Revisiting Rock Mass Indices: Improving and Applying the Measurement of Erodibility

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ABSTRACT

Erodibility is an important factor in studies of geomorphology. Along with other factors such as climate, time, and tectonics, it contributes to the shape and evolution of landscapes. Several methods exist to quantify erodibility that examine rock mass properties such as fracture characteristics and strength of intact rock. These systems can be used to predict such varied properties as the slope of a rock mass, the geometry of bedrock channels, and the likelihood and type of potential slope failures. Yet, these systems are limited by shortcomings such as subjectivity, limited calibration, and failing to produce reasonable predictions of slope when rocks are mechanically or chemically weak. To address these and additional issues, original and modified versions of three erodibility rating indices are applied in a variety of lithologic, climatic, and erosional environments. Ratings are compared to topography for calibration purposes and to examine whether erodibility and topography will correlate in all environments studied. Several of the techniques tested are successful at improving ratings' correlation to topography in slowly eroding landscapes, while other landscapes do not correlate to ratings. A new adjustment factor for chemically weak rocks further improves this correlation in certain environments. Finally, suggestions are made for the future use of erodibility indices that incorporate specific techniques and alterations from the study as well as general impressions from use.

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Chapter 1: Introduction

1.1 Overview

Bedrock erodibility is one of the core variables contributing to landscape evolution and the efficiency of various erosional processes (Gilbert, 1877; Hack, 1960; Whipple et al., 2000; Sklar & Dietrich, 2001; Molnar et al., 2007; Wohl, 2008). In some landscapes, such as the Valley and Ridge Province of the Appalachian Mountains, the topography appears to be directly controlled by erodibility, with hard, competent rock comprising ridges and soft or heavily fractured rock comprising valleys (Hack, 1960). It is further recognized as contributing to geomorphology by its inclusion in the stream power law, where it is expressed as a coefficient of erosion (K).

Despite erodibility's having an effect on landscape evolution, erodibility is still not always addressed. Studies of the dynamic interactions between erosion, tectonics, climate, and topography often ignore erodibility entirely, downplay its significance, or assign rocks a simple designation of weak or strong (Spotila et al., 2002; Bishop et al., 2005; Harkins et al., 2007). Where attempts are made to measure erodibility, its measurement is often simplified to include only compressive strength (Duvall et al., 2004; Wohl & Grodek, 1993; Craddock, et al., 2007; Mitchell, et al., 2005), completely ignoring the effect of discontinuities.

The rock mass properties that are generally thought to control erodibility include joint properties (frequency, orientation, resistance to shearing) and intact rock strength (compressive, tensile) (Bieniawski, 1973; Barton & Choubey, 1977; Selby, 1980; Sklar & Dietrich, 2001). While characterizing these rock mass properties has been largely effective in approximating rock stability for engineering purposes (i.e. human timescales) (Bieniawski, 1988; Romana, 2003), fewer studies have been completed to determine whether these same properties are sufficient to approximate erodibility on geologic timescales and in varied environments (Selby, 1980). If geomorphology researchers are to account for erodibility, then the systems that are used to characterize erodibility must be better calibrated for the study of processes that span geologic timescales, lithologies, erosional processes, and tectonic environments.

1.2 Existing Erodibility Rating Indices

The idea of rating the strength of whole rock masses originates in geological engineering (Deere et al., 1969; Bieniawski, 1973) but was later adapted for use in geomorphology (Selby, 1980). Several rating systems for characterizing erodibility are currently employed by engineers and geologists. They generally address the compressive strength of unfractured rock, the extent to which groundwater is present, and the spacing, continuity, aperture, and infilling of fractures. While there is a rating index specifically designated for use in geomorphology, its roots lie in preexisting engineering indices, and it has not been calibrated to address the issues that geomorphological studies have found with it (Moon et al., 2001; Brook & Hutchinson, 2008).

The Geomechanical Classification, which has come to be known as the Rock Mass Rating (RMR) system, was introduced by Bieniawski (1973) for use in geological engineering. Multiple changes have been made to the parameters of this index since its initial publication in order to more accurately characterize rock masses (Banks, 2005). Ratings from this system correspond to approximations of stand-up time (over human time scales) and span distance for mines and tunnels, along with recommendations for rock face support and excavation design. Estimates of rock cohesion and friction angle are also included. Table 1a shows the parameters that make up the RMR index as well as guidelines for assigning ratings for each parameter. Rating parameters can be roughly categorized into compressive strength, joint characterization, weathering, or groundwater. RQD stands for Rock Quality Designation, a percent value that describes the amount of a rock core that is considered “hard” and “sound” (Deere et al., 1969). Additional qualitative parameters not shown are used to adjust for discontinuity orientation with respect to tunnel, mine, or foundation orientations. Also not shown is a qualitatively assigned adjustment for slope orientation, which has since been improved upon to create the Slope Mass Rating technique.

The Slope Mass Rating (SMR) technique was created by Romana (1985), modifying RMR for use in slope stability analysis (Table 1b). Also intended for engineering use, this rating system incorporates a quantitatively assigned adjustment factor that accounts for the orientation of discontinuities with respect to the orientation of the slope face, as well as an adjustment factor based on the type of excavation used on the outcrop, if any. Ratings correspond to potential failure type probabilities and suggestions for slope support (Romana et al., 2003). Tested in at least 25 separate studies, this system has generally been found to accurately characterize the potential modes of failure and necessary reinforcements in outcrops, though it is often slightly conservative (Romana et al., 2003). This index is often used in place of rather than in addition to RMR, as it only differs in the slope adjustment factors, and these it handles much more in depth. Unlike other commonly used rating systems, SMR is one of few to consider what type of failure may occur and make adjustments accordingly (Pantelidis, 2009). While RMS (described below) and RMR account only for discontinuity orientation, SMR considers the potential for planar, wedge, toppling, and mass failures (Romana, 2003; Pantelidis, 2009).

The only erodibility index specifically designed for use in geomorphology is Selby’s (1980) Rock Mass Strength (RMS) index (Table 1c). It has very similar parameters to RMR and SMR, but it was calibrated using natural outcrops only and designed to be easily and inexpensively implemented in the field. The main reason that RMS is easier and cheaper than the engineering indices described is that it lacks RQD, or Rock Quality Designation (Deere et al., 1969), which relies on the characterization of rock cores. Without this coring requirement, a single researcher can go into the field and collect all the necessary data to calculate a rating. Excluding RQD also makes RMS a non-destructive index to implement, which makes permits easier to obtain if not unnecessary when researching in protected or private sites. All of these factors make RMS one of the most widely used rock mass strength rating methods in geomorphology (e.g. Banks, 2005; Augustinus, 1995; Wohl, 2008; Goode & Wohl, 2010), and in total it has been cited 179 times (based on GoogleScholar as of 19 April 2012).

One final rating system that has not been as widely applied in geomorphology studies is the Geologic Strength Index (Hoek, 1994; Marinos & Hoek, 2001). It relies only on sketches and text descriptions of structure/discontinuities, and text descriptions of joint surface conditions. The resulting rating, along with approximations of other parameters such as uniaxial compressive strength, unit weight, and effects of groundwater, can be used to approximate Mohr failure envelopes (the stresses that will cause failure in a given rock mass). The GSI method will not be further addressed in this study due to the subjective and qualitative nature of the index, the fact that several rock properties are only incorporated into calculations rather than into the rating itself, and the system’s being unsuitable for characterizing rock masses whose failure methods are structurally controlled.

The RMS index has been widely applied in geomorphology studies, especially in fluvial geomorphology. It has been shown to affect fluvial profiles and incision rates (Wohl et al., 1994; VanLaningham et al., 2006; Whittaker et al., 2007), and was used along with channel slope to successfully predict bedrock channel morphologies (Wohl and Merritt, 2001). In glacial environments, it has been implemented to determine whether valley slopes are in equilibrium and how they will erode over time (Augustinus, 1995; Brook & Tippett, 2002). It has also been used in engineering to indirectly calculate RMR values, thus combining the ease of measurement of RMS with the design recommendations of RMR (Banks, 2005; Orr, 1992; Orr, 1996).

Although RMS is the only erodibility index specifically designed for geomorphologic use, RMR and/or SMR are often applied to geomorphology problems as well. SMR has been used especially to characterize cliffs, such as in Moore's (et al., 2009) comparison of SMR ratings to erosion rates in alpine environments, and in Andriani and Walsh's (2007) study of coastal geomorphology. SMR has also been widely applied to geology and engineering studies attempting to map slope stability or landslide hazards (e.g. Romana, 2003; Chacón et al., 2006; Di Crescenzo & Santo, 2007). SMR and RMR have both been used to characterize weak rock masses as well (Moon et al., 2001; Brook & Hutchinson, 2008). While RMR also appears frequently in the literature (Bieniawski's 1973 paper has been cited 437 times as of 19 April 2012 according to GoogleScholar), its application appears to be much more limited to the geological engineering literature. SMR and RMR are also frequently applied for practical engineering purposes (Bieniawski, 1988).

1.3 Shortcomings of Erodibility Indices

Despite widespread use, the existing erodibility indices are hindered by a lack of calibration. RMR was originally calibrated for engineering purposes ranging from tunnels and mines to foundations and slopes (Bieniawski, 1973), but the adjustments for slope were reexamined and re-calibrated to create SMR (Romana, 1985). Neither of these has been calibrated for geomorphology studies. RMS was originally calibrated for use in geomorphology, but despite the author's recommendation that it be further calibrated (Selby, 1980), subsequent studies have not altered it.

RMS is generally applied as it was originally published. Thus, the only calibration of RMS that has occurred took place in two regions: an arid, Antarctic region and a warm, humid region of New Zealand (Selby, 1980); subsequent tests of the index did not attempt re-calibration of the originally published parameters despite the addition of new field sites in different climates and lithologies (Selby, 1982; Abrahams & Parsons, 1987). Furthermore, calibrations were only performed on naturally occurring outcrops, meaning non-outcropping rocks that must be viewed in excavated sites were not considered. This exclusion explains why only about 16 out of 98 field sites used for Selby's (1980) calibration were below the angle of repose. Examining plots of RMS versus slope reveals that for many studies (Selby, 1980; multi-sourced data synthesized in Abrahams & Parsons, 1987) the correlation between ratings and topography breaks down if sites above the angle of repose are excluded (see Figure 1a). Due to the large extent of continental crust that is at or below this angle, this poor correlation bears further examination.

The lack of calibration for low-slope rocks also explains the results of studies that find RMS to be a poor predictor of slope when rock masses are weak or soft, such as mudstones (Moon et al., 2001; Brook & Hutchinson, 2008). These studies showed that such soft rocks, highly prone to weathering and slaking, begin to behave like soils and are prone to creep. Some of the rocks in these studies were only accessible at road cuts, as they were too weak to form natural outcrops, validating the hypothesis that RMS calibrations likely did not include many weak rock outcrops. These same studies show RMR and SMR to produce ratings poorly correlated to topography as well, suggesting that something in the underlying parameters of all of these scales is insufficient to characterize weak rock masses. Brook and Hutchinson (2008) made some vague suggestions about altering the weight of intact rock strength to improve correlations, but did not design or test such an adjustment. Moon et al. (2001) suggested ignoring erodibility indices entirely and using a stereonet to predict failures. Yet, without at least attempting to adjust erodibility indices to account for weak rocks, it seems that they should not be entirely cast off.

It is also suspected that chemically weak rock will not be accurately characterized by existing indices, which have no parameters or adjustments for chemical resistance. Fresh exposures of dolostone or limestone, for example, may show high compressive strength and, in man-made outcrops, little or no signs of weathering. Yet, in well-adjusted landscapes such as the Valley and Ridge of the Appalachians, chemically weak rocks such as carbonates comprise low relief valley bottoms. Thus, it is expected that chemically weak rocks will produce relatively high erodibility ratings that do not accurately characterize the strength of the rock mass over geologic timescales and that do not correlate to topography.

Erodibility indices are also not calibrated for different erosional mechanisms, instead focusing on the potential for failures along discontinuities (Bieniawski, 1989; Romana, 2003; Selby, 1980). Yet, in fluvial studies, intact rock strength is most important to erodibility if abrasion is the dominating form of erosion, while if plucking is the dominating erosive process then joint spacing and characterization is most important (Whipple et al., 2000). Glacial and shoreline erosive processes are likewise expected to be impacted by certain rock mass properties more than others. Therefore, erodibility indices may not accurately predict the topography of a geologic formation if the erosive agent at work is affected by certain parameters in proportions different than those used in the index.

