TOPOGRAPHIC, GEOLOGIC, AND DENSITY DISTRIBUTION MODELING IN SUPPORT OF PHYSICS EXPERIMENTS AT THE SANFORD UNDERGROUND RESEARCH FACILITY (SURF)

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ABSTRACT

The Sanford Underground Research Facility (SURF) has constructed laboratories on the 4850 Level in the underground. These laboratories are hosting particle physics investigations, such as those associated with neutrino physics and dark matter searches. The laboratories are located in the underground to take advantage of the overlying rock that shields the experiments from the effects of cosmic radiation. The efficiency of the shielding typically is evaluated in terms of water equivalent depth, which is the thickness and density of rock that would be the equivalent depth of water. In order to provide a basis for evaluation of the effects of the shielding rock, we developed a geologic model using available data and densities assigned to the rocks making up a cone of material centered over the Davis Campus on the 4850 Level. This information is presented in a series of cones that are contoured in terms of water equivalent depths. Paths are shortest in the area directly over the laboratory and longest at shallow angles that penetrate greater columns of rock. The analysis of the density cones shows that the most important effect is due to variations in topography. Although variations in the density of the rock affect the water equivalent depths, particularly in the western area of the site, the effects are secondary. The influence of stopes or mined out areas are not significant due to backfilling of most of the voids and the generally small mined volumes in relation to the much larger volume of the geologic cone of analysis.

Keywords

Sanford Laboratory, attenuation, density

INTRODUCTION

The mission of the Sanford Underground Research Facility (SURF), located in the Black Hills of South Dakota, relies upon relationships involving physics, geology, and mining. This interplay became evident during the preliminary planning and construction phase of the laboratory (Lesko et al. 2011), when issues of excavation, rock stability, and attenuation of cosmic radiation by the overlying rock were investigated. Particle physics laboratories have been and are being constructed at SURF to support studies of neutrino physics and searches for dark matter. The primary reason for location of these laboratories underground is to shield the experiments from the effects of cosmic radiation that would add unacceptably high background signals if they were located at the surface (Lesko et al. 2011). Although neither the postulated dark matter particles nor neutrinos are significantly impeded by the rock, the overburden attenuates the muon flux, thus providing an effective filter for particle physics studies. Similarly, the shielding effect of the rock is important in detectors that are searching for very rare events associated with local sources of radioactive decay, such as those experiments searching for neutrinoless double-beta decay. The rock above the laboratories provides crucial shielding for the detector systems at depth for both of these types of studies.

The attenuation of muons is a function of the depth, surface topography, and rock densities being traversed by the cosmic radiation (Lesko et al. 2011). Mei and Hime (2006) showed that the expected decrease in muon intensity is exponential and is a function of the overburden density. The common measure that combines these two attributes is water equivalent depth, which is the distance travelled by a muon through water corrected for the difference in density between water and the density of the material. Therefore, the attenuation of cosmogenic muons is due to both the distance traversed by the muons and the density of the rock through which they travel. Use of the average density of the rocks is a good first approximation in conjunction with the observed topographic relief, which causes the thickness of the rock shield to change. However, the Sanford Laboratory is constructed in a complexly folded metasedimentary and metaigneous terrain with some variation in rock densities among the geologic units. Therefore, the goal of this project was to evaluate the effect of those variations in rock density based upon the best available geologic model of the volume surrounding the laboratories and the topography in the vicinity of the facility.

SURF Stratigraphy and Structural Geology—SURF, which was the site of the former Homestake Gold Mine, is located in the northern end of the Black Hills of South Dakota. The site is characterized by a youthful topography with canyons that are narrow and steep sided. The average elevation in the vicinity of the laboratory site is ~1,640 m above sea level and has a maximum relief of ~220 m in the area investigated.

