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Revised Geologic Site Characterization of the North Korean Test Site at Punggye-ri

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An evaluation of terrain characteristics provides a way to make geologic interpretations for denied-access sites. This contribution illustrates the utility of this approach by developing a revised geologic map of the North Korean test site through reconnaissance-based geomorphometrics (defined as the science of quantitative land surface analysis) and geospatial investigation. This study provides a way to quantify the geologic differences at the test site and suggests that geologic factors contributed to the prompt release of detected radionuclides associated with the 2006 nuclear test event compared to the 2009 and 2013 events. This method is relevant for test monitoring by providing: 1) A better understanding of host rock integrity and geologic coupling characteristics; 2) A means to facilitate a more accurate determination of explosive yields; 3) A better understanding of event containment and the likelihood of venting, and 4) An enhanced understanding of potential radionuclide transport mechanisms that might assist in future monitoring and verification of clandestine tests.

INTRODUCTION

Currently, the geologic characterization of denied-access sites is limited to simplistic representations of the subsurface geology (e.g., either half-space or planar geologic layers). This is a critical shortcoming given that many proliferation detection applications could benefit from more comprehensive 3-D models of the subsurface geology. Examples include the modeling of seismic wave

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propagation and potential leakage pathways of radionuclides through rock fractures, as well as *a priori* site characterization and evaluation for treaty monitoring. One way to address this shortcoming is by integrating terrain analysis and pattern recognition techniques into a methodology for improving the surface geologic characterization.[1] The central thesis of this approach is that the surface topography and nature of the underlying bedrock geology are intimately related. Early work by NASA at the Pisgah Crater test area (Figure 1) has been extensively used for correlating the relationship between the topography and underlying geology. The site is located in the Mohave (Mojave) Desert, 40 miles southeast of Barstow, California, and was originally selected as a possible lunar analog.[2] The geology is dominated by Tertiary and Quaternary lava flows and Quaternary alluvium. Studies from this site have concluded, "The original hypothesis that surface roughness reflects the geologic nature of rocks appears to be correct," with the caveat that "... it quickly becomes apparent that the scale of sampling required to demonstrate the hypothesis may vary for each area studied."[3]

One source of information to constrain the surface geology of a denied-access area is the use of commercial satellite imagery for reconnaissance geologic mapping and site characterization. The application of such data specifically for nuclear test sites in denied-access areas for verification applications is not new.[4]

An historical example of the use of remote sensing for geologic characterization was a study conducted by Los Alamos National Laboratory (LANL) in 1990 which focused on the Nevada Test Site as a test case and integrated the relevant datasets (including remote sensing data, geophysical data, geological and geomorphological data) to identify and characterize the geology of a region where only incomplete or inaccurate datasets exist, or where direct geological data is unavailable or unattainable. That study employed the best available imagery at that time which included four primary data sets: Landsat Multispectral Scanner (MSS, 60 meter resolution); Landsat Thematic Mapper (TM, 30 meter resolution); SPOT Multispectral (XS, 20 meter resolution); and SPOT Panchromatic: (Pan, 10 meter resolution). That study concluded that despite a limited sensor suite, there was sufficient spatial resolution and spectral band positions to make possible the extrapolation of spectral reflectance and morphologic information into unmapped regions for lithologic discrimination. New procedures for image analysis and thematic map production were beginning to be developed and applied to regions for which there is a paucity of *a priori* geologic information. One method being examined at the time:

> ...extrapolates image product and "ground truth" observations from a previously mapped region into an adjacent region that has been imaged with the same data as the "ground truth" region. The next logical step in the progression of remote sensing applications (and one of our primary research efforts) is the