Another issue with the existing erodibility indices is the subjectivity associated with assigning a rating. Some published literature has noted this downside (Brook & Tippett, 2002; Milne et al., 1998). Index creators themselves have published some recommendations intended to maximize the internal consistency of measurements (Selby, 1980; Deere & Deere, 1988), but they do not fully account for differences in opinion amongst independent researchers. This issue of subjectivity is further complicated by a lack of instruction in the published methods for determining rock mass strength ratings. For example, RMS, RMR, and SMR all include a joint spacing parameter. While the justification for including such a parameter is explained in the original publications for these indices, the user is given no indication of which joint sets to count or how to handle measurements from multiple joint sets. Therefore, users are left to come up with their own interpretation, which introduces subjectivity into a parameter that otherwise appears fairly objective.

Along these same lines, the outcrop history may prove to complicate rating assignments. For example, blasting at outcrops has been observed to leave scars on the rock both from drilling to place charges and from the explosions themselves. Such excavation-induced fractures may be misleading when characterizing joints. Natural outcrops, on the other hand, may be hundreds or thousands of years older than excavated outcrops. Thus, they may appear more weathered despite the resistance to erosion that allowed them to form outcrops. While SMR has an excavation adjustment that benefits natural outcrops and penalizes certain excavations, other systems do not address this issue of outcrop history.

A final consideration of erodibility indices' potential limitations is the underlying requirement that rock masses be directly accessible to researchers via outcrop or excavation. This fundamental stipulation means that any bedrock that does not outcrop in multiple locations, naturally or otherwise, will most likely not be accurately characterized if it can even be characterized at all. This problem also contributes to the lack of field sites below the angle of repose that were used for the calibration of RMS. Furthermore, as such bedrock can only be studied in man-made outcrops, Selby's (1980) calibration for natural outcrops may prevent RMS from accurately characterizing these rock masses.

1.4 Purpose of Study

The general purpose of this study is to examine rock mass strength rating systems in detail. The RMS, SMR, and RMR indices are applied to a diverse set of lithologic, erosional, and tectonic environments to determine whether one rating system is best overall, or whether any rating system is particularly suited for use with certain lithologies or erosive processes. In particular, rating systems are examined with respect to topography in southwest Virginia in order to test the hypothesis that erodibility controls topography in this region.

Several newly specified measurement and rating calculation techniques are also applied in an attempt to reduce the subjectivity of ratings that results from varied user interpretations. These methods include both field measurement techniques intended to improve the reproducibility of results, as well as varied rating calculation methods. The goal of this application is to determine whether more precise guidelines for use can improve the correlation between ratings and topography by improving user consistency.

The issue of limited calibration of erodibility rating systems, particularly RMS, at slopes below the angle of repose is also addressed. More than two-thirds of field sites in this study are at or below repose. This dataset, coupled with the testing of techniques to reduce scatter in ratings, is used to determine whether the poor correlation between ratings and low slopes in other datasets (e.g. Banks, 2005) represents true variation in erodibility, a weakness in erodibility rating methods that needs to be addressed, or inconsistent measurements due to a lack of detailed instruction for rating system use.

Lastly, to address the issue of limited calibration of indices in general, the relative weight of parameters in each index is systematically varied to maximize the correlation between ratings and topography. These results are compared to existing weightings to determine whether any changes should be considered. Similarly, an adjustment factor for chemical weatherability is calibrated with the goal of more accurately characterizing chemically weak rock masses and improving the overall correlation between erodibility ratings and topography.

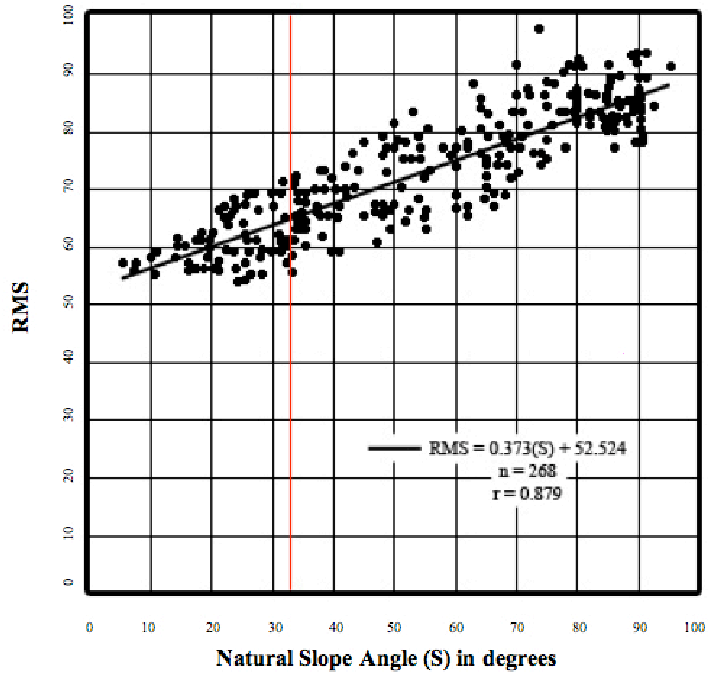


Figure 1a Plot of RMS vs slope, based on data from Banks, 2005. Note poor correlation between RMS and slope when only slopes at or below the angle of repose are considered.

Uniaxial Compressive Strength (MPa)		>250	100-250	50-100	25-50	<25
	Rating	*15*	*12*	*7*	*4*	*2*
RQD (%)		90-100	75-90	50-75	25-50	<25
	Rating	*20*	*17*	*13*	*8*	*3*
Joint Spacing		>2m	0.6-2m	20-60cm	6-20cm	<6cm
	Rating	*20*	*15*	*10*	*8*	*5*
Joint Condition	Persistence (m)	<1	1-3	3-10	10-20	>20
	Rating	*6*	*4*	*2*	*1*	*0*
	Aperture (mm)	None	<0.1	0.1-1	1-5	>5
	Rating	*6*	*5*	*4*	*1*	*0*
	Roughness	Very Rough	Rough	Slightly	Smooth	Slickensided
	Rating	*6*	*5*	*3*	*1*	*0*
	Infilling	None	Hard <5mm	Hard >5mm	Soft <5mm	Soft >5mm
	Rating	*6*	*4*	*2*	*2*	*0*
	Weathering	Unweathered	Slightly	Moderately	Highly	Decomposed
	Rating	*6*	*5*	*3*	*1*	*0*
Ground-water	Joint: Flow: Description:	Dry None Completely dry	Stained None Damp	Damp None Wet	Wet Occasional Dripping	Wet Continuous Flowing
	Rating	*15*	*10*	*7*	*4*	*0*

Table 1a The Rock Mass Rating (RMR) system with scores for each parameter (based on data from Bieniawski, 1988, 1989).

Uniaxial Compressive Strength (MPa)		>250	100-250	50-100	25-50	<25
	Rating	*15*	*12*	*7*	*4*	*2*
RQD (%)		90-100	75-90	50-75	25-50	<25
	Rating	*20*	*17*	*13*	*8*	*3*
Joint Spacing		>2m	0.6-2m	20-60cm	6-20cm	<6cm
	Rating	*20*	*15*	*10*	*8*	*5*
Joint Condition	Persistence (m)	<1	1-3	3-10	10-20	>20
	Rating	*6*	*4*	*2*	*1*	*0*
	Aperture (mm)	None	<0.1	0.1-1	1-5	>5
	Rating	*6*	*5*	*4*	*1*	*0*
	Roughness	Very Rough	Rough	Slightly	Smooth	Slickensided
	Rating	*6*	*5*	*3*	*1*	*0*
	Infilling	None	Hard <5mm	Hard >5mm	Soft <5mm	Soft >5mm
	Rating	*6*	*4*	*2*	*2*	*0*
	Weathering	Unweathered	Slightly	Moderately	Highly	Decomposed
	Rating	*6*	*5*	*3*	*1*	*0*
Ground-water	Joint: Flow: Description:	Dry None Completely dry	Stained None Damp	Damp None Wet	Wet Occasional Dripping	Wet Continuous Flowing
	Rating	*15*	*10*	*7*	*4*	*0*
Joint Orientation Adjustment	Planar: $\lvert\alpha_j-\alpha_s\rvert$	>30º	30º-20º	20º-10º	10º-5º	<5º
	Toppling: $\lvert\alpha_j-\alpha_s-180\rvert$	>30º	30º-20º	20º-10º	10º-5º	<5º
	F_1	*0.15*	*0.40*	*0.70*	*0.85*	*1.00*
	Planar: $\lvert\beta_j\rvert$	<20º	20º-30º	30º-35º	35º-45º	>45º
	Toppling:	F_2 = 1.00 for Toppling				
	F_2	*0.15*	*0.40*	*0.70*	*0.85*	*1.00*
	Planar: $\beta_j-\beta_s$	>10º	10º-0º	0º	0º-(-10º)	< -10º
	Toppling: $\beta_j+\beta_s$	<110º	110º-120º	>120º	-	-
	F_3	*0*	*-6*	*-25*	*-50*	*-60*
Method of Slope Excavation Adjustment		Natural	Presplitting	Smooth blasting	Blasting or Mechanical	Deficient Blasting
	F_4	*+15*	*+10*	*+8*	*0*	*-8*

Table 1b The Slope Mass Rating (SMR) system with scores for each parameter (based on data from Bieniawski, 1989; Romana, 2003). α_j = joint dip direction, α_s = outcrop dip direction, β_j = dip of joint, β_s = dip of outcrop.

Intact Strength (Schmidt Rebound)	100-70	69-57	56-53	52-50	49-48	47-46	45-44	43-42	41-40	39-38	37-36	35-33	32-29	28-25	24-17	<17
Rating	*20*	*19*	*18*	*17*	*16*	*15*	*14*	*13*	*12*	*11*	*10*	*9*	*8*	*7*	*6*	*5*

Weathering	Unweathered	Slightly Weathered	Moderately Weathered	Highly Weathered	Completely Weathered
Rating	*10*	*9*	*7*	*5*	*3*

Joint spacing (m)	*>3*	*3-2.2*	*2.2-1.9*	*1.9-1.6*	*1.6-1.4*	*1.4-1.2*	*1.2-1.0*	*1.0-0.8*	*0.8-0.7*	*0.7-0.6*	*0.6-0.5*	*0.5-0.4*	*0.4-0.3*	*0.3-0.25*	*0.25-0.2*	*0.2-0.15*	*.15-.1*	*.1-.07*	*.07-.05*	*.05-.03*	*.03-.025*	*.025-.02*	*<.02*
Rating	*30*	*29*	*28*	*27*	*26*	*25*	*24*	*23*	*22*	*21*	*20*	*19*	*18*	*17*	*16*	*15*	*14*	*13*	*12*	*11*	*10*	*9*	*8*

Joint Orientation	>30° into slope	<30° into slope	Horizontal and Vertical	<30° out of slope	>30° out of slope
Rating	*20*	*18*	*14*	*9*	*5*

Joint Width (mm)	<0.1	0.1-1.0	1-5	5-20	>20
Rating	*7*	*6*	*5*	*4*	*2*

Joint Continuity & Infill	None continuous	Few continuous	Continuous, no infill	Continuous, thin infill	Continuous, thick infill
Rating	*7*	*6*	*5*	*4*	*1*

Groundwater	None	Trace	Slight	Moderate	Great
Rating	*6*	*5*	*4*	*3*	*1*

Table 1c The Rock Mass Strength (RMS) system with scores for each parameter (based on data from Selby, 1980; Moon, 1984)

Chapter 2: Methods

2.1 Objectives

The goals of this project are twofold: first, to see how rock mass strength indices perform in various erosional and lithologic settings, and second, to determine if the methodology behind existing rating systems can be better constrained to produce more consistent and meaningful results. Thus, multiple field sites in different settings are required, and multiple measurement techniques were required. After calculating several versions of each rating system for all field sites, the results were calibrated against topography. Ratings are expected to correlate to topography in the Appalachian region, where topography seems to be controlled by erodibility, but the more powerful erosional agents and more rapid erosion present in glacial and coastal areas may overtake erodibility as the most important factor in shaping topography in those regions. The desired outcome of this study is a set of recommendations for measuring outcrops and calculating ratings that will make ratings more objective and improve rating systems' predictions of topography.

2.2 Field Sites

The requisite data to calculate RMS, RMR, and SMR were collected in three geographic regions: southwest Virginia, coastal Maine, and the Teton Range. These regions were selected in order to provide a swath of rock types, tectonic histories, and erosional environments. See Appendix A for detailed descriptions, data, and pictures from each outcrop.