The southern portion of the Black Hills is a structural dome consisting of a core of intensely folded Precambrian metamorphic schists and phyllites (Redden and Lisenbee 1990). The Precambrian rocks are overlain unconformably by Paleozoic sedimentary rocks that dip gently away from the core of the dome. The northern Black Hills, where the Sanford Laboratory is located, were created primarily by the intrusion of Tertiary-age rhyolites, trachytes, and phonolites. These intrusive rocks have domed the overlying Phanerozoic rocks and exposed the Precambrian crystalline rocks at the site, and sedimentary rocks are absent in the immediate vicinity of the laboratory. The laboratory is developed within

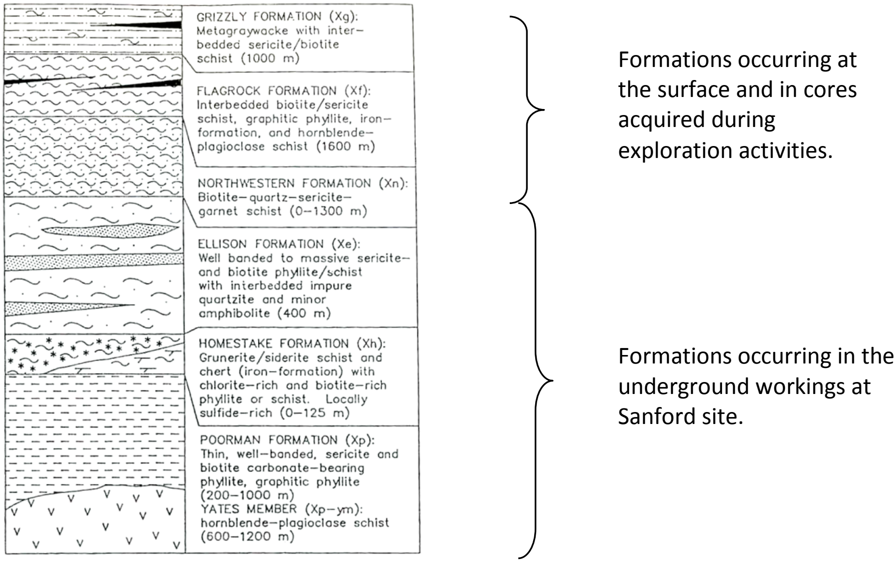

Figure 1. ***Precambrian stratigraphy at and near Sanford Laboratory (after Bachman and Caddey 1990). The Grizzly and Flagrock Fm. are not exposed by the underground workings, and only the lowermost portion of the Northwestern Fm. is present in the underground drifts.***

a thick series of Precambrian metasedimentary and metaigneous rocks that were deposited during the Precambrian at approximately 2,000 Ma based on dating of a tuffaceous unit in the Ellison Fm. (1,974 ± 8 Ma [Redden et al. 1990]). The sediments were fine-grained sands, silts, and muds with lesser amounts of chemical precipitates, and the protolith of the igneous rocks was basalt (Dodge 1942). The sedimentary and igneous rocks were metamorphosed subsequently to become the phyllites, schists, and amphibolites present at the site. The Precambrian units that make up the stratigraphy of the SURF site are shown in Figure 1.

The geologic structure of the Homestake Mine was summarized by Morelli et al. (2010) who listed five deformational events, many of which were associated with large tectonic movements related to the assembly of this part of North America during the Proterozoic. The net result of these events was to produce complexly folded metasedimentary units cored by the mafic Yates Member amphibolite (Caddey et al. 1991).

Goals and Approach—The approach for calculating the effects of density differences in the geologic units consisted of constructing a geologic model of the structure based upon available information, estimating the densities along selected virtual drill holes, applying the average density and length of the virtual drill hole in the rock to convert the results to a depth equivalent attenuation model. A virtual drill hole is defined for the purpose of this study as being the predicted geology and associated densities if a hole were drilled at a selected location and orientation. In order to assess the effect of geology on the cosmic radiation attenuation, we created a family of paths that intersect the

Davis Campus through the cone of geology being considered. An example of two such paths is shown in Figure 2 (dotted lines). This information was then contoured to display the depth equivalent values.

Geologic Model--Calculation of the density distribution required the production of a geologic model for the subsurface in the vicinity of the site. The model was developed using the Maptek Vulcan mine design software package along with numerous other data sources. These included diamond drill core logs, review of the historical underground geology mapping (both the rough field mapping and the finalized inked maps available at the Homestake Adams Research and Cultural Center [HARCC], Deadwood, SD), underground on-site review of the mapping, and surface mapping (Redden et al. 2010). Other published sources that were particularly useful for the geological analysis included Dodge (1935; 1942), Nutsch (1989), and Caddey et al. (1991). Once the geologic data were assembled, reviewed and adjusted, geologic cross-sections were developed using the Vulcan software. Those portions of the geologic model that fit within a 45° cone centered on the Davis Campus were evaluated for the effect of density and topography (Figure 2).