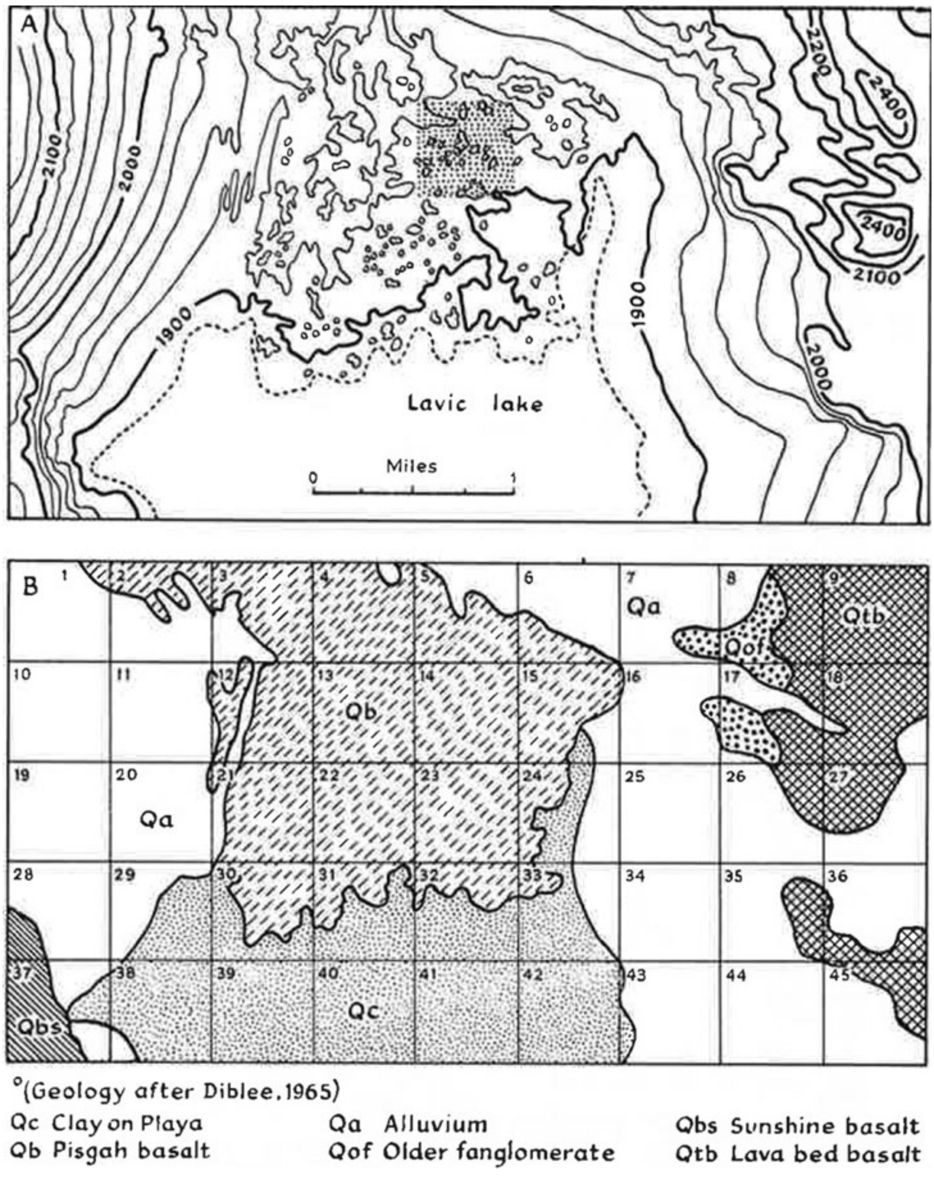

Figure 1: The relationship between topography (upper panel) and bedrock geology (lower panel) from the Pisgah Crater, California. This site was used extensively in the 1960s and 1970s by NASA as a test bed for estimating the geology from remote sensing data.

development of "transportable" image processing techniques and feature identification databases that can be used to characterize the geologic environment of an inaccessible region for which there is essentially no a priori knowledge ("ground truth") of the region's geology.[5]

Furthermore, that study concluded that determination of the local subsurface geology requires sound knowledge of the regional geologic setting and that a skilled remote sensing geologist with no prior knowledge about the geology of an area can derive a basic regional geological model by assessing various factors as physiography, geomorphology, structural geology, stratigraphy and lithology, hydrogeology, and vegetation through inferences drawn from both spectral and spatial analysis. Identifications could be derived directly based upon spectral signature (ideally when bedrock is exposed) or through pattern recognition (subjectively by inspection using terrain analysis, or, more objectively, using image processing algorithms). As the authors point out, "Drainage patterns can provide substantial information on the nature of rock outcrops, e.g., lithology, surface slope, age, and weathering processes that have affected the outcrop. Likewise, the assessment of geographic context and morphology (landform shape and relief) has aided geomorphologists in the identification of landforms and in the interpretation of geologic landscapes."[6]

That preliminary work has established the fundamental methodology for geologic site characterization of denied-access locations.

The ultimate goal of geologic site characterization (in this context) is the determination of rock properties that can aid in the location and/or yield estimates that are germane to test event evaluation.[7]

This article examines what information from the surface topography can be used to understand variations in the geologic properties that influence coupling characteristics that could inform yield estimations for clandestine tests. The geology at the test site clearly has an influence on the release of radionuclides. The 2006 test clearly had a prompt leakage (which we interpret as being the result of the highly fractured rock in this location); there was no detection of any leaked radionuclides from the 2009 test; and, while there was no detection of prompt leakage from the February 12, 2013 test, there was a delayed detection of leakage that occurred approximately 8 weeks after the event on April 7, 2013. The cause of the leakage after such a delay is either due to slow migration through natural or explosion created cracks and fissures, or is the direct result of human activity (e.g., re-entry into the test cavity for sampling, etc.) The fact that new human activity was observed as having begun at the west portal sometime March 22, 2013 and 21 April 2013 (on commercial satellite imagery) suggests that it could have been a likely cause. Geology can contribute to the venting of radionuclides in several ways; the most likely being the migration of gases along preexisting factures to the surface. Because fractured rock is likely to produce a different surface topographic signature (as compared to more competent rock) the analysis presented below offers a viable way to remotely evaluate test sites for gas leakage potential *a priori* to a test.

GEOLOGIC ASSESSMENT OF THE PUNGGYE-RI NUCLEAR TEST SITE

Precise, large-scale (1:50,000 or better), ground-survey-sourced geologic maps are entirely lacking for the immediate area of North Korea's underground nuclear test site near Punggye-ri, and given that the nuclear test site is a sensitive and denied-access site, such maps are unlikely to become available in the foreseeable future. The available maps for the test site area are of small scale (e.g., varying from 1:500,000 to 1:1 million scale), and include one openly published by North Korea in 1994. High quality large-scale (1:50,000) ground-survey geologic maps do exist for the neighboring regions around the test site, and include a pair of large scale geologic maps (quadrangles) abruptly terminating 12 kilometers south and east of the test site in "folios" of Japanese geologic reporting dating back to the 1920s and 1930s. In 2010, the United States Geological Survey (USGS) conducted a remote sensing reconnaissance mapping study to arrive at a clearer and more accurate understanding of the geologic setting of the North Korean underground nuclear test site. That study involved an interpretive extrapolation from a combination of three larger scale (1:50,000) geologic map folios (quadrangles covering areas south, southeast, and east of the test site produced in the 1920s and 1930s by the Japanese) together with both low resolution (varying from 15–90 m) Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) 14-band multispectral satellite imagery and GeoEye high resolution (1.8 m MS and .44 m PAN) commercial satellite imagery. Spectral analysis was also conducted using the ASTER imagery, and surficial geomorphic comparative analysis was based on the global digital elevation model (GDEM) generated from the ASTER imagery through a joint effort with NASA and Japan's Ministry of Economy, Trade, and Industry (METI). The USGS study acknowledged the limitations of the resultant extrapolations (particularly given stated limitations associated with the spectral profile analysis) for geologic mapping of the nuclear test site proper, but nonetheless concluded, "While this interpretation relies heavily on subjective qualitative interpretations of the structural and spectral characteristics of the geology, it remains the best approximation that can be made with the available information."[8]