Southwest Virginia is located in the Valley and Ridge Province of the Appalachian Mountains (Figure 2a). The last mountain-building activity associated with the Appalachians ended approximately 300 million years ago with the Alleghanian orogeny. Denudation has since been the dominating force in shaping the landscape (Pazzaglia & Brandon, 1996). A Late Triassic rifting event may have resulted in uplift of the Appalachian region, which would cause an increase in exhumation rate, but generally the shaping of the Appalachians has been controlled by long, slow erosional processes (Spotila et al., 2004). Current erosion rates are estimated between 0.001 mm/yr and 0.04 mm/yr (Hancock & Kirwan, 2007; Ward et al., 2005). Due to the time scale over which denudation has been controlling the landscape, it is expected that the topography would be controlled by the erodibility of bedrock being exhumed from a thickened orogenic root. Outcrops visited in Southwest Virginia are a mixture of natural outcrops, road cuts, and quarries. Man-made outcrops had to be used to gain access to non-ridge forming formations, as the landscape is fairly well adjusted to erodibility. Rock units studied include the Tuscarora/Clinch sandstone, Price siltstone and sandstone, Juniata siltstone, Rose Hill sandstone, Millboro shale, Huntersville chert, Knox Group dolostone, and Rome dolostone.

The coastal outcrops visited in Maine are in Cape Elizabeth and Acadia National Park (Figure 2b). Similar to the southern Appalachians, this area experienced regional uplift and exhumation until 1.6 million years ago (Miller & Duddy, 1989), when it was depressed hundreds of feet by the last ice sheet (Marvinney, 2005). As the ice sheet retreated, the land rebounded until about 12,000 years ago (Maine Geological Survey, 2008). Since then, the land has been subsiding at <0.8 mm/yr (Boon et al., 2010), but outcrops are more likely controlled by the average shoreline erosion rate of 40 cm/yr (Pilkey & Thieler, 1992). All outcrops visited in coastal Maine are naturally occurring and subject to direct wave action from the Atlantic Ocean. Rock units studied include the Kittery granofels and phyllite, Cushing gneiss, Cadillac Mountain granite, and Shatter Zone of Cadillac Mountain granite and Devonian gabbro-diorite.

The Teton Range runs along Wyoming's western border with Idaho (Figure 2c) and began experiencing uplift about 10 million years ago (Kiver and Harris, 1999). The range continues to uplift ~0.8 mm/yr (Roberts & Burbank, 1993) along the Teton fault and erode 0.05-0.1 mm/yr (Foster et al., 2010). The area is still affected by glaciers today. All outcrops visited in the Teton Range are naturally occurring and included Mount Owen quartz monzonite, Archean layered gneiss, and Madison Group limestone.

Five to ten field sites were chosen in each study area. Sites were chosen with the goals of: collecting data for as many different rock types as possible (both overall and within each study area), collecting data for rocks that comprise different topographic features, obtaining data for single geologic formations in multiple locations, and generally visiting as many field sites as possible within each study area. These study areas were chosen for their diversity of lithology and erosional processes. The geology of southwest Virgina provides a repeatable stratigraphy of sedimentary rocks that have varying erodibility, and the topography appears to be controlled by the erodibility of each rock type. Erosion in southwest Virginia is also fairly slow and dominated by chemical weathering and fluvial erosion. The Teton Range, in contrast, provides exposures of crystalline rocks and is affected by glacial erosion and rapid uplift. Finally, outcrops in coastal Maine also provide crystalline rocks, but the landscape is subject to rapid lateral erosion from direct wave action. Therefore, these three study areas provide sedimentary, igneous, and metamorphic rocks, and three different types of dominant erosional processes. It is expected that rock mass strength rating scores will correlate with topography best in the southwest Virginia study area. In the Tetons, rapid uplift and glacial erosion may overtake erodibility as the most important factors shaping the topography. Similarly, the powerful erosive force of wave action in coastal Maine may overwhelm erodibility in controlling topography.

2.3 Measurement Techniques

The Rock Mass Strength (Selby, 1980), Rock Mass Rating (Bieniawski, 1973, 1989), and Slope Mass Rating (Romana, 1985, 1995) systems were used to measure rock mass strength. General measurement procedures established by the authors were used, but, in addition, some new techniques were used in an effort to improve the objectivity of ratings. Many of the measurements taken are needed for all three indices, allowing for the comparison of three indices without taking three times as many measurements.

Strike and dip of joints and outcrop faces were taken with a Brunton compass. Joint Width (RMS) or Aperture (RMR/SMR) was measured for all fracture sets and then combined in various ways (see 2.4; Rating Calculations). Where joints were V-shaped (more open at the surface than deeper into the rock), measurements were made as deeply into the rock as possible.

Groundwater, weathering, joint infilling, joint roughness, and joint weathering were all determined using each index's text descriptions, with the most commonly matched description being chosen. If two or more major joint sets or segments of outcrop had highly differing characteristics, they were all noted and a weighted average was taken to determine an overall score for the parameter. Further work needs to be done, however, to determine the best way to handle multiple joint sets and highly mixed outcrops (e.g. focus on the weakest joints, use a weighted average, or focus on the strongest rock features). When characterizing groundwater at coastal outcrops, the rating that described the greatest amount of water present was given in order to account for tides, inundation, and wave action. These qualitative, text descriptions were at times difficult to assign with confidence, as they seemed dependent on the relative variation between outcrops. For example, an outcrop that at first may appear highly weathered seems less weathered when compared to another outcrop that has even greater weathering. Likewise, the

RMS groundwater designations such as “slight” or “great”, or the RMR/SMR joint roughness designations such as “very rough” or “slightly” seem entirely relative. An effort was made to take notes on the outcrops, take pictures, and, when possible, collect samples, so that initial designations could later be compared to other outcrops and changed if necessary. In this manner, consistency within the dataset might be better than if adjustments were not made, but this method still leaves room for great disparity between different researchers’ datasets.

An N-Type Schmidt Hammer was used to obtain rebound values for the Intact Strength Rating parameter of RMS, and these same values were converted into MPa for the Uniaxial Compressive Strength parameter of RMR and SMR (see 2.4; Rating Calculations for discussion of rebound-to-strength conversion). Schmidt rebound values were adjusted for the angle at which the hammer was held using the chart printed on the hammer. Any hits that sounded hollow or that fractured or pulverized the rock were discounted. At least 20 hits were made at each outcrop. This number was arrived at by calculating sequential means for rebound values, which showed that means tended to vary by less than one after 20 hits. The Schmidt hammer used was also calibrated before and after being taken into the field, and corrections were made for any drift.

Rock Quality Designation, or RQD, is used in RMR and SMR and was obtained with a number of intersecting scanlines rather than with rock cores (in the manner of Moore et al., 2009). Scanlines were laid out both parallel and perpendicular to joint sets, and in multiple locations along the rock exposure; where no regular jointing occurred, scanlines were made perpendicular to one another (see Figure 2d). The substitution of scanlines for rock cores allows for easy, quick, non-destructive implementation in the field, which in turn allows for more scanlines in more directions than may be feasible when coring. Since scanlines do not provide fresh, unweathered rock, an effort was made to ignore fractures and areas of weakness that appeared to be superficial (the result of weathering or blasting) rather than structural. In the case of blasted rock faces, this differentiation was made by discounting fractures that only appeared along the semi-cylindrical scars that remain from drilling to place charges. In the case of weathering, any highly weathered or slaked surfaces were removed if possible before counting fractures, and highly discontinuous, irregular, and non-repeating fractures were discounted. Areas where heavy weathering appeared to penetrate the rock mass were not counted towards the percentage of sound, hard rock. This differentiation is similar to that made when studying a core to separate naturally weak or fractured areas from those weakened by coring or removal of core rock from in situ stresses. It should also be noted that whether rock cores or scanlines are used, an effort should be made not to mix the two into the same dataset, as cores and outcrop faces provide two different pictures of the rock mass, and mixing them could reduce the consistency of measurements.

Joint continuity was measured together for RMR and SMR, and separately for RMS. This separation is due to differences in the diagnostics for RMR/SMR and RMS. RMS uses a purely qualitative scale that incorporates joint infill, or gouge, into the same parameter (e.g. "Continuous, no infill"), and so the description that matched the majority of major joint sets was used. RMR and SMR have joint infill as a separate parameter and give diagnostic joint persistence values in meters, making joint persistence a measured parameter rather than one based off of general observation of the outcrop. In an effort to obtain objective quantitative measurements of persistence and remove any sample bias due to the size or shape of the sample window, multiple circular windows were used with Mauldon's (2001) mean trace length estimator, given by:

$$\mu = \frac{\Pi r}{2} \bullet \frac{n}{m}$$

where μ = mean trace length, r = radius of circular scanline or window, n = number of joint intersections with circular scanline, and m = number of joint endpoints inside circular window. A tape measure and chalk were used to draw multiple circles of a known radius on the outcrop, after which n and m were counted (see Figure 2d). As with RQD scanlines, an effort was made to differentiate between superficial and pervasive fractures in order to only count fractures that weaken the rock mass as a whole.

Joint spacing was measured using scanlines. Although joint spacing is quantitatively defined in all three systems, quantitative is not synonymous with objective, and in practice it has been found that researchers pick joints to measure that they find representative of the whole outcrop. The intent of such measurements is valid, but choosing which joints to measure is inherently subjective. Thus, scanlines were used to measure joint spacing. Taking measurements along a scanline requires closer examination of the rock face, and in determining which joints are superficial and which are pervasive (in the same manner as described for RQD), the researcher must consider additional joint sets or ones with greater fracture spacing than those that are immediately obvious. Scanlines were laid out in the same manner described for RQD measurements.

2.4 Rating Calculations

Data analysis was comprised of three main tasks: calculating RMS, RMR, and SMR values; regressing those values against various topographic metrics; and optimizing the weightings of the resulting "best" rating method to improve correlation with topography and take chemical weathering of carbonates into account. Several different interpretations of the three erodibility indices were calculated in hopes of further specifying the use of these indices and thus improving their objectivity; including all these versions, a total of 20 techniques were tried (see Figure 2e).

Four different versions of RMS were calculated by varying how averages were calculated from raw data for various parameters and by combining data from multiple joint sets in two different ways. Raw measurements were averaged by taking both the mean and the median, then carrying those values through to come up with separate ratings. The first method for combining measurements from different joint sets was to first find the average for each joint set (median or mean), and then to take the mean of all joint sets' individual averages. The second method was to combine the raw data of all joint sets before taking an average, such that joint sets that had higher frequency within the sample window were weighted proportionally. When assigning a rating for each parameter, a refinement of Selby's original table (found in Moon, 1984) was used that includes a greater number of subdivisions for each parameter; this table was used in the hope of its increasing the consistency of ratings assigned.

Eight different versions of SMR were calculated by varying the average type, the combination of multiple scanlines, and the conversion from N-type Schmidt Hammer rebound values into uniaxial compressive strength. Raw data was averaged using both median and mean, as described above. RQD percentages were also treated with two different approaches. The first approach was to calculate an RQD decimal percentage for each scanline, then multiply all of these percentages together. The hypothesis behind this approach was that weaknesses in a specific direction may control strength for the entire rock mass, and that multiplying the decimal percentages would better reflect this weakness. For example, if one scanline yielded an RQD value of 1 and a scanline in another direction yielded an RQD value of 0.5, multiplying the RQD values yields a total RQD of 0.5, whereas averaging them together would yield an RQD of 0.75.

The second approach to handling multiple scanlines for RQD was to combine raw data from all scanlines together and calculate a single RQD value for the entire set (essentially treating multiple scanlines as one, long scanline).

Two different formulas to convert from Schmidt Hammer rebound value into uniaxial compressive strength were used. Many formulas were initially tested (Cargill & Shakoor, 1990; Haramy & Damarco, 1985; Sheorey et al, 1984; Kidybinski, 1980; Kahraman, 2001) and compared to the conversion table given in Selby's (1980) original RMS paper as well as the conversion graph on the Schmidt Hammer. For those formulae that required a density value for the rock tested, an approximation based on rock type and geologic formation was made. The resulting comparison of these methods can be seen in Figure 2f. The values from Selby's table are much higher than any other values produced by the formulas tested or by the conversion graph on the Schmidt hammer. The values from the Schmidt hammer conversion graph fall roughly in the middle of all values produced by other conversion methods, but using some sort of formula was preferred for the sake of data processing and removing error from reading a graph. Thus, two formulae were chosen: one that overlapped the Schmidt conversion graph at lower rebound values (~49 or lower) and one that overlapped the Schmidt conversion graph at higher rebound values (~49 or above). These two formulae include Kidybinski's (1980; via Kahraman, 2001), given by:

$$q_u = 0.477e^{(0.045R_n + \rho)}$$

where q_u = uniaxial compressive strength (MPa), R_n = Schmidt Hammer rebound value, and ρ = density of the rock (g/cm^3),

and Kahraman's (2001), given by:

$$q_u = 6.97e^{(0.014R_n\rho)}$$

where q_u = uniaxial compressive strength (MPa), R_n = Schmidt Hammer rebound value, and ρ = density of the rock (g/cm^3).