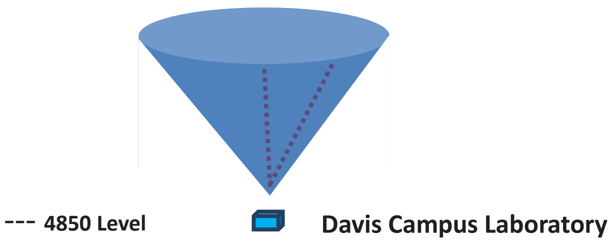

Figure 2. ***Diagrammatic sketch showing the cone centered over the Davis Campus at the 4850 Level. This is the cone that will contain the geologic model. Also shown are two virtual drill holes that were used to generate the water equivalent model.***

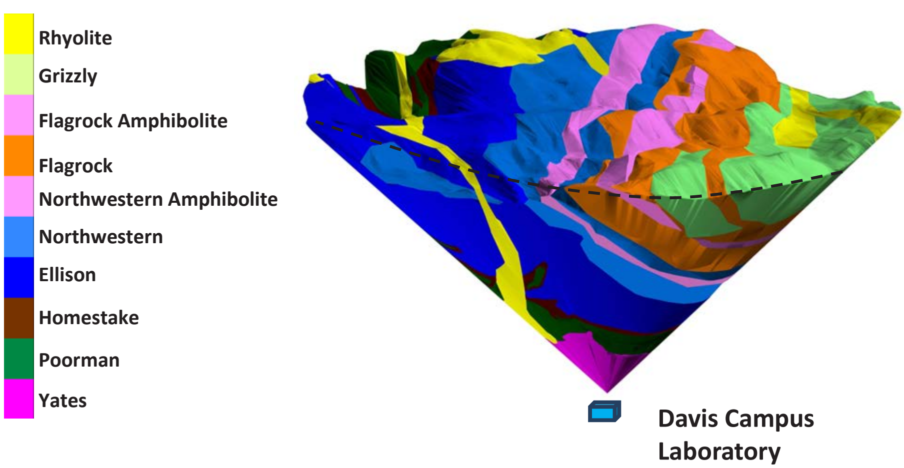

Figure 3. Geologic model within the 45° cone centered on the Davis Campus located at the 4850 Level.

Based upon the geologic cross sections and model, the cone of Figure 2 was populated with the developed geologic model (Figure 3). As in Figure 2, the cone is centered over the Davis Campus that is constructed on the 4850 Level of SURF. The cross-cutting relationship of the rhyolite (yellow) is displayed in the western part of the area.

Estimation of Densities—Although the geologic formations are well-defined mapping units, acquisition of representative samples for the determination of densities may be complicated by variations in lithologies within those geologic units. With the exception of the amphibolite units of the Yates Member of the Poorman Formation, the other metasedimentary units typically have varying proportions of schists, phyllites, and quartzites. The lack of matrix porosity simplifies the density modeling, however, and overall fracture porosity is limited as well. Jones (2010) reported that the rock on the 4850 Level trapped large bubbles of air in the roof of that level even though it was flooded to a depth of 97.5 m (320 ft) for over 16 months. This indicated that permeabilities, and, by inference porosities, were very small. Therefore, the densities are predominately due to the individual mineral densities and are not a function of porosity.

Table 1 lists the densities used to calculate the water equivalent depths. Nutsch (1989) measured 32 samples for density measurements and also referenced internal Homestake studies including 24 samples by Sumner (1965, HMC Report), and 18 samples by Mathisrud (1947, HMC Report). Density measurements were also acquired as part of the preliminary design for development of the laboratory (Lesko et al. 2011), which included primarily the Yates Unit, the upper part of the Poorman Formation, and rhyolites intruding the sequence on the 4850 Level. These are identified as RESPEC RSI in Table 1. All density values were given the same weight in this investigation even though the data were collected and determined by various authors over time.

Because no published values were available for the Northwestern, Flag Rock, or Grizzly Formations, density measurements were made as part of this study. Hole 17462 from the Homestake Core Archive was drilled from the 6800 Level in a generally southerly direction and penetrated all three of these units. Ten samples from this drill hole were measured from each of these three units and their average densities are included in Table 1. Surficial weathering and thin Cambrian sandstones that cover a small portion of the site were not considered due to their minor contributions.