One of the problematic features of the USGS mapping is the close proximity of an inferred geologic boundary between diorite and dolomite/limestone rock (see Figure A1 in supplemental Appendix) to the 2009 and 2013 underground nuclear test epicenters, which is at odds with the strong likelihood of containment failure near such an interface. Furthermore, there has been no established basis for understanding the possible radioactivity venting mechanisms for the 2006 test, as compared to the higher yield 2009 test which did not leak, beyond the argument that larger tests are more likely to create "stress containment cages."[9] Nor had an objective basis been established for determining the likelihood of such venting occurring as a result of any future nuclear testing in the area.

A subsequent LANL review of that effort found that while the conclusions pertaining to an inferred lithological boundary in the eastern half of the test site are plausible, a second inferred lithological boundary (suggesting the presence of dolomite/limestone in an active area of nuclear testing) in the western half of the test site is questionable. That review led to a proposal for additional analysis, which formed the basis for this study, with a reevaluation of all available geologic information and commercial-satellite-sourced remote sensing data, and integration of these results with a LANL-derived quantitative terrain analysis technique in an attempt to derive a clearer understanding of the geologic setting and character of North Korea's nuclear test site at Punggye-ri.

This study is the first to address these issues specific to Punggye-ri nuclear test site geology. We integrate subjective inspections involving commercial satellite image analysis with an objective quantitative "geomorphometric" approach that extracts the terrain characteristics that are indicative of the underlying geology. Additional information used in this study includes more recently available open-source geospatial information about the locations of the test events, quantitative image processing techniques, and the availability of a high resolution (5-meter) digital elevation model (DEM) for the site.

Regional Geological Setting

The following description of the regional geological setting is excerpted from an unpublished USGS report by Buttleman and Matzko, *Summary Statements, Geological Atlas of Chosen Folios*:[10]

> The FY08 study of the geology at the location of the North Korean underground nuclear test of October 2006 suggests that the test occurred in Jurassic-aged granite of Mt. Manthap in the northeastern part of the country. A North Korean geologic text states that Manthapsan is a multiphase intrusion into carbonate rocks of the Puktaechon Series, dipping 40 to 70 degrees towards the country rock. The first phase consists of diorite and quartz diorite; the second phase is mainly granite; the third phase is mainly alaskite. Mt. Manthap is part of the very large Kwanmobong batholith of the Hyesan Complex, related to the Songnim tectonic Movement.
>
> A widespread, thick carbonate sequence (the Matenrei or Puktaechon Series, of Lower Proterozoic age) is mapped to the south of the test site (Folio 14); a small-scale map shows these rocks surrounding Mt. Manthap. The carbonates are of interest because of the potential containment problems they present, and their presence may limit the locations of future tests in this region. The large-scale maps also indicate that blocks of carbonates are preserved within the granite masses as roof pendants.

> The relatively low resolution maps (small scale) 1:1 million scale maps (which do cover the area of the test site) likewise show extensive development of Quaternary mafic volcanic rocks to the north and west of the test site along an Achaean plutonic boundary (granite) within the test site proper.

Supplemental Appendix Figure A2 shows the extent of the Japanese geologic mapping from the three key Japanese "Folios" (Nos. 3, 4, 14) located closest to the Punggye-ri nuclear test site as overlain by Buttleman and Matzko onto the smaller scale North Korean geologic map from 1994. The key point is that the compilation corroborates the existence of both Precambrian (Proterozoic) carbonates (dolomite/limestone) and Tokureido diorite (labeled Cretaceous age) being present just south of the test site. The small scale 1994 North Korean map does not show either of those rock types continuing north into the test site proper. However, the "Tanchon Complex Jurassic granite" on the newer small scale North Korean maps appears to be one and the same as the unknown age, but likely Jurassic, "Meisen schistose granite" shown on the older large-scale Japanese maps. A joint North Korean/Chinese report from 2009 includes a very small scale map, which similarly identifies the area of the nuclear test site as being situated in the "Middle Jurassic Tanchon Complex," apparently granite, next to "Neogene volcanic rocks," again consistent both with the Japanese mapped Shintokuri basalt and volcanics and 1994 North Korean mapping.

On the 1994 country level geological map, the North Koreans also show a northwest-southeast trending fault that terminates just west of Mt. Manthap and likely through the area now accessed by the "South Portal." We can neither confirm a fault at this location nor provide insights on any potential impact such a fault might have with regard to future testing in association with the "South Portal." However, the nearly straight, north-south trending valley between Punggye-ri and Mt. Manthap is at least suggestive of possible local faulting. Nonetheless, the Punggye-ri/Mt. Manthap region is in an area of low natural seismicity.[11]

Summary of Reconnaissance Mapping Methodologies

Various reconnaissance mapping methodologies were employed in the creation of the 2010 USGS geology map of the Punggye-ri nuclear test site by Peter Chirico, who noted, ". . .interpretations were made to correlate the previously mapped geologic units to area where no geology data was available. To extend the geologic map data into the unmapped area, the spectral analysis, Principal Components Analysis (PCA), and DEM data were interpreted with the previously mapped folio mapped information."[12]