Some specific approaches were taken for non-varied parameters as well. Joint condition ratings were assigned using a table that separates joint condition ratings into joint persistence, aperture, roughness, infilling, and weathering (Chart E from Bieniawski, 1989; also within Table I from Moore et al., 2009; see Chapter 1, Tables 1a and 1b) as opposed to the traditional table found in Romana (2003); the more detailed version was used in an effort to make the most accurate and consistent rating assignments possible. To find the joint orientation adjustment for SMR, the adjustment factor was calculated for all joint sets using the formulas for both planar and toppling failures. The joint set and failure mechanism combination that gave the greatest detraction was then chosen under the assumption that the weakest joint set will control the strength of the rock mass as a whole.

RMR, like SMR, was calculated in eight different ways. The only difference between SMR and RMR calculations is that RMR does not include a joint orientation adjustment factor or a method of excavation adjustment factor. The same variations in calculating averages, RQD values, and uniaxial compressive strengths were applied to RMR as described above.

2.5 Topographic Metrics

Calculating various versions of each rating system yielded a large range of scores for each outcrop, and so some sort of metric was required in order to determine which interpretation of each rating system was best overall. Traditionally, ratings have been compared to the slope of the outcrop or formation (Selby, 1980; Moon et al., 2001; Brook & Hutchinson, 2008). We chose to test the ratings against mean slope, as well mean relief and a semi-quantitative topographic index that was designed for this study. Mean slope and relief of each formation were obtained using spot measurements (n=20) of areas within the formation that appeared to be representative of the formation as a whole. Slope measurements were made at approximately 1:10,000 scale using 30m or better DEMs, or on GoogleEarth. Measruements were taken in locations that showed the maximum slopes that the rock formation tended to hold up. Relief measurements were made similarly to represent the mean height of the formation above local base level, rather than the average relief of the area as a whole. The semi-quantitative topographic index is described in Figure 2g.

2.6 Calibration of Rating Techniques

Ratings from each interpretation of each system were regressed against each of the topographic metrics described above. Additional regressions were performed by creating sub-groups within each rating type (see Table 2a); for example, regressions were run that included only non-carbonate field sites, or field sites from a single geographic area. A linear trendline was then fitted to each plot (in the manner of Selby, 1980) and an R^2 value recorded. By varying the rating systems' interpretations, the topographic metric used, and the sub-groups created, a best fit was found for each rating system. Additional trendline types were then tried on these datasets, and it was determined that logarithmic fits had the most potential to improve R^2 values. Therefore, logarithmic trendlines were fitted to some additional datasets and their R^2 values recorded. Schmidt hammer rebound values were also plotted against all topographic metrics in order to test whether compressive strength is a valid proxy for erodibility, or whether the joint characterizations in rating indices must be included. In total, 217 runs were completed, from plotting a chosen rating technique and dataset to recording an R^2 value for a linear and/or logarithmic trendline.

The idea of testing erodibility measurements against topography is standard practice (Selby, 1980; Moon et al., 2001; Brook & Hutchinson, 2008) and is based on the assumption that long-term, adjusted topography of a rock formation is controlled by erodibility. Therefore, if topography is controlled by uplift or erosion's causing over-steepening, then rock mass strength rating systems would not be expected to correlate to topography. As the Tetons are experiencing both glacial erosion and rapid uplift, and the coast of Maine is constantly eroded and steepened by waves, these areas may not correlate well to any topographic metric. In order to test this theory, southwest Virginia ratings were compared to topography both with and without the other field sites to see if correlation to topography is better when only using areas whose topography is adjusted to erodibility.

2.7 Optimization

An optimization program was written with the goal of improving the correlation between rating systems and topographic metrics by varying only the weights of existing parameters. The program was written for MATLAB and took advantage of the software's built-in minimization function, which uses a gradient descent algorithm to find the minimum value of a multivariable function given certain parameters. Conceptually, the gradient descent algorithm works by examining the solution space around an initial point (in this case, the initial weights given to the parameters of a rating system), and moving in the direction of steepest downward slope, then examining the solution space around this new point and moving in the direction of steepest downward slope again, repeating this process until a minimum is found. In MATLAB, the step size at each iteration is varied based on steepness; if the steepest slope is fairly shallow, a small step is taken, and if it is very steep, a larger step is taken under the assumption that a steeper slope is farther from the global minimum. Since the maximum R^2 value was desired, but a minimization function was being used, the program was written such that the negative of R^2 would be minimized, resulting in the largest possible R^2. In order to ensure that this program was in fact finding a true minimum and not local minima, the program used random initial weights and was run 10-20 times for each rating system. In all cases, a set of ideal weights was found that varied by less than 0.01 with each trial. A copy of the optimization program can be found in Appendix C.

The above optimization would theoretically improve systems using their existing parameters, but rock mass strength rating systems are notorious for yielding poor correlations to topography when rocks are mechanically weak (Moon et al., 2001; Brook & Hutchinson, 2008), and preliminary results of field work showed a disparity between the high ratings of carbonate formations and their tendency to comprise low-relief areas and valley bottoms, presumably due to the solubility of calcium carbonate in water. Therefore, an additional parameter was desired that would account for chemical weatherability; no existing methods have such an adjustment factor. Therefore, the optimization program described above was modified to include an additional parameter for chemical weatherability, and then altered such that all parameters except for this new one would remain constant throughout optimization. As carbonates were the only rock types particularly susceptible to chemical weathering in this study's field sites, rocks were differentiated as either carbonate (=1) or non-carbonate (=0). Thus, when this modified version of the optimization program found an ideal "weight" for the chemical weatherability parameter, it was essentially just calculating an adjustment factor to be added to non-carbonates that would maximize R^2 (by minimizing the negative of R^2). A copy of this version of the program can also be found in Appendix C.

Figure 2a Southwest Virginia (Valley and Ridge Province) study area. Top left: road cut of siltstone, sandstone, black chert, bentonite clay, and shale. Top right: quarry of dolostone. Bottom left: representative topography of study area (note long, repeating ridges running northeast/southwest). Bottom right: general geographic region of SW Virginia. Study area circled in red.

Figure 2b Coastal Maine study area. Top left: natural outcrop of granofels and phyllite. Top right: natural outcrop of granite. Bottom left: representative topography of study area (note relief decreases markedly toward the coast). Bottom right: general geographic region of coastal Maine. Study areas circled in red.

Figure 2c Teton Range study area. Top left: natural outcrop of quartz monzonite. Top right: natural outcrop of gneiss. Bottom left: representative topography of study area. Bottom right: general geographic region of the Teton Range. Study area circled in red.

Figure 2d Top: example of a circular window (110 cm diameter) with red circle highlighting the drawn chalk line. Several of these were used at each outcrop. Bottom: example of intersecting scanlines, with red line representing the orientation of a second scanline.

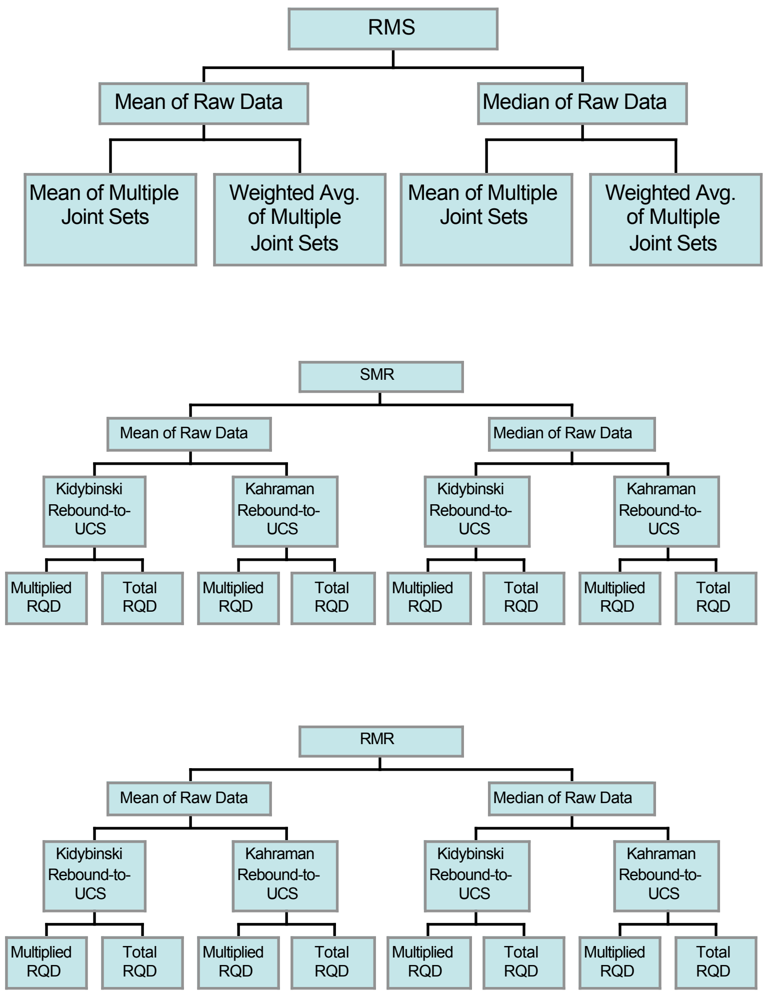


Figure 2e Flow charts display how multiple versions of each rating system were constructed.

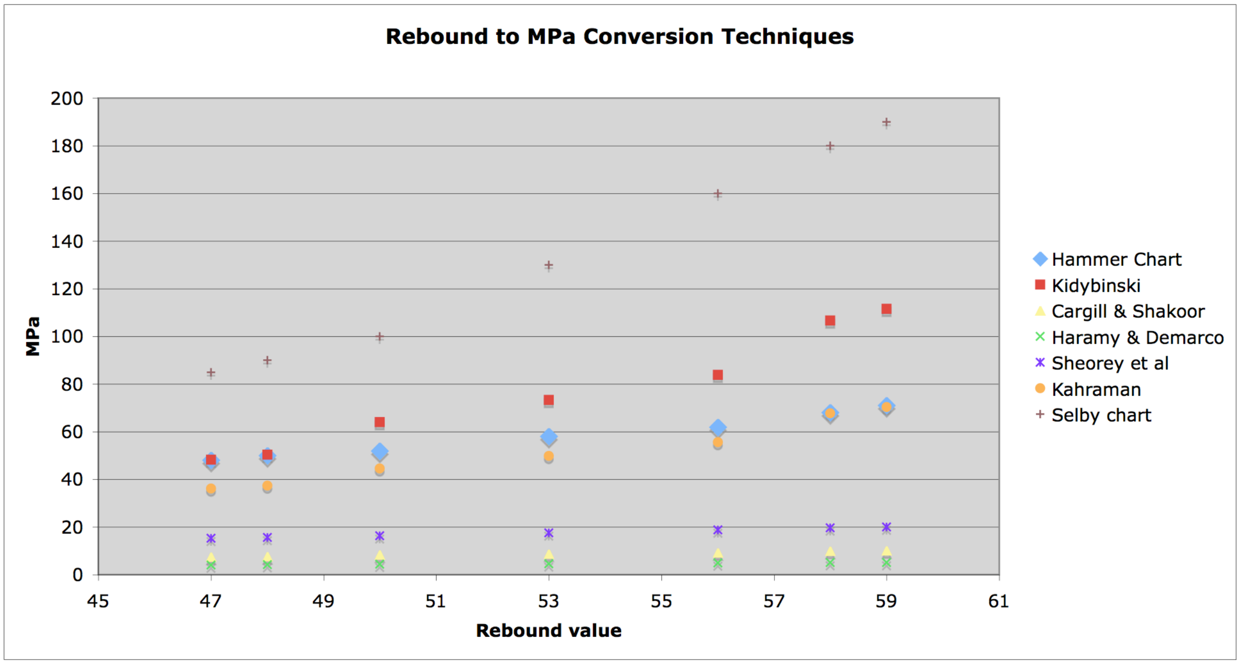


Figure 2f Plot of all tested techniques for converting Schmidt hammer rebound values into uniaxial compressive strength values in MPa. A mixture of formulae, charts, and graphs were used for conversion. Note that the chart from Selby (1980) yields significantly higher values than any other method.