In order to construct a representative volume based on a cone centered in the SURF underground based upon density distribution of lithologies and topography (Figure 2), we created virtual drill holes using the Vulcan software environment. These virtual drill holes consist of the lithologies and expected densities that would be encountered if the drill hole were drilled in the specified location and orientation. A family of virtual drill holes was created every 22.5° around the center overlying the Davis Campus. Within each of the 22.5° families a drill hole was created every 5° vertically. The average densities for each drill hole were then plotted at the point of intersection between the virtual drill hole and the horizontal plane. These values then were contoured as water equivalent depths (Fig. 4).

Table 1. ***Densities used for the calculation of water equivalent depths. Standard deviations are shown as ± for densities determined during this study (HMC refers to Homestake Mining Company reports and RSI refers to Report of Site Investigations).***

Formation	**Density**	**References**
Grizzly Formation	2.78 ± 0.06 g/cm^3	This study
Flagrock Formation	2.98 ± 0.15 g/cm^3	This study
Flagrock Amphibolite	2.98g/cm^3	Assumed to be same as Northwestern Amphibolite
Northwestern Formation	2.84 ± 0.05 g/cm^3	This study
Northwestern Amphibolite	2.98g/cm^3	Nutsch (1989)
Ellison Formation	2.73 g/cm^3	Mathisrud and Sumner (1967, HMC Report); Nutsch (1989); Bachman and Marlowe, HMC Memo (1991, HMC Report)
Homestake Formation	3.26 g/cm^3	Mathisrud and Sumner (1967, HMC Report)
Poorman Formation	2.86 g/cm^3	Mathisrud and Sumner (1967, HMC Report); Nutsch (1989); Bachman and Marlowe, HMC Memo (1991, HMC Report)
Yates Amphibolite	2.93 g/cm^3	Nutsch (1989); RESPEC RSI. May 2010; RESPEC RSI. June 2010
Rhyolite Dikes	2.54 g/cm^3	Nutsch (1989); RESPEC RSI. May 2010; RESPEC RSI. June 2010

Figure 4 shows the distribution of densities derived from the analysis of the virtual drill holes and the effect of density on the water equivalent depth. The most obvious feature in the plot of the densities in Figure 4a is a density low in the western area that is associated with a rhyolite dike swarm. Figure 4b shows the water equivalent depths using a density of 2.84 g/cm^3, which is the average value for rocks at the site weighted for volume and their respective densities. Because the density does not vary in this plot, the plot shows only the effects of topography. Figure 4c used the densities for the rock including the geologic model developed as part of this study. Figure 4d shows the difference between the contoured plots of Figure 4b (using an average density of 2.84 g/cm^3) and Figure 4b (using densities derived in this study).

Mining operations during gold production excavated extensive volumes of rock, and the resulting stopes and workings are well documented in the Vulcan database for the Laboratory. Although the total amount of the stoped volumes that were backfilled cannot be determined unambiguously, most were backfilled. The effects of the mined areas are included in the model of Figure 4c assuming a reduction of 22 percent from the average density of 2.84 g/cm^3. However, the volumes of rocks removed as part of the mining process affect only 0.5 percent of the volume of the cone, and the stoped volumes do not affect the plots significantly.