Building upon this effort, we have employed additional reconnaissance mapping methodologies that include correlation with new geomorphometric

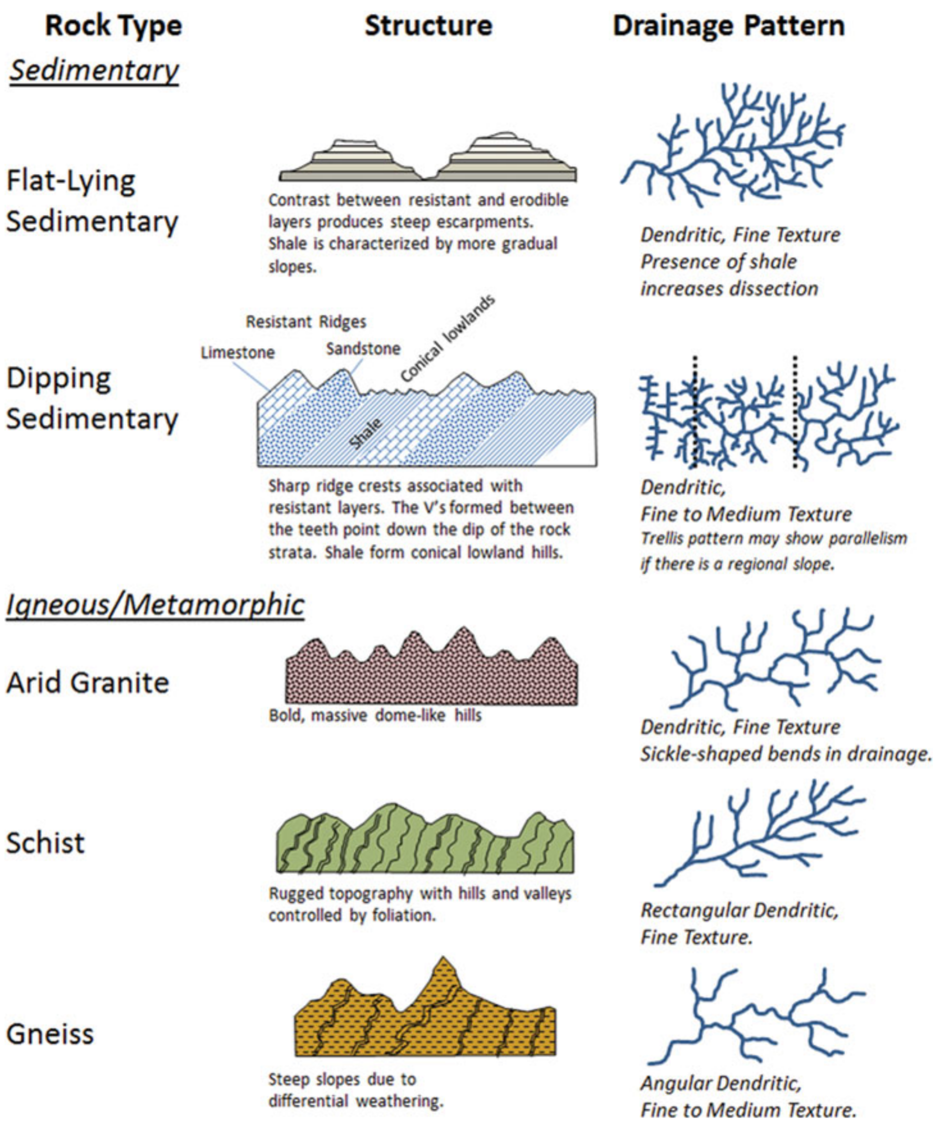

Figure 2: Schematic of the relationship between geology, terrain character and, drainage patterns (D. Way).

information as derived from a 5-meter DEM of the area supplemented with high resolution Digital Globe commercial satellite imagery (as visualized in 3-D perspective using Google Earth), and integrated with recently published detailed geo-positional information on the Punggye-ri nuclear test site. This approach provides a more objective basis for identifying lithologic units and their boundaries such as are present on the USGS reconnaissance geology map between the mapped Mesozoic diorite and the Precambrian gneiss. Our approach exploits the relationship between geology and the drainage networked formed by erosion. How a landscape drains and forms drainage networks can provide important information about the underlying rock type and structure. Drainage networks are categorized by pattern type, texture, and density. Drainage pattern is the most important single parameter for quantifying landforms.[13] We have developed a methodology which uses a quantitative analysis of the drainage pattern derived from a DEM to extract geologic information. The relationship between various underlying geologies and the observed drainage patterns is schematically illustrated in Figure 2 (Supplemental Appendix Figure A3). In particular, we concentrated on the drainage pattern produced by bedrock with a greater degree of fracture, which given its less competent character, could be identified by a more angular drainage pattern. Our analysis of the drainage pattern suggests a differential stream pattern consistent with two different rock types along a lithologic boundary as inferred and mapped by the USGS in 2010 and separating the two types of host rock associated with underground nuclear testing.

Geomorphic landscape features reflect the interplay between tectonic-associated processes of uplift and climate-associated processes of erosion. The underlying geology controls the character of the landscape for both of these processes. Recent advances in the field of geomorphometrics provides a methodology to quantitatively measure landscape features and provide an objective approach for evaluating the geology (e.g., rock type, fault and fracture distributions) that influence the character of landscapes.

Our approach to quantitative terrain analysis is based on three methodologies:

1. An eigenvalue analysis which provides information about the topographic organization and shape factor (a measure of the strength of the dominant linear fabric to the terrain).