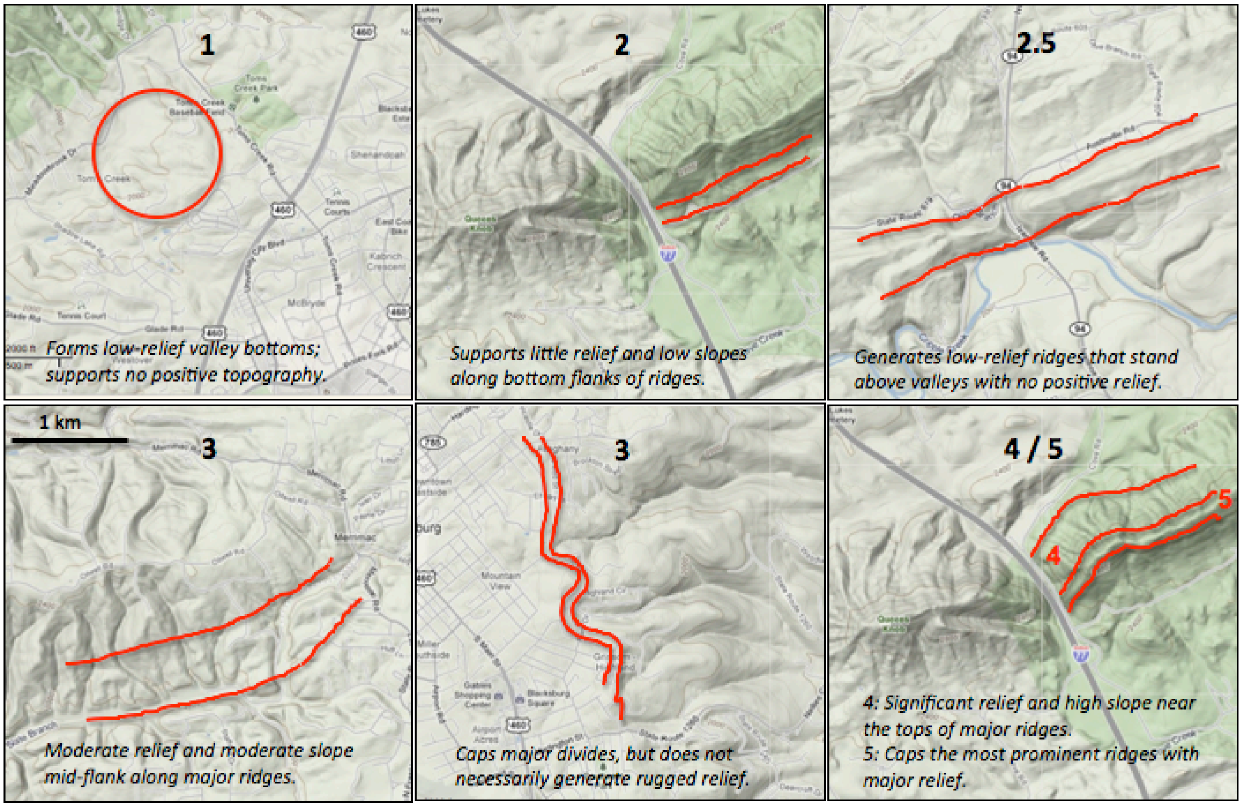


Figure 2g This semi-quantitative scale accounts for elevation, relief, hillslope gradient, and the degree to which the unit "holds up" the surrounding topography. The above examples are from the Valley and Ridge Province of southwest Virginia.

Geographic constraints	**Rock type constraints**
None	None
None	No carbonates
East coast (little to no uplift)	None
East coast (little to no uplift)	No carbonates
SW Virginia	None
SW Virginia	No carbonates
SW Virginia	No carbonates or shales
Maine	None (no carbonate field sites in Maine)
Tetons	No carbonates

Table 2a In addition to calculating erodibility ratings in various ways, ratings were also regressed against topography using the various data constraints listed in the table.

Chapter 3: Results

3.1 Field Data

A total of 23 field sites were tested, with 11 sites in southwest Virginia, 5 sites in coastal Maine, and 7 sites in the Tetons. See Appendix A for detailed descriptions, images, and ratings of each outcrop. Taking measurements, pictures, and notes at an outcrop took a minimum of two hours if the outcrop was small, homogenous, and regularly jointed. Larger outcrops that had varied fracture patterns, extensive weathering, or heterogeneous rock or joint characteristics took up to 4 hours to test, as a larger amount of data had to be collected and more extensive notes and pictures taken. Where outcrops were not naturally limited (e.g. continuous coastline), they were measured in 10-20 m windows. More confidence is placed in results from outcrops that had 3 or more surfaces visible (generally due to 3 or more nearly-perpendicular joint sets), as this allowed for a more thorough understanding of patterns within the rock mass and provided a greater number of orientations from which to measure joint spacing and orientation. These sites included the Tuscarora sandstone (southwest Virginia), the Kittery granofels/phyllite (southern coastal Maine), the Shatter Zone of granite and gabbro-diorite (central coastal Maine), the Pebble Beach outcrop of Cadillac Mountain granite (central coastal Maine), the South Fork of Cascade Canyon outcrop of Mt. Owen quartz monzonite (Tetons), and the Madison limestone (Tetons).

In general, southwest Virginia field sites showed more evidence of weathering, such as slaked rock faces, residual soil, and open joints with soft infill. However, this visible weathering is thought to be at least partially the result of low erosion rates relative to coastal Maine or the Tetons, and not simply from a greater amount of weathering. This hypothesis is supported by observations at Maine outcrops, where infill was completely lacking in the surf zone, but fairly thick (on the order of 1cm) outside of the surf zone where waves and tides could not wash away weathering products. However, Maine and Tetons outcrops were also generally metamorphic or igneous, as opposed to the sedimentary rocks of Virginia sites, and so differences in rock type cannot be completely discounted as contributors to weathering.

Some outcrops in the Tetons that were in valleys or canyons showed evidence of glacial polishing. Fewer Schmidt hammer measurements had to be discarded on these surfaces, presumably due to the even contact achieved between the hammer and rock surface. On unpolished surfaces (particularly monzonite), suspiciously low rebound values were obtained when the entire force of the hammer was put on a protruding crystal. Therefore, when a very low rebound value was observed in tandem with isolated visible shattering of rock crystal, the rebound value was discarded. This phenomenon was also observed in granite outcrops of coastal Maine, where fewer Schmidt rebound values had to be discarded along smooth fracture surfaces. In Maine, protruding crystals were a greater problem due to the fact that certain minerals were preferentially weathering out of the rock, leaving many isolated, protruding quartz grains. This issue made it difficult to obtain trustworthy measurements with the Schmidt hammer unless the aforementioned polished fracture surfaces could be found. While visible crushing of rock allows for the discounting of measurements, the above observations bring up the point of whether smaller scale destruction of rock that cannot effectively be accounted for contributes to the high standard deviation of Schmidt hammer measurements (as high as 10 for 34 hits).

Overall, using RMS, SMR, and RMR was fairly easy in terms of data collection, but not in terms of rating assignment. Where parameters of the scale differed along the outcrop, notes to that effect were made along with estimates of what percent of the outcrop had what qualities. Where there were uncertainties about determining qualitative parameters, descriptions and pictures of the outcrop were taken. The main difficulty arose in choosing a final rating for each parameter. None of the rating systems give any insight as to how to treat variations along an outcrop except to say that if sections of outcrop are markedly different, that they should be treated as separate outcrops. However, this instruction does not account for differences between multiple joint sets in the same section of outcrop, which gave a great deal of uncertainty to ratings for these parameters. Therefore, the description that matched the majority of major joint sets was used. If no clear majority was present, the qualitative descriptions were "averaged" by assigning a rating in between those observed.

Further uncertainty arose when qualitative parameters seemed to take on different meanings as an increasing number of outcrops were visited. As mentioned in Methods (2.3; Measurement Techniques), notes, pictures, and (where possible) hand samples were taken and reevaluated after all field sites had been visited. For example, many joint roughness ratings were altered after fieldwork was completed due to the increased total range of roughness observed in all locations. This problem arose for the following parameters: joint roughness (RMR/SMR), weathering (RMS/RMR/SMR), groundwater (RMS only; RMR/SMR gave clearer descriptions), and continuity/infill (RMS only; RMR/SMR relies on quantitative continuity or "persistence" measurements and quantitative infill thickness measurements).

One final observation was the extent of spatial variation in erodibility ratings. Twelve of the field sites visited were within only five geologic formations, allowing for the comparison of ratings at different locations within the same formation. Variation was most pronounced in the Tetons, where RMS ratings for the same formation differed by as much as 21 points and SMR ratings differed by as much as 50 points. In Maine and Virginia these differences were less pronounced, with a maximum variation of 7 for RMS (Maine) and 10 for SMR (southwest Virginia).

3.2 Calibration of Rating Techniques

A complete table of all regressions run, including which rating calculation methods, datasets, topographic metrics, and trendline types were used, can be found in Appendix B. Table 3a lists all field sites with their topographic data and ratings used for Figures 3a-3e.

It is apparent from the calibrations that the approach one takes toward calculating an erodibility rating can have a significant impact on how well that rating will correlate to the topography of the area of study. Furthermore, which geographic area is being studied can determine whether or not erodibility will correlate to topography at all. And while some techniques tested have clearly improved R^2 values, other potential results would need to be verified by adding more field sites to the dataset.

The most consistent result across all measurement, rating, and topographic index types was that ratings and topography correlated to one another the best when the data excluded carbonates and were limited to the southwest Virginia area. This result validates the hypothesis that the mechanical strength of carbonates is misleading when studying landscape evolution, as its vulnerability to chemical weathering will control carbonate topography in non-arid climates. In addition to pointing to the need for a carbonate adjustment factor, this result also lends credence to the hypothesis that rock mass strength, however it is measured, will only correlate to landscapes that are adjusted to erodibility and eroding slowly; stronger tectonic or erosive forces will overwhelm erodibility's signature in the topography of the landscape. Interestingly, the R^2 value for RMS has a maximum value of 0.09 when carbonates are not excluded, but SMR has a maximum R^2 value of 0.78 when carbonates are not excluded. It appears that this difference largely arises from the relative weight of groundwater in each scale. Where SMR assigns a maximum of 15 points for having no groundwater, RMS assigns only 6 points for having no groundwater. As all 4 carbonate field sites in southwest Virginia showed more groundwater than most non-carbonate sites, more potential points were lost when assigning SMR ratings. It also makes sense that groundwater parameters' being weighted differently would account for this difference in ratings for carbonates, as carbonates are frequently conduits for groundwater.

Rating systems did not show a consistent improvement in correlation to one topographic metric in particular. Figure 3d shows that SMR has a stronger correlation to relief than to slope or to the semi-quantitative topographic index, while RMS correlations do not vary as much based upon which topographic metric is used. While the top 10 SMR fits were plotted against relief or slope, the top 10 RMS fits included all three topographic metrics. Table 3b shows each rating system's best correlation to each topographic metric. However, as topography is being treated as the independent variable in these tests, it is perhaps best not to assume that these results can be used to determine a best topographic proxy for erodibility, when we are in fact trying to validate erodibility ratings based on topography. This trend is worth noting, though, and may bear further research (see Chapter 4: Discussion).

Overall, SMR produced the highest R^2 values for both logarithmic and linear trendlines (Figure 3a and Figure 3b), followed by RMS (see Table 3c for top R^2 values in each system). The maximum R^2 values obtained for both of these systems were found using only SW Virginia field sites and excluding carbonates; the progression of rating improvements as the dataset is thus specified can be seen in Figure 3c.

Across all measurement types, it appears that using the mean of raw data creates higher correlations to topography (see Table 3d), but only SMR shows a large difference between the two methods (R^2 increases by 0.1). It is difficult to discern whether these results are truly showing that the mean produces better results, whether it depends on the rating system chosen, or whether determining the “best” average type would require higher level statistics or additional field sites due to the large number of variables within the tested system. Within SMR, using the mean of raw data appeared to give the best results, with the top 7 results using the mean of raw data. Within RMS and RMR, neither the median nor mean dominated; the top 10 results for each system were split evenly between methods using mean and median. Schmidt hammer measurements showed an increase in R^2 value when the mean was used instead of the median, all else held constant, but this improvement was not consistent, ranging from 0.003 to 0.11.

The top 5 RMS results all used the mean of multiple joint sets rather than using a weighted average of joint sets based on joint frequency, but overall neither technique for combining multiple joint sets clearly dominated.

The effect that average type has on intact rock strength in particular was also examined. In SMR and RMR, only one field site’s rating was different depending on whether the median or mean of Schmidt rebound values was used. The median rebound value was 1.8 higher than the mean, resulting in a difference of 9 MPa when the Kidybinski conversion was used. As this placed the resulting strength values on either side of a division in the rating scheme, using the median caused the final rating to be 5 points higher than using the mean. In RMS, 7 out of 23 field sites had final scores one point higher when the median of Schmidt rebound values was used instead of the mean, with a maximum difference in rebound values of only 1.5. Thus, for intact strength parameters, the final rating will most likely not be significantly affected by using one type of average in place of another. These results do show, however, that a continuous rating scheme for SMR strength ratings may give results that are more truly representative of the rock mass.

When calculating RMR and SMR ratings, using Kidybinski's (1980; via Kahraman, 2001) formula for Schmidt rebound conversion into uniaxial compressive strength gave consistently higher R^2 values than Kahraman's (2001) formula, all else held constant (see Table 3e).

