase their domestic uranium-production capabilities. Pakistan especially wishes to increase its domestic uranium supply due to the continued barriers it faces in accessing the global uranium market. However, variability in the quality of ore deposits, general lack of reported data, and the use of the inconspicuous ISL mining method create challenges for gathering data and analyzing the two countries comparatively.

Geospatial analyses of uranium mines and mills in China, North Korea, India, and Pakistan provides valuable insights, not only into mining and milling capabilities, but also into the extraction methods used, and the future of uranium production in these countries. The data reported by China and India provides insight into Pakistan and North Korea's more secretive programs, as they use similar mining methods. For example, analysts can use Chinese-reported data on ISL mining to better understand Pakistan's ISL capabilities. India's open-pit and underground mining operations offer excellent optical signatures and easily-accessed production estimates, which can be compared with operations of similar size and method in North Korea. However, many of the issues complicating geospatial analysis of Northeast Asian mines, such as low-resolution images and clandestine mining operations, hold true in the South Asian context as well.

Despite such obstacles, remote sensing technology still offers analysts meaningful insights and expands the general understanding of mining techniques worldwide. Enhanced hyperspectral capabilities and emerging geospatial tools have the potential to improve this process for the open-source community even more in the near future. In the meantime, analysts can still glean valuable information from government-reported data or even sophisticated imagery obtained through non-satellite means, such as hyperspectral imagery obtained via drone or airplane.

In the next paper, titled "Geospatial Tools for Identifying and Monitoring Uranium Mining and Milling Activities," CNS researchers will discuss these insights and how these remote sensing capabilities can be used to monitor mining and milling worldwide.

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[26] Maria Sultan et al. "Governing Uranium in Pakistan," (Copenhagen: Danish Institute for International Studies, 2015), http://pure.diis.dk/ws/files/184536/DIIS_RP_2015_08_FINAL.pdf.

[27] "China and Pakistan to Co-Operate on Uranium Exploration," *Nuclear Engineering International*, August 4, 2017, https://www.neimagazine.com/news/newschina-and-pakistan-to-co-operate-on-uranium-exploration-5891435.

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Melissa Hanham is a senior research associate at the James Martin Center for Nonproliferation Studies (CNS) at the Middlebury Institute of International Studies at Monterey (MIS). She studies East Asian security, with a particular focus on North Korean WMD capabilities, procurement and proliferation networks, and China's nuclear posture. Hanham is an expert on open-source intelligence, incorporating satellite and aerial imagery, and other remote sensing data, large data sets, social media, 3D modeling, and geographic information system mapping. She is particularly focused on the monitoring and verification of international arms-control agreements using open-source evidence. Hanham also uses open-source information to study export-control systems and proliferation finance activities. Hanham is an affiliate of Stanford University's Center for International Security and Cooperation, and is a regular contributor to Arms Control Wonk, the leading blog and podcast on disarmament, arms control, and nonproliferation. In 2018, she was awarded the Paul Olum Grant Fund for being one of the most inventive scientific and technical minds working to reduce the threat of nuclear weapons. She previously worked at the Middlebury Institute of International Studies in Monterey and the International Crisis Group in Seoul and Beijing.

Grace Liu is a research associate in the East Asia Nonproliferation Program at the James Martin Center for Nonproliferation Studies (CNS). She translates Korean and Chinese sources, conducts geospatial analysis, and uses 3D-modeling techniques to assess North Korea's weapons of mass destruction (WMD) and ballistic-missile capabilities. Her research focuses on applying open-source intelligence to verify arms control treaty compliance. Ms. Liu served as an all-source intelligence officer in the armed forces. She holds a Master's in Nonproliferation and Terrorism Studies from the Middlebury Institute of International Studies at Monterey (MIIS), a Master's of Business Administration in International Management, and a Bachelor's in Military Science from the University of New Mexico.

Joseph Rodgers is a graduate research assistant at CNS and holds a Master's degree in Nonproliferation and Terrorism Studies from MIIS. Formerly, he was a visiting research intern at the United Nations Institute for Disarmament Research, Lawrence Livermore National Laboratory, and the Arms Control Association. His research applies a variety of technologies to verify global WMD facilities.

Ben McIntosh is a graduate research assistant at CNS, where he focuses on methods of diplomatic engagement and open source monitoring of Northeast Asian countries, most notably North Korea. From 2015 to 2017, McIntosh served at the US Department of Agriculture as well as various congressional and presidential campaigns. Ben received his MA from MIIS in Nuclear Nonproliferation and Terrorism Studies in 2019 and his BA in International Studies from the University of Oregon in 2013.

Margaret Rowland a graduate research assistant at CNS, where she focuses on issues related to the East Asia Nonproliferation Program. Her areas of research include North Korean WMD and missile proliferation, multilateral nonproliferation and arms control treaties, and nuclear safeguards and disarmament verification. Previously, Margaret worked as a political affairs intern at the United Nations Office for Disarmament Affairs, an international nuclear safeguards policy intern at Lawrence Livermore National Laboratory (LLNL), and as an analyst at the Center for Homeland Defense and

Security at the Naval Postgraduate School (NPS). She is an MA candidate at MIIS and earned her AB in Anthropology from Dartmouth College in 2014.

Mackenzie Best is a research assistant with the Department of Geology at Middlebury College working on this project. She is concurrently a grade control geologist at a high-altitude open pit copper mine in Espinar, Peru. Beginning in January 2019, she will be a Master of Science student at the New Mexico Institute of Mining and Technology. She holds a Bachelor's degree in Geology and Biology from Middlebury College.

Scott Milne is a graduate research assistant at CNS. His work at the Center focuses on tracking developments within WMD-capable countries and writing reports for the Nuclear Threat Initiative. He is a candidate for a Masters of Arts in Nonproliferation and Terrorism Studies from MIIS and holds a Bachelor of Arts in HIsotry from Hamilton College

Octave Lepinard is an undergraduate at Middlebury College studying Geology and Computer Science, with a focus in remote sensing. During the summer of 2018, he was a research assistant at CNS, where he worked with satellite imagery and various image-processing software to track developing and growing WMD programs around the world. He also studies the use of new technologies such as hyperspectral analysis to develop methods for identifying covert uranium mines.

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