2. A measure of the surface roughness based on the "rugosity" of the surface, calculated by computing the average elevation change between a grid cell and the eight neighboring grid cells.

3. Correlation of the surface drainage network with the bedrock geology and structure.

This information is then integrated with data collected by various remote sensing platforms and mapped and visualized with Global Mapper[14] and Google Earth[15] (together with correlation of available regional geologic maps of the area to refine the geologic site characterization).

The elevation contours (50 meter) for a high resolution (5-meter) DEM map of the Punggye-ri nuclear test site is shown in Figure 3. This DEM was used to evaluate the various stream drainage patterns (Figure 4) as an expression and potential indicator of the underlying geology. Most readily identifiable

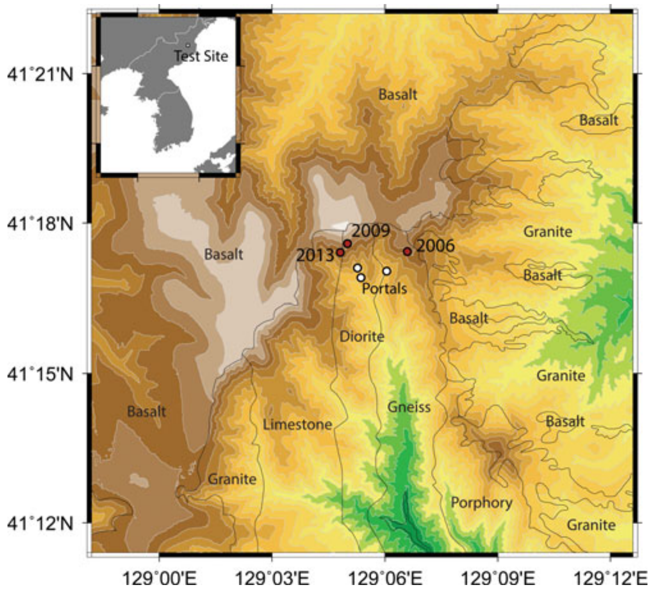

Figure 3: Elevation contours (100 meter) for the 5-meter digital elevation model map of the Punggye-ri nuclear test site showing the test locations and relative locations of the tunnel portals. Inset: Location of the Punggye-ri nuclear test site on the Korean Peninsula. The geological labeling and boundaries are as derived in the first reconnaissance mapping effort by Chirico (USGS) in 2010.

are the feather-like patterns arising in the nearly flat-lying basalt layers. The Oligocene age Ryudo (Yongdong) alkalic basalt in the lower right (southeast) corner of the map is clearly distinguishable from the Quaternary Shintokuri olivine basalt that encompasses the test site on the top and left (western and northern sides).

Supplemental Appendix Figure A4 shows the rugosity (or surface roughness) of the test site as determined from the elevation data. The Shintokuri basalt cap stands out sharply in dark blue on the west and north, while the mapped dolomite/limestone roof pendant appears as a light blue ovoid near the bottom center. This pendant is the eroded remnants of overlying limestone that were underlain and uplifted by the batholithic granitic rocks, and which surround the remnants.

Using a correlation algorithm to relate surface roughness to terrain types, the base terrain types of the DPRK test site provide insight into the geologic setting. The terrain characterization map (Supplemental Appendix Figure A5) illustrates how the region of high terrain complexity (rough topography generated by fractured and foliated schists and gneisses) extends up to the area of the DPRK test site. Capping basalts and volcanic layers mask the northern most extent of the basement rock terrain type, but it is reasonable to assume that it continues northward under the basalt and volcanic layers. Fine-tuning