The last parameter that was varied in SMR and RMR was the calculation of RQD: whether the RQD decimal percent was calculated separately for each scanline and then multiplied by all others, or whether data from all scanlines were combined and then one RQD value calculated (see Table 3f). Changing this parameter in SMR did not make a large difference in R^2 values (maximum change of 0.03) and was not consistent between logarithmic and linear fits. RMR values were somewhat improved by using multiplied RQD, with R^2 values increasing by up to 0.09 when multiplied RQD values were used instead of total RQD.

The calibration of all rating systems was focused on linear regressions, but it was found that when linear fits had R^2 values of ~0.2 or higher, that a logarithmic regression sometimes produced a significantly improved fit. For example, the best overall fit of any rating system was found using SMR and the following parameters: only SW Virginia data, no carbonates, the mean of raw data, multiplied RQD values, and Kidybinski's (1980) UCS formula, all plotted against average relief. The R^2 value for a linear fit was found to be 0.84, while a logarithmic fit improved that R^2 value to 0.92 (compare Figure 3a and Figure 3b).

As a final, direct comparison of methods, SMR and RMS were plotted against one another using three datasets: southwest Virginia with no carbonates, all sites, and all sites with no carbonates (Figure 3e). The southwest Virginia non-carbonate dataset produced a high correlation (R^2=0.96), which shows that the two methods perform essentially the same for this dataset. When all sites were included in the dataset, this correlation almost disappeared, producing R^2=0.29. Due to differences in the rating systems' carbonate scores, such a result was not unexpected. However, when scores from all non-carbonate sites were compared, the resulting correlation was still not strong (R^2=0.49). Closer examination of this result showed SMR having a greater range of scores than RMS (9-92 for SMR, 51-85 for RMS). This difference is largely due to SMR's joint orientation and excavation adjustments. The joint orientation adjustment lowers the minimum possible SMR score, and the excavation adjustment has the potential to lower the minimum score or raise the maximum score. While SMR allows for up to 60 points to be subtracted from a score for unfavorable joint orientation, RMS gives 5 points to the least favorable joint orientation. This difference did not make a large difference in southwest Virginia ratings due to the more subdued topography compared to the Tetons and cliffs in coastal Maine.

3.3 Optimization

As RMS and SMR showed the most promise overall, these systems were used for optimization. In order to use the same rating calculation methods for both the overall optimization and the optimization of the chemical weatherability adjustment factor, the carbonate-inclusive dataset and topographic metric that together provided the best linear R^2 value were chosen, but carbonates were removed from the dataset for optimization of original parameters (carbonates were included for the optimization of the chemical weatherability adjustment factor). The datasets that met these qualifications both excluded sites not in southwest Virginia.

Unfortunately, limiting data to non-carbonates in southwest Virginia meant that SMR had more parameters than there were points, which means the system had an infinite number of weighting combinations that would give R^2 equal to one. Therefore, optimization for SMR was performed with carbonate sites included in order to provide more field sites than parameters. The optimized weights are very different from published SMR weights, yet the results of this optimization did not improve R^2 values, suggesting that the optimization was not successful. RMS optimization was also performed with the carbonate-inclusive dataset in order to compare the resulting weights to the weights found in SMR optimization. The comparison did not show weight being placed on similar parameters, further confirming that optimizations performed on carbonate-inclusive datasets are not successful (see Table 3g).

A single, mathematically valid weighting optimization was found for RMS using non-carbonate data points (Table 3g), as it has fewer parameters than SMR. This optimized set of weights improved R^2 values by 0.18. This result may indicate that the optimized weights should be used instead of published weights, but a larger carbonate-exclusive dataset should be used in the optimization program to confirm this.

SMR and RMS were used to find chemical adjustment factors as well. The adjustment factor was designed as a positive amount to be added to the final rating of non-carbonate rocks in order to reflect their relative resistance to chemical weathering (carbonates were the only rock type within the areas studied that were particularly susceptible to chemical weathering). For each rating system, the carbonate-inclusive dataset and topographic metric that together provided the best linear R^2 value were used to optimize the adjustment factor. These datasets, their adjustment factors, and resulting R^2 values can be found in Table 3h.

Neither adjustment factor was able to improve R^2 values as much as simply removing carbonates, but due to error and noise in measurements, this is to be expected. The adjustment factor for SMR was not able to improve R^2 values at all, most likely due to the fact that SMR ratings already correlated well to topography when carbonates were included (see Figure 4f). This appears to be the result of a coincidence, as groundwater accounts for a larger percent of SMR ratings and the carbonate sites visited in southwest Virginia happened to have more groundwater than other sites. This coincidence would likely disappear if more carbonate data were available. The adjustment factor for RMS, however, increased the R^2 value by 0.42, a substantial improvement (see Figure 4f for RMS correlation before adjustment factor). Although the resulting R^2 was only 0.51, it seems likely that if the total number of field sites and number of carbonate field sites could be increased before running the optimization, the correlation could be further improved. Unfortunately, altering the data set in the optimization to include all field sites only adds one additional carbonate site and adds sites whose ratings are not necessarily expected to correlate to topography, so more fieldwork with carbonates must be performed to improve the calibration of these adjustment factors.

3.4 Summary

SMR appears to give ratings that best correlate to topography, especially when plotted against average relief. These results potentially indicate that the greater number of quantitative parameters (7 quantitative parameters as opposed to 4 in RMS; persistence measured with circular windows (Mauldon, 2001) in SMR versus qualitatively in RMS) and the addition of joint orientation adjustments (not present in RMR) may be responsible for yielding better ratings. Using Kidybinski’s (1980) formula for converting from Schmidt hammer rebound into uniaxial compressive strength emerged as producing better correlations between SMR and topography when other calculation techniques were held constant, but other calculation tests (average type for raw data, RQD calculation type) did not show an obvious best method. Calculation methods tested in RMS and RMR (average type for raw data, how to combine multiple joint sets, and methods that overlap between SMR and RMR) were largely inconclusive. This problem is perhaps the result of only having 23 field sites, compared to the ~100 sites that others have used for calibration (e.g. Selby, 1980).

For all rating methods, the type of average used on raw Schmidt hammer data had a very small impact on the average obtained (generally a difference of 2 or less). In RMS this difference only yielded one-point differences in overall ratings. However, RMR and SMR's large range of strength values within each rating category ended up causing 5-point differences in overall scores for strength values that lay just on either side of a dividing value. A more continuous scale, such as Moon's (1984) continuous version of RMS, would likely improve these misleading score differences.

A very telling result is the change in ratings' correlations to topography when the dataset was cut down to southwest Virginia sites only. In order to confirm that ratings did not simply correlate differently in Maine or the Tetons, RMS and SMR regressions were run for each of these areas individually, resulting in $R^2 \leq 0.05$ in all cases. The fact that the highest R^2 values for all rating systems' regressions occurred when only southwest Virginia sites were used suggests that topography may only be a valid proxy for erodibility where tectonic and erosive forces are relatively small. In coastal Maine and the Teton Range, it is not unlikely that wave action, glacial erosion, and uplift are strong enough to control topography regardless of the relative erodibility of rock formations present.

Another significant result is that Schmidt hammer rebound values only correlate well to topography when compared to the Topographic Index ($R^2 = 0.90$). The best correlations found against relief gave $R^2 = 0.55$ and against slope gave $R^2 = 0.40$. Given the small number of field sites and the large dependence on which topographic metric was used, these results bear further research. It is especially important to further explore this area due to the contrast between rating indices giving intact rock strength a maximum of 20% of possible points, while some tectonic and fluvial geomorphology studies use Schmidt rebound values alone to approximate erodibility (Duvall et al., 2004; Wohl & Grodek, 1993; Craddock, et al., 2007; Mitchell, et al., 2005).

The optimization results show that RMS weightings need to be reevaluated with a greater number of field sites, as the optimization program improved R^2 values by 0.18 and completely eliminated the use of some RMS parameters. The adjustment factor for chemical weatherability improved the correlation between ratings and topography, but ideally a greater number of field sites, including additional carbonate field sites, would be used to re-calculate this adjustment factor. Although the adjustment factor for SMR should most likely not be used as-is, the RMS adjustment factor could be used as a preliminary step towards improving a dataset.

Finally, although ratings can be easily obtained in the field, their variability requires that further analysis (and possibly additional fieldwork) be performed before making any assumptions or deductions about the rock mass as a whole. For example, ratings from different outcrops within the same geologic formation varied by as much as 21 points in RMS and 50 points in SMR, despite using the calculation methods that produced the best correlation to topography. This spatial variation was less pronounced in older landscapes of lower relief (Maine and Virginia sites), where maximum differences were 7 for RMS and 10 for SMR.

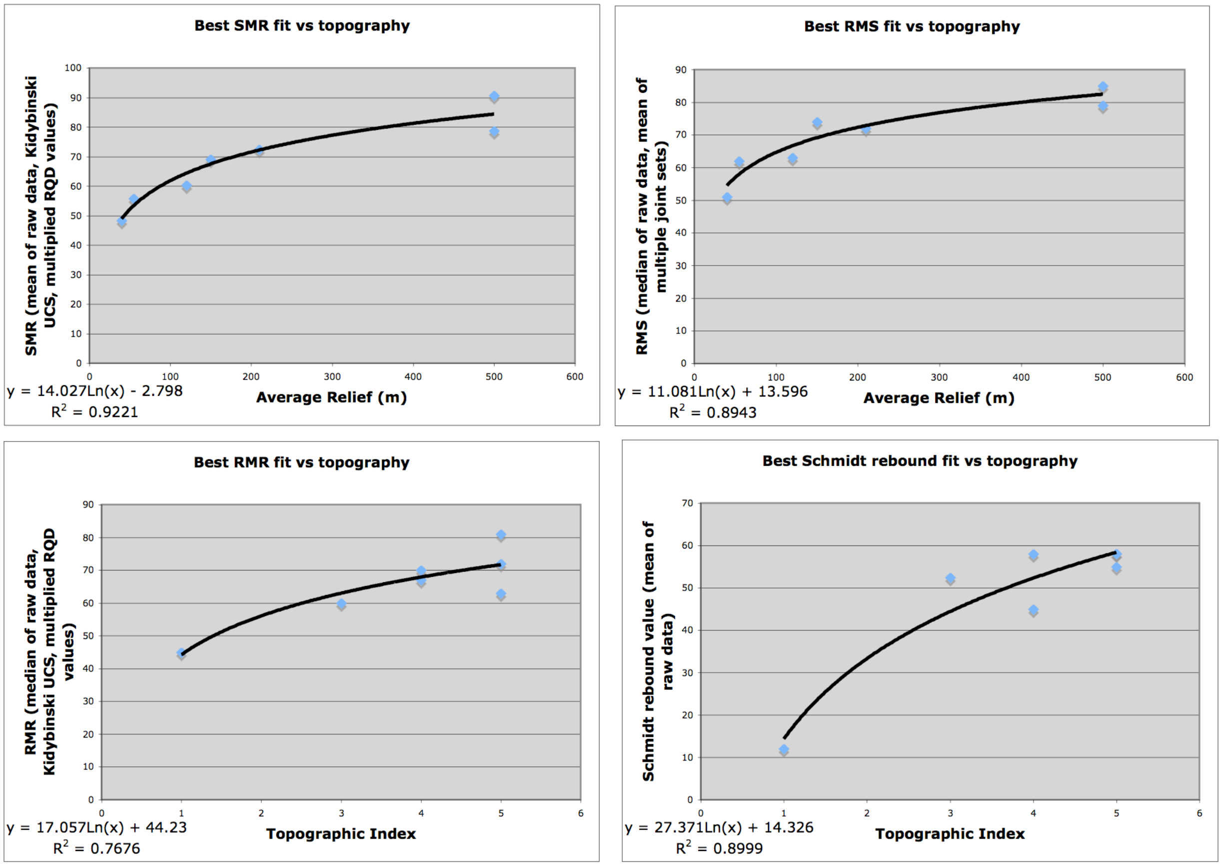


Figure 3a Each plot shows the calculation method that produced the best correlation between a given rating system and topography when using a logarithmic fit; fitting a logarithmic trendline to these datasets yields the highest overall R^2 values for SMR and RMS. All data above are non-carbonates from SW Virginia, as narrowing the dataset thus produced much higher R^2 values. Note: the Schmidt rebound regression was run again with the point at approximately y=11 removed; removing it did not improve the R^2 value. A complete table of the data used in these plots can be found in Table 3a.