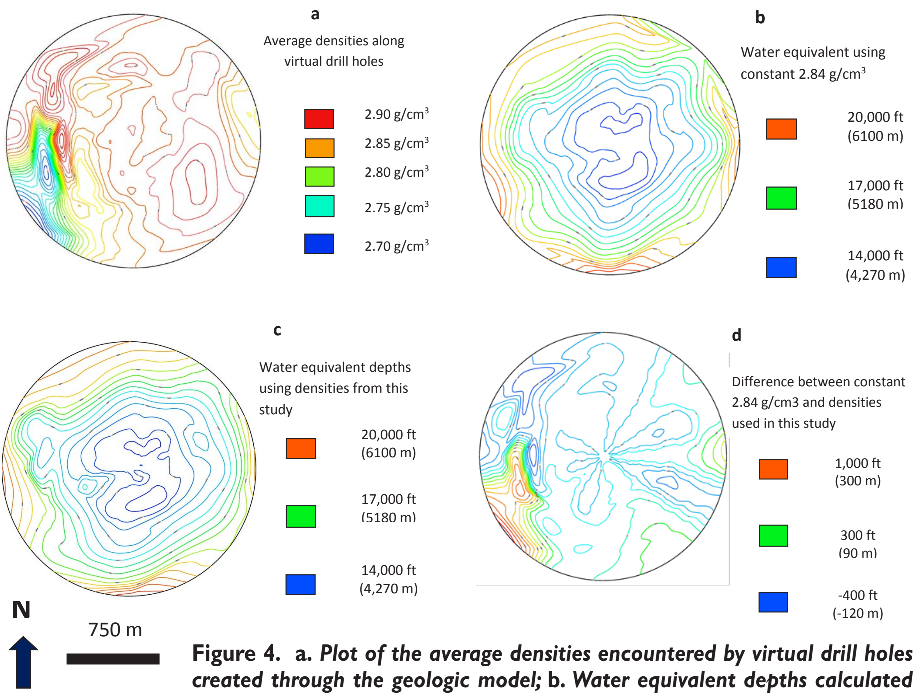

Figure 4. a. ***Plot of the average densities encountered by virtual drill holes created through the geologic model;*** **b.** ***Water equivalent depths calculated using an average density of 2.84 g/cm³;*** **c.** ***Water equivalent depths calculated using densities derived during this study;*** **d.** ***Plot of the difference between the plots using an overall average density of 2.84 g/cm³ and the densities used in this study.***

DISCUSSION

The geologic model from which the water equivalent depths were calculated relies heavily upon the availability of subsurface data such as mapping in the drifts and exploration drill holes. At greater distances from the underground workings direct information becomes less abundant and, therefore, the geologic model is more dependent upon surface mapping, such as the geologic map of the Lead Quadrangle by Redden et al. (2010), as well as cores and logging acquired as part of the exploration activities of the Homestake Mine. The dike swarms, for this model are assumed to be one hundred percent rhyolite in composition. However, these dike zones are not 100% rhyolite, but rather are a mixture of rhyolite and intruded host rock, which reduces the effects of the lower density of the rhyolite. Some smaller rhyolites may not be included in the model due to their apparently lesser extents and insufficient data to determine their locations accurately. These include the dike swarm within the west wall of the 4850 Davis Campus, the dike swarm east of the present 4850 Davis Campus, the dike swarm cutting through the Northwestern, and a dike swarm cutting through the Flag Rock. Additionally, the surface exposure of a rhyolite sill east of the Open Cut is not part of the model. The relatively thin phonolite intrusives that are oriented east west and which dip to the north also are not addressed in the model.

In addition to topography, the analysis presented here takes variations in rock density into account along with the angle at which incident muons would arrive at a laboratory located at the 4850 Level at SURF. The composition appears to be reasonably consistent within individual metasedimentary formations, which allows a limited number of density measurements to reflect the average density of the units. The one exception to this observation occurs in Flagrock Formation, which has more pyrite-rich intervals resulting in higher densities in those short sections. Table 1 shows that the standard deviation for the Flagrock is over twice that of the adjacent Grizzly and Northwestern Formations as a result of this variation in composition. Metamorphic grade changes within the limits of the mined underground which may also have some effect on the overall density pattern.

Figure 4a shows the plot of the average densities encountered by the virtual drill holes. In general, the densities are uniform in the eastern portion of the area with greater differences in the west. This is due primarily to the influence of the rhyolite dike system. Figures 4b, 4c, and 4d show that the greatest effect on the water equivalent depth is due to variations in topography. This point is emphasized by Figure 4d which shows the difference between using an overall average density of 2.84 g/cm^3 and the use of identified formation densities along with the geologic structure. Differences do exist but their effects are not pronounced with the possible exception of the rhyolite intrusions in the western portion of the plot. These results are consistent with the observation that, in general, large variations in density in the Precambrian crystalline rocks do not occur with the exception of the Homestake Fm. (Table 1), which has a significantly greater density than the other crystalline rocks. This unit, however, is volumetrically small and does not appear to have a significant effect. Although some areas of the Homestake underground hosted large stopes where ore was mined, most were backfilled. They are volumetrically insignificant (< 0.5 percent of the volume of the cone) and affect the water equivalent calculations only slightly.

The geologic model shown in the cone centered on the Davis Laboratory is the most detailed approximation of the geology in the vicinity of SURF currently available. As shown in Table 1, in general, the rocks at SURF tend to have a density slightly less than three times that of water. Based upon the water equivalent contoured values, topography is the primary factor affecting the water equivalent depths for different paths. The rhyolite intrusions have the next most important effect although their influence is limited to the western area of the cone of investigation.

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