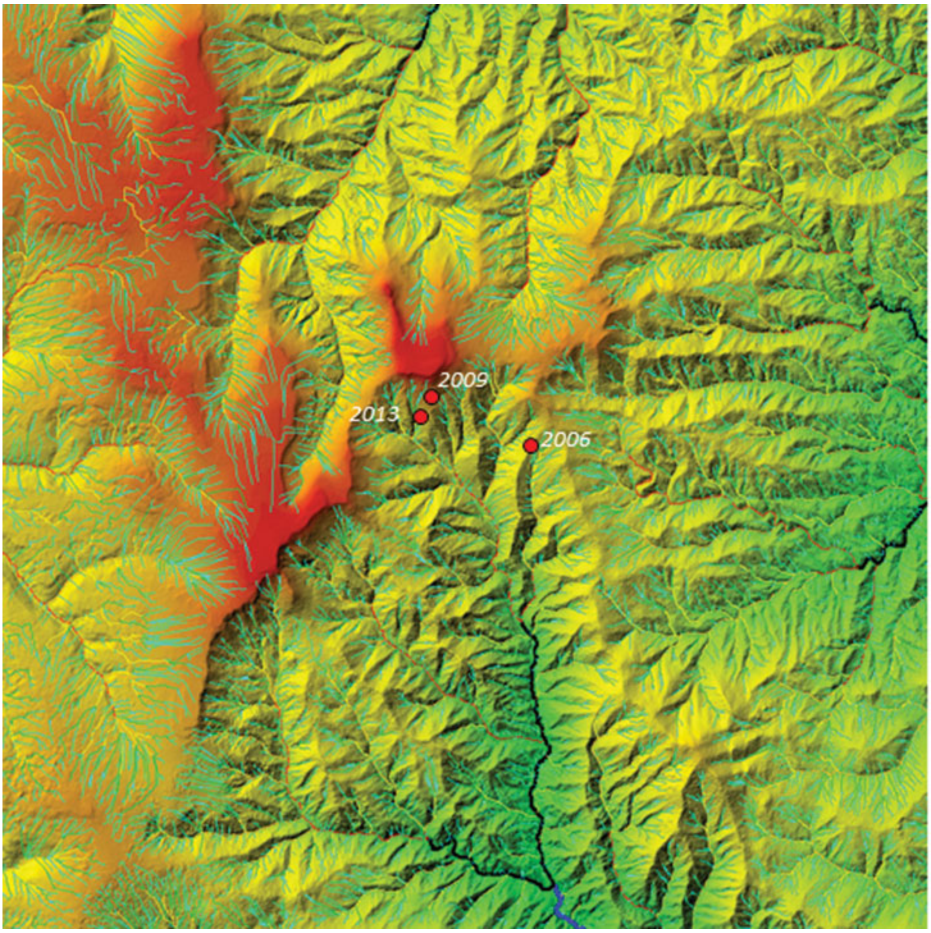

Figure 4: Stream drainage patterns derived from the topographic surface. Steam paths are colored by the Stream Order. Variations in the drainage patterns can be related to the underlying geology. Circles designate the approximate locations of the tests conducted at the test site. In the online color version the background coloration is representative of the relative elevations (green/lower, yellow/medium, red/higher). The red regions are generally flat-lying having feather-like drainage patterns typical of basalt flows and which are mapped as the capping Shintokuri olive basalt.

of the terrain type map and conversion to a plausible geologic map requires the incorporation of additional information. For example, Figure A6 in the supplemental Appendix illustrates the synthesis of the topographic data and the surface roughness information to further delineate the location and extent of a limestone pendant. At present, this "data fusion" step is achieved by visual inspection by a trained spatial analyst. It remains as much art as science. Future work would include additional automation of this step.

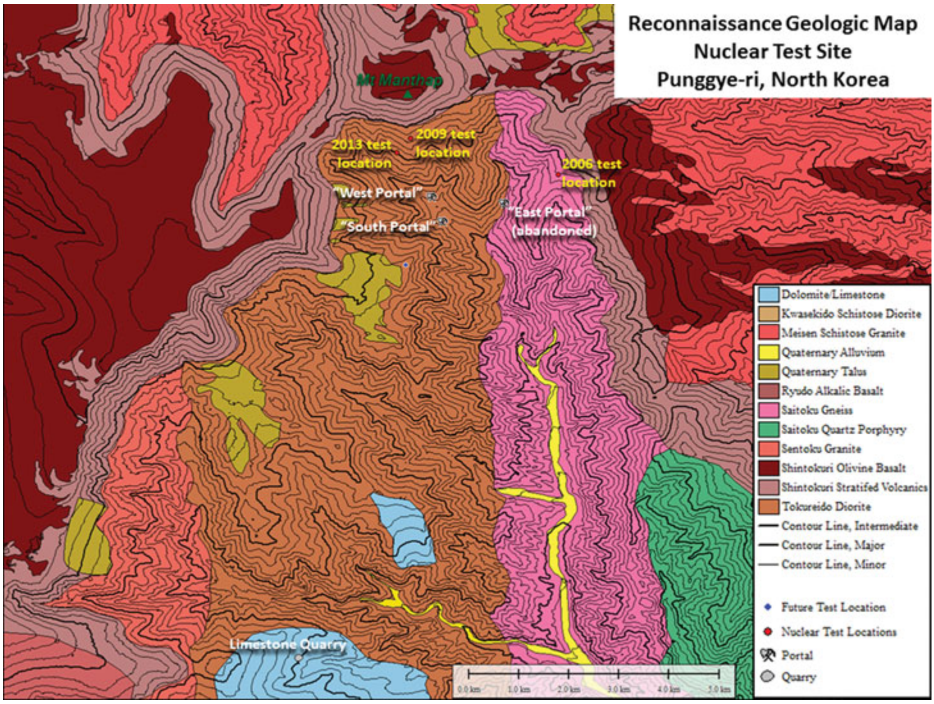

Figure 5: The local large scale predicted geologic map of the Punggye-ri nuclear test site derived from the various sources of geologic data and terrain analysis discussed in the text.

Our final geologic synthesis map of the Punggye-ri underground nuclear test site is shown in Figure 5 (See supplemental Appendix Figure A7 for overview and Appendix Figure A8 for detail). These maps combine all of the available information and are the product of both computer-automated analysis routines and fine tuning by geologic analysts.

Our geologic interpretation confirms that the test site is bordered on the west by the eastern limit of the Quaternary "Paektusan Volcanic Plateau," also known as the Kaima Plateau consisting of a sequence of horizontal volcanic strata including the Shintokuri olivine basalt sourced to the Paektusan (a.k.a. Baitoushan, Hakutosan, Mt. Changbai) volcano, located 110 kilometers northwest of Punggye-ri on the North Korea/China (42°06 N and 128°04 E).[16] That stratified volcanic sequence (including likely tuffaceous ash falls) forms the top 200 meters of Mt. Manthap and includes a thin capping layer of basalt that forms a prominent scarp along the western and northern portion of the test site. The sequence, which has been dated to 1.4 ma, lies uncomformably upon the basement rocks within the test site proper.[17]

Rockslides, consisting of greyish basalt talus and scree, extend downslope at multiple locations from a break in slope that marks the unconformity boundary. Erosion channels are most prominent beneath gaps in the otherwise protective basalt cap and escarpment. Severe flooding in the late summer of 2012 caused marked erosion scars which contributed to downslope scouring of the major steam beds along with adjacent vegetation that exposed bare bedrock in many places within the test site proper (thereby providing new candidate sites for future hyper-spectral analysis).

The main area of the test site tunneling underlying these volcanics is situated in the basement rocks, most often described as Jurassic-aged granite, (e.g., "Meisen schistose granite"), but more likely consisting of a variety of rocks including granite, diorite, gneiss, and possibly quartz porphyry. These basement rocks form a large south sloping and eroded drainage basin.