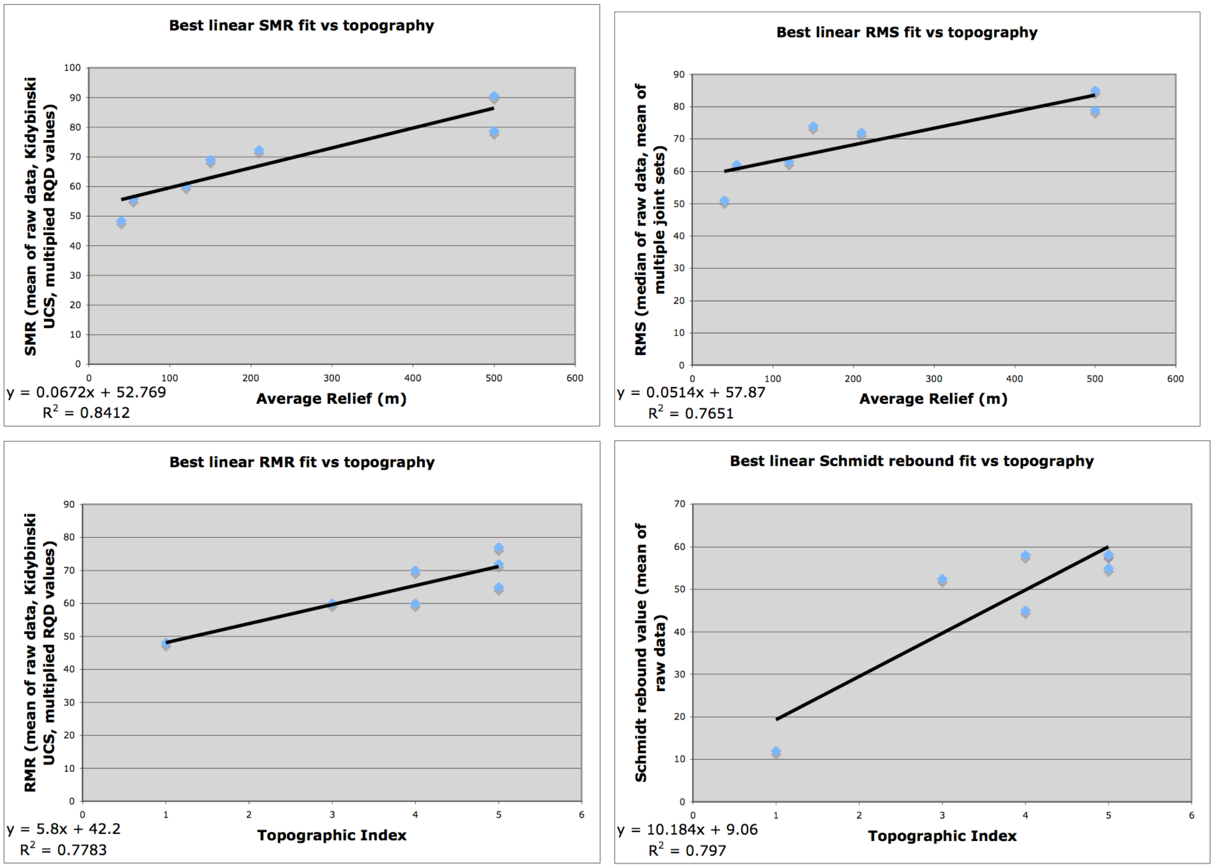


Figure 3b Each plot shows the calculation method that produced the best correlation between a given rating system and topography overall, but shows the results of fitting a linear rather than logarithmic trendline to the data. A linear fit produced the highest overall R^2 values for RMR and Schmidt rebound. All data above are non-carbonates from SW Virginia, as narrowing the dataset thus produced much higher R^2 values. Note: the Schmidt rebound regression was run again with the point at approximately y=11 removed; removing it did not improve the R^2 value. A complete table of the data used in these plots can be found in Table 3a.

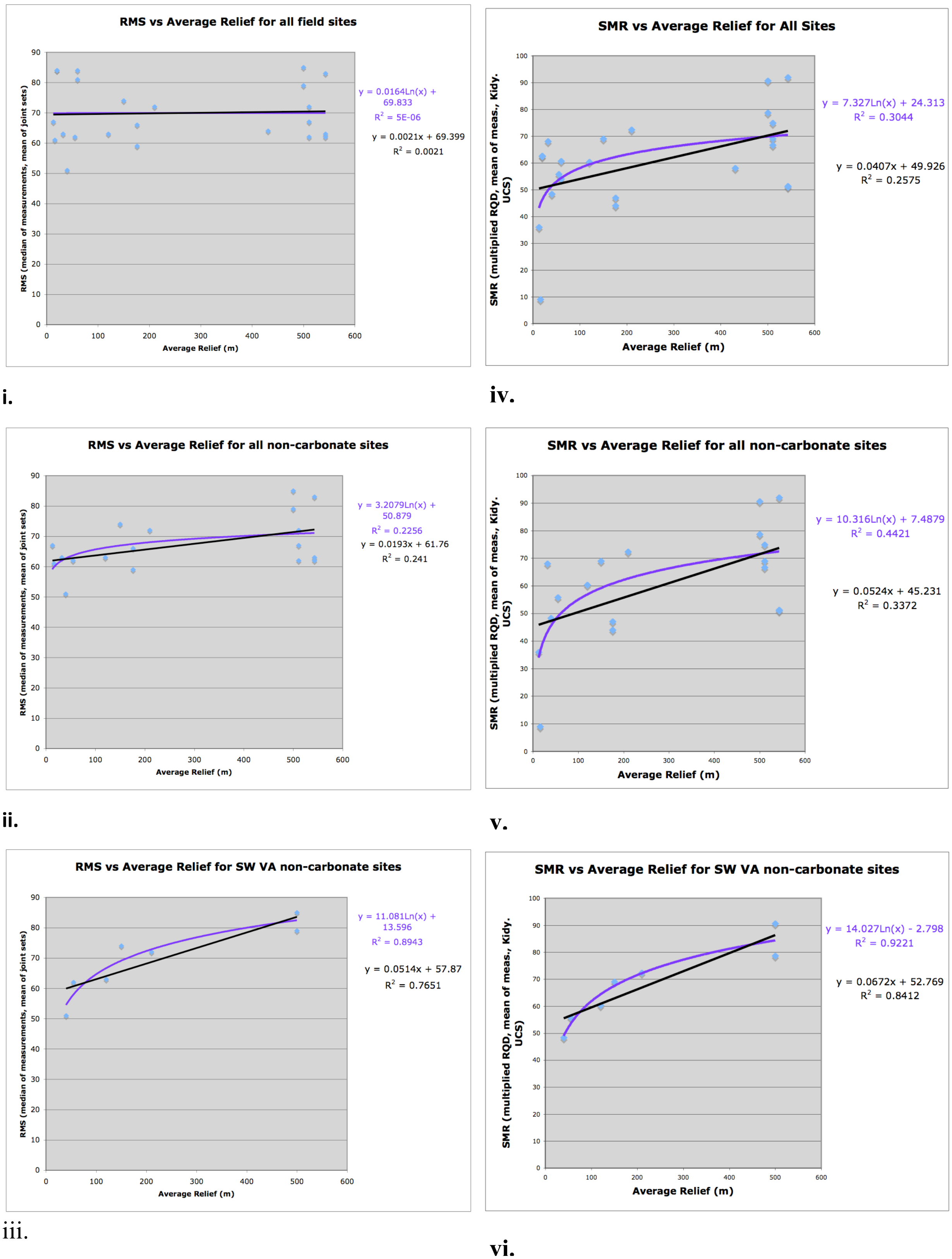
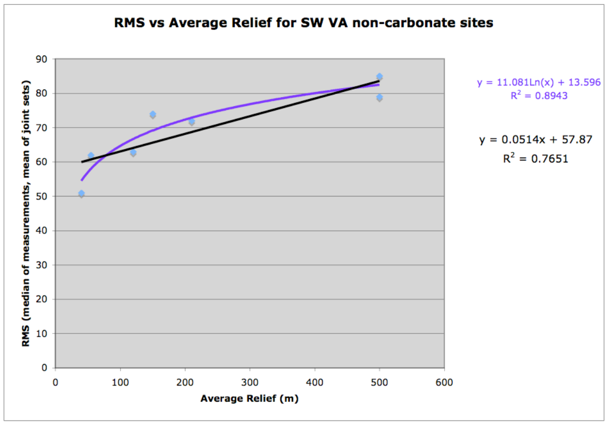
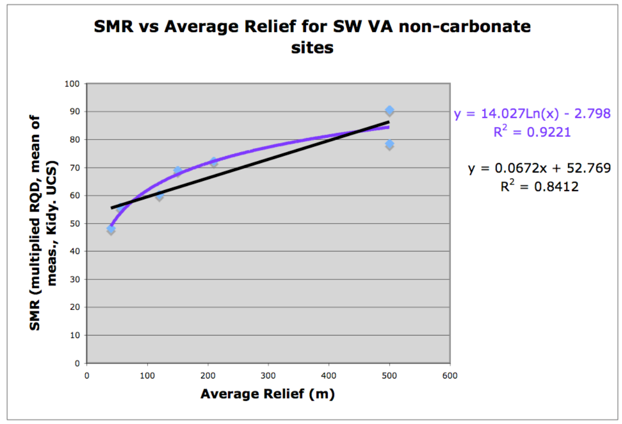


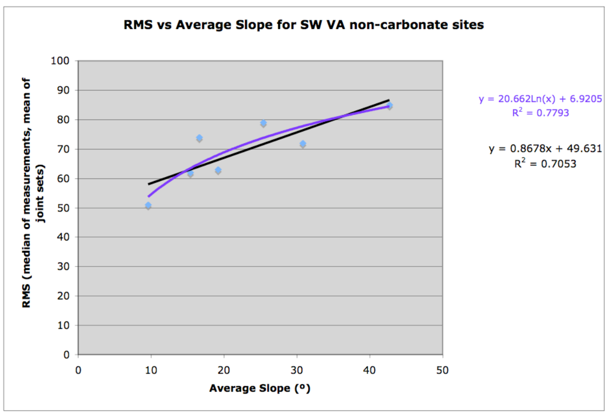
Figure 3c Plots show scores correlating better to topography as data is narrowed first to only non-carbonates, and then to non-carbonates in SW VA. i-iii show RMS, iv-vi show SMR. A complete table of the data used in these plots can be found in Table 3a.



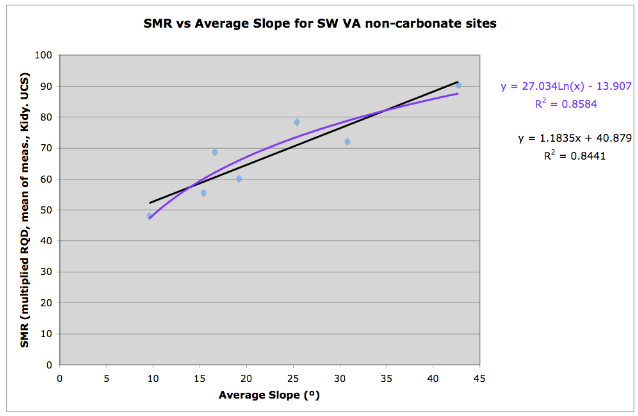
i.



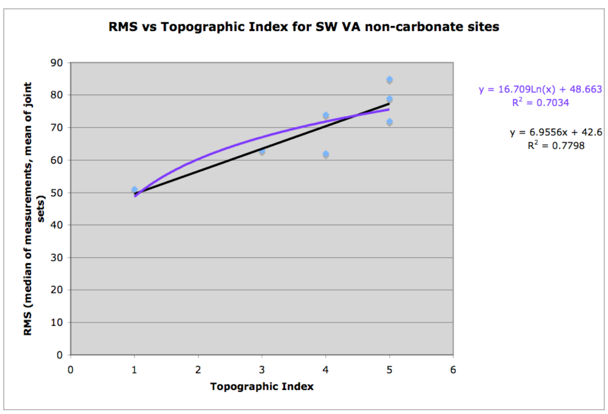
iv.



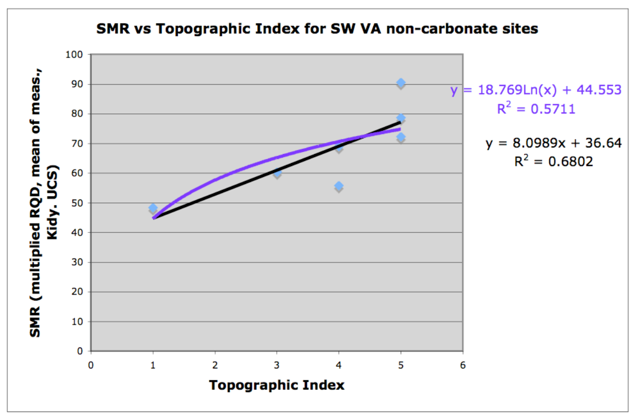
ii.



v.



iii.



vi.

Figure 3d Plots show that both RMS (i-iii) and SMR (iv-vi) correlate best to average relief in southwest Virginia, but RMS also correlates well to Topographic Index. The rating calculation methods used for all three plots of each rating system are those methods that produced the highest overall R^2 value. A complete table of the data used in these plots can be found in Appendix D.

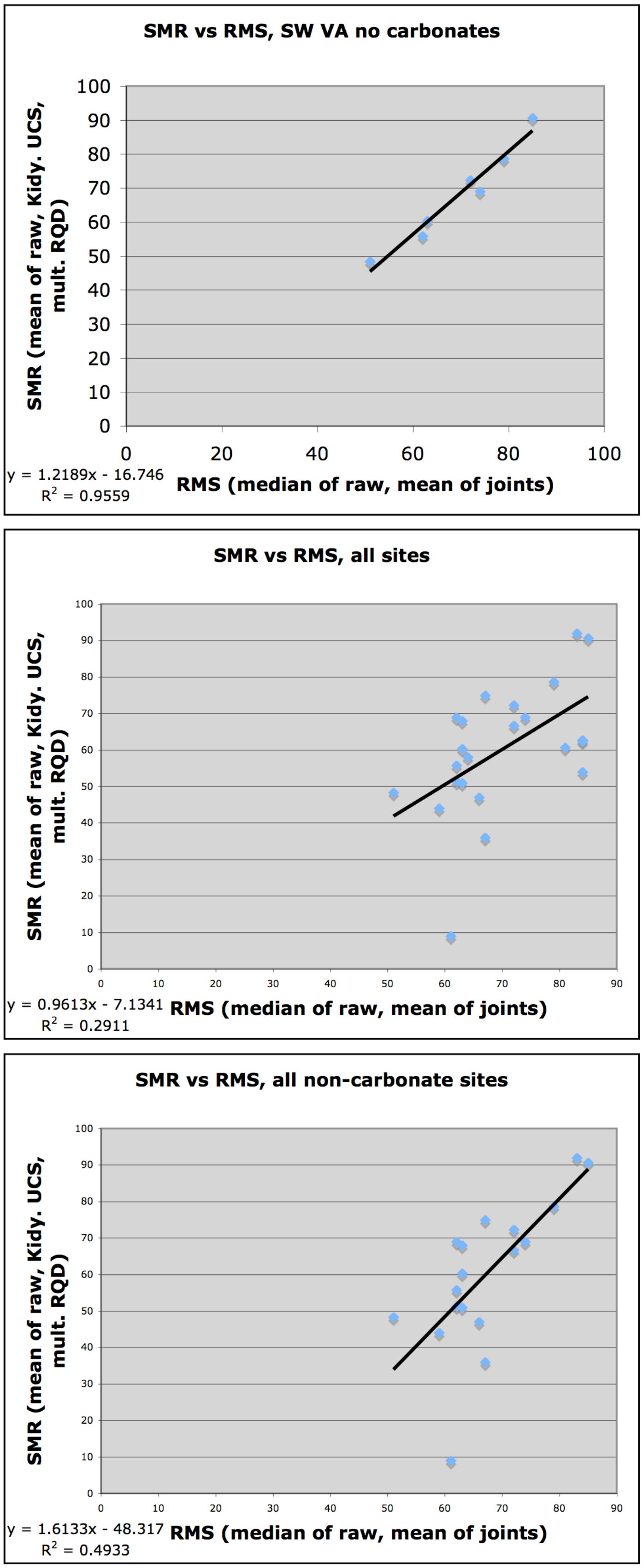
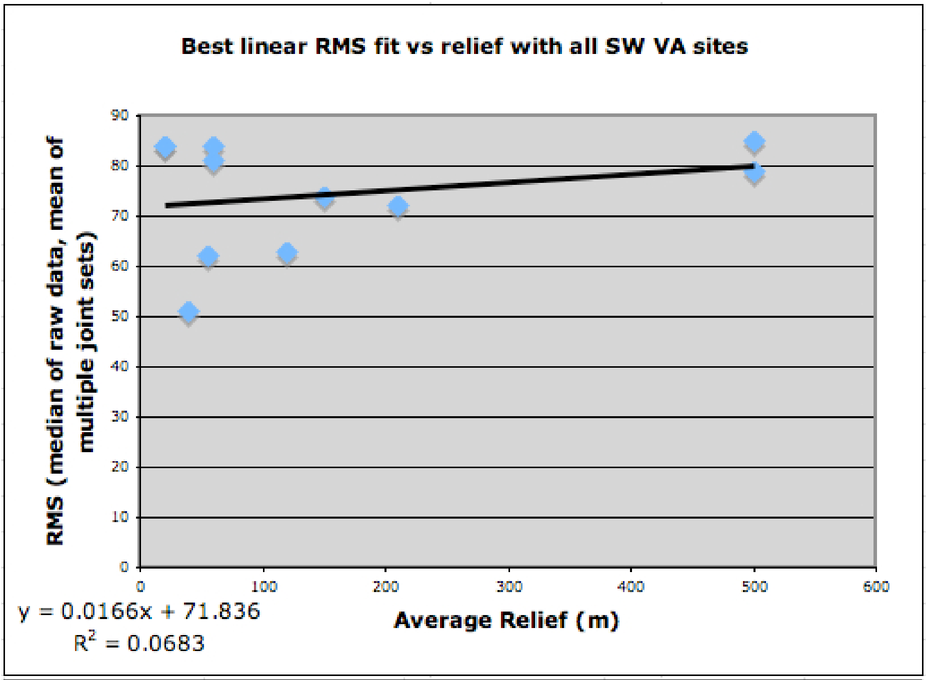


Figure 3e Plots of SMR versus RMS for the following datasets: southwest Virginia no carbonates (top), all sites (middle), and all non-carbonate sites (bottom). Note larger range of SMR scores than RMS scores.



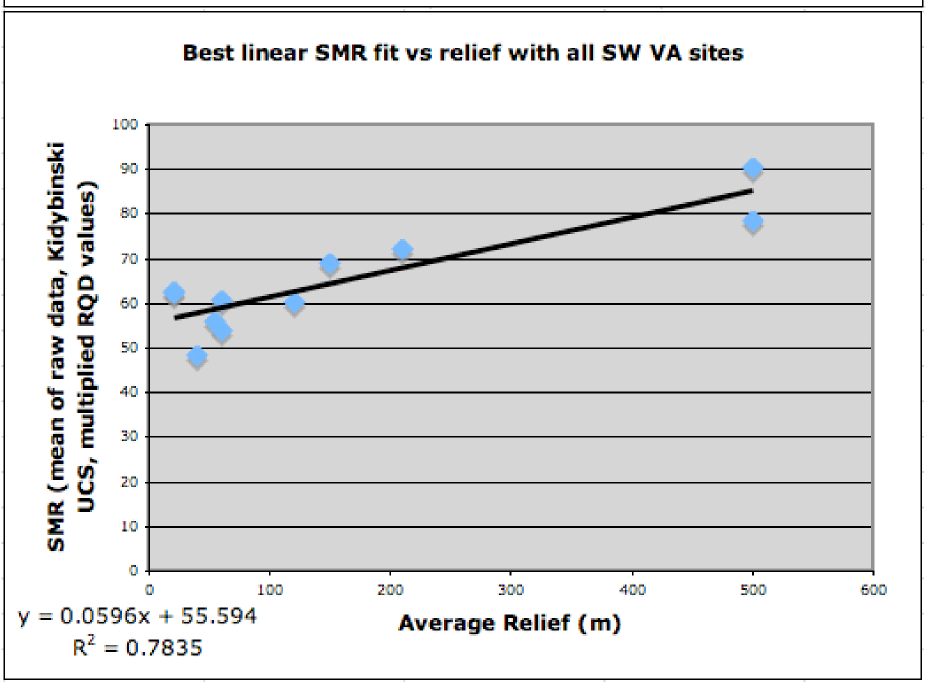


Figure 3f Plots of RMS and SMR from the dataset used in calculation of the chemical weatherability adjustment factor. Note SMR has a much higher correlation to relief than RMS when carbonates are included, most likely due to water at carbonate sites combined with SMR's heavier weighting of groundwater.

Region	Location	Formation	Rock Type(s)	Slope (°)	Relief (m)	Topographic Index	RMS	SMR	RMR
SW VA	Huckleberry Trail	Price	Sandstone, Siltstone	15.4	55	4	62	55.8	67
SW VA	Cascades Recreation Area, Jefferson National Forest	Tuscarora	Sandstone	42.7	500	5	85	90.65	81
SW VA	Cascades Recreation Area, Jefferson National Forest	Rose Hill	Sandstone	25.4	500	5	79	78.65	63
SW VA	Cove Mtn.	Juniata	Siltstone	19.2	120	3	63	60.35	60
SW VA	Cove Mtn.	Clinch	Sandstone	30.8	210	5	72	72.35	72
SW VA	Cove Mtn.	Huntersville	Chert	16.6	150	4	74	69	70
SW VA	Cove Mtn.	Millboro	Shale	9.6	40	1	51	48.35	45
SW VA	Hokie Stone Quarry: North Cut	Knox Group	Dolostone	5.3	20	1	84	62.65	67
SW VA	Hokie Stone Quarry: South Cut	Knox Group	Dolostone	5.3	20	1	84	62.4	64
SW VA	VA-94/Ivanhoe Rd: Northern Exposure	Rome	Dolostone	18	60	4	84	54	60
SW VA	VA-94/Ivanhoe Rd: Southern Exposure	Rome	Dolostone	13.7	60	4	81	60.7	58
Maine	Two Lights State Park	Kittery	Granofels, Phyllite	19.9	13	1	67	36	49
Maine	Fort Williams Municipal Park	Cushing	Gneiss	20.7	16	1	61	9	54
Maine	Blackwoods Campground, Acadia National Park	Cadillac Mtn	Granite	33.8	176	3	66	47	56
Maine	Pebble Beach, Acadia National Park	Cadillac Mtn	Granite	33.8	176	3	59	44	55
Maine	Newport Cove, Acadia National Park	Shatter Zone	Granite, Gabbro-Diorite	17.7	32	2	63	68	62
Tetons	Death Canyon	(Archean)	Gneiss	42.1	511	5	62	69	57
Tetons	Paintbrush Canyon	(Archean)	Gneiss	42.1	511	5	67	74.9	65
Tetons	South Fork of Cascade Canyon	(Archean)	Gneiss	42.1	511	5	72	66.65	54
Tetons	Delta Lake	Mt Owen	Quartz Monzonite	43.1	543	5	83	92	82
Tetons	Garnet Canyon	Mt Owen	Quartz Monzonite	43.1	543	5	62	51.3	68
Tetons	South Fork of Cascade Canyon	Mt Owen	Quartz Monzonite	43.1	543	5	63	51	62
Tetons	Blacktail Butte	Madison Group	Limestone	41.8	431	3	64	58	68

Table 3a All field sites by geographic location, including geologic formation, rock type, topographic data, and ratings used in Figures 3a-3e.

Rating System	**Calculation Techniques**	**Topographic Metric**	**Geographic Constraints**	**Rock Type Constraints**	**Trendline Type**	**R^2 value**
SMR	Mean of raw, Kidy. UCS, mult. RQD	Relief	SW VA	No carbonates	Logarithmic	0.92
SMR	Mean of raw, Kidy. UCS, mult. RQD	Topographic Index	SW VA	No carbonates	Linear	0.68
SMR	Mean of raw, Kidy. UCS, mult. RQD	Slope	SW VA	No carbonates	Logarithmic	0.86
RMS	Median of raw, mean of joints	Relief	SW VA	No carbonates	Logarithmic	0.89
RMS	Median of raw, mean of joints	Topographic Index	SW VA	No carbonates	Logarithmic	0.82
RMS	Mean of raw, wtd. avg. of joints	Slope	SW VA	No carbonates	Logarithmic	0.77
RMR	Mean of raw, Kidy. UCS, mult. RQD	Relief	SW VA	No carbonates	Logarithmic	0.64
RMR	Mean of raw, Kidy. UCS, mult. RQD	Topographic Index	SW VA	No carbonates	Linear	0.78
RMR	Mean of raw, Kidy. UCS, mult. RQD	Slope	SW VA	No carbonates	Logarithmic	0.79
Schmidt	Mean of raw	Relief	SW VA	No carbonates	Logarithmic	0.55
Schmidt	Mean of raw	Topographic Index	SW VA	No carbonates	Logarithmic	0.90
Schmidt	Mean of raw	Slope	SW VA	No carbonates	Linear	0.41

Table 3b Best correlations found for every method with each topographic metric.

Rating System	Calculation Techniques	Topographic Metric	Geographic Constraints	Rock Type Constraints	Trendline Type	R^2 value
SMR	Mean of raw, Kidy. UCS, mult. RQD	Relief	SW VA	No carbonates	Logarithmic	0.92
SMR	Mean of raw, Kidy. UCS, total RQD	Relief	SW VA	No carbonates	Logarithmic	0.90
SMR	Mean of raw, Kidy. UCS, total RQD	