The eastern portion of the test site, which has been associated with North Korea's first nuclear event in 2006, is characterized by highly foliated and fractured rock. Although we have tentatively mapped this lithologic body as an extension of the Saitoku gneiss consistent with Chirico, we cannot rule out it being a western extent of the "Meisen schistose granite," which would also be consistent with the small scale 1994 North Korean origin geologic map. Japanese geologists (in particular, Yoshio Kinosaki) noted that the rocks of the Precambrian Matenrei System (that include the Saitoku gneiss and the dolomite/limestone) are not only "intensely comingled with each other, but also intruded by so many dikes and lit-par-lit injections of various rocks such as aplite, pegmatite, schistose granite, and schistose diorite, that they cannot be differentiated on the maps." The host rock for the 2006 underground nuclear test is highly foliated, and likely highly fractured, which might help to explain the prompt venting of radioactivity detected outside of North Korea following that first nuclear event.

The western portion of the test site proper, where both the 2009 and 2013 underground nuclear tests occurred, has been tentatively identified and mapped as Tokureido diorite, although we cannot rule out a less foliated and fractured version of the Meisen schistose granite (or perhaps a younger Mesozoic granite like the Sentoku). In either case, based on our geomorphometrics-based analysis, the host rock directly under Mount Manthap is likely a hard and competent one, more like diorite or granite, and thus likely a good choice for containing underground nuclear explosives tests.

DISCUSSION

Several topics of interest relevant to the North Korean test site can be reexamined given the results presented above.

Carbonate Rocks in the Vicinity of the Punggye-ri Nuclear Test Site?

This study provides an objective basis for evaluating the plausibility of dolomite/limestone units in the immediate vicinity of the 2009 nuclear test epicenter (as suggested by the results of the USGS ASTER image evaluation). Our conclusion is that there is little evidence to support the existence of such a distinct lithologic boundary bifurcating Mt. Manthap near the 2009 nuclear test event epicenter. According to Buttleman and Matzko:

> . . .Although no carbonates are shown in the immediate area of the test site on the small-scale geologic maps available, the differences in the maps suggest some uncertainty as to the extent and proximity of the carbonates to the site, and even the possibility of roof pendants within the Mesozoic (Jurassic) granites of the Mt. Manthap area. While there is presently no evidence that the nuclear test of October 2006 was conducted in carbonates, their presence may limit the locations of potential future tests in this region.[18]

Although we have found little evidence to indicate the presence of carbonate rocks (Matenrei system dolomite/limestone) in the immediate vicinity of the test site proper, by employing "geomorphometrics" and visual inspection of commercial satellite imagery, we did find evidence of one likely "roof pendant," which may have also served as the location of a former limestone quarry. From our analysis, together with previous USGS reporting, we found agreement with the small scale North Korean geological map from 1994 which shows the northernmost extent of a main block of dolomite/limestone is also the location of an active limestone quarry. This quarry was first identified as likely being for limestone by Chirico based on spectral analysis of ASTER multi-spectra imagery in combination with interpretation of commercial satellite electro-optical imagery in 2010.

It could also be argued that since this is the closest observed limestone quarry to the underground test site, it is unlikely that a source of limestone is present any closer to the test site proper. Limestone is an important ingredient in cement, a commonly used material either alone or mixed in concrete for reinforcing tunnel walls and/or for emplacement purposes (Pakistan was reported to have sealed its nuclear test tunnel at Ras Koh with a mixture of sand and 6,000 bags of cement in 1998). If such a source of limestone were readily accessible closer to the test site, then it would likely have been tapped to limit transportation costs in terms of time, distance, and diesel truck fuel.

Rock Type at the North Korean Underground Nuclear Test Site

In assessing the regional geologic setting, Buttleman and Matzko point out:[19]

> In general, low porosity, dense, massive rocks such as granite. . .offer good environments for underground nuclear tests. The tectonic history of this area suggests, however, that rocks pre-dating the Mesozoic Songnim movement have suffered deformation from this movement, and are folded, sheared, and fractured, thus reducing the integrity of the rocks. The ground photographs provided in the

atlas suggest that many rocks, including those post-dating the Songnim tectonic movement, might be highly fractured and thus complicate containment, and require adequate technical remediation.

Murphy, similarly commented:[20]

> ... the surface rock types identified from the limited available literature sources for the NK test site area suggest competent hard rocks, consistent with the inference that the nuclear tests were conducted in "good coupling" media.

Our analysis identifies evidence of potentially highly fractured rock near the "East Portal." A comparison of available ground photos of the highly fractured Saitoku quartz porphyry near the village of Punggye-ri with outcrops in the eastern portion of the test site is made possible with commercial satellite imagery available on Google Earth (supplemental Appendix Figure A9). The rocks in the eastern portion of the nuclear test site proper are highly foliated and broken and thus likely fractured. The presence of foliations is consistent with descriptions of the Meisen schistose granite.[21]

Based on reporting by the Japanese geologist, Iwao Tateiwa, the Meisen schistose granite is included in the regional intrusive basement described as being of unknown age (but labeled by others as Mesozoic/Jurassic). Tateiwa described these rocks as having been "intensely pressed" and that the "strike and dip of their schistosity plane, which is obviously of the pre-Tertiary, are variable as shown in the geologic maps. Overall, these planes strike NW-SE and dip sharply to the northeast or nearly vertical." The foliations in the outcrops in the eastern portion of the Punggye-ri nuclear test site strike NW-SE (approximately 300-120 degrees) and also dip steeply (approximately 65 degrees), albeit to the southwest, consistent with the regional strike (supplemental Appendix Figure A10).

While the lithology of the eastern portion of the Punggye-ri underground nuclear test site consists of foliated rock and at least one prominent rock pillar (supplemental Appendix Figure A11), the western portion is subdued with rounded slopes and a less angular dendritic stream pattern more indicative of a non-foliated granite or diorite. The host rock that has been excavated from the "East Portal" is somewhat darker grey than the excavated host rock from either the "West Portal" or the "South Portal" which appear to be lighter grey in color (supplemental Appendix Figure A12).

Such potential differences in lithology between the host rock accessible via the "West Portal" and that accessible via the "East Portal" may explain why the "East Portal" has been abandoned. That the "East Portal" has indeed been abandoned is indicated by the removal of all but two buildings outside the portal, the lack of any vehicular track activity, and most importantly, the lack of road or bridge repair work of any kind following the heavy flooding of the test site in the summer of 2012. Contrariwise, such repair work has been regularly observed at both the "West" and "South" portals, with mining and vehicular activity ongoing in association with those portals.

Containment Factors Associated with North Korean Underground Nuclear Testing

A number of factors may provide insights as to why the first test in 2006 (associated with the "East Portal") vented detectible radioactivity in the form of noble gases, while the subsequent two tests in 2009 and 2013 (associated with the "West Portal") did not.

These factors could include:

1. That the 2006 test was emplaced at a location affording less overburden, hence shallower depth of burial than the following tests and hence closer to the surface to facilitate easier gas migration.
2. Higher yield tests (e.g., 2009 and 2013), are more likely to produce "containment stress cages" than the yield test of 2006.
3. The detection of radionuclides could have been a spurious detection unrelated to the 2006 test.
4. The geology of the host rock used for the 2006 test was less competent than that used for the 2009 and 2013 tests (supported in part by the geomorphological analyses in this study).
5. The North Koreans may have employed more robust containment strategies for the post-2006 tests (as the North Koreans apparently claim in an animation video publicly broadcast in 2010).
6. The presence of ground water onsite.

There is a dearth of specific reporting on the ground water, water table depths, and rock saturation in the vicinity of the Punggye-ri nuclear test. However, surface water can be regularly observed in the streambeds throughout the test site proper, and, more importantly, water has apparently flowed regularly from the "South Portal." A possible diversion channel for draining ground water has been observed in the vicinity of the "West Portal" based on imagery from 2013 (the location of both the 2009 and 2013 tests and where new tunneling is now underway) and it is unclear if water has ever been visible near the "East Portal" (associated with the 2006 test) in the past.

A Comment on Generating Geologic Framework Models for Denied-Access Sites

This study illustrates the procedure for generating and refining the surface geologic map for a denied-access site. This information is critical for constraining information used for a 3-D geologic framework model (GFM) which extends the geologic information into the subsurface. The GFM provides a structural framework populated with subsurface physical properties and forms the basis for both near- and far-field modeling efforts. The procedures discussed in this study for refining and modifying the surface geologic map illustrate the need for an expert analyst to provide interpretation of the data and develop plausible geologic relationships.

Additional Spectral Analysis Work

An opportunity exists to acquire and evaluate more current, post-flooding 14-band ASTER or 220-band HYPERION imagery or 29-Band WorldView-3, preferably in early spring, post-snowmelt and pre-foliage, and to specifically focus on those areas of newly exposed bedrock (and newly excavated tunnel spoil) to cross-check our findings with the ASTER spectral geologic library.

Additional Applications for Synthetic Aperture Radar Imagery

The application of commercially available high resolution synthetic aperture radar (SAR) imagery could also help to shed new light on the underlying lithologies and the extent of foliations and fracturing, and, if both pre- and post- test radar imagery for each event (including any future events) could be obtained, interferometric coherent change detection would likely also reveal subtle surface disturbances yielding even greater precision with respect to the event geo-locations.

CONCLUSIONS

This study provides a revised reconnaissance-based geologic map, site characterization, and geologic report for the area surrounding the underground nuclear test site near Punggye-ri, North Korea. Our research involved a reevaluation of all available geologic information combined with original analysis of commercial-satellite-sourced remote sensing data to derive a more accurate understanding utilizing a novel integrated “geomorphometric” approach.

The results indicate that the North Korean nuclear test site is located in Mesozoic/Jurassic age granitic-like basement rock, similar to that mapped on a small-scale North Korean geology map published in 1994. However, our findings also show that there is reason to believe that this basement host rock may vary in competency, with the 2006 event most likely having occurred in less competent, e.g., fractured, host rock (either Precambrian Saitoku gneiss (as mapped) or Jurassic-age Meisen formation's schistose granite), while the subsequent 2009 and 2013 tests more likely occurred in a more competent host rock (either Cretaceous Tokureido diorite or less fractured Mesozoic-age granite) thereby providing better containment and better coupling. Such information offers a new basis for understanding possible radionuclide venting mechanisms for the 2006 test, as compared to the higher yield 2009 test that did not leak detectible radioactivity, while also helping to provide insights on the cause of subsequent abandonment of the "East Portal," which had been used to support of the 2006 test.

We also found that there is a low probability for the existence of Precambrian (Proterozoic, "Matenrei") limestone/dolomite in the immediate vicinity of the nuclear test site, which thus mitigates the likelihood of prompt venting due to non-condensable carbon dioxide gas generation as a result of any future nuclear testing in the area. This study is the first to address these issues specific to the absolute event locations associated with North Korean nuclear testing at the Punggye-ri nuclear test site.

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SUPPLEMENTAL MATERIAL

Supplemental data for this article can be accessed on the publisher's website.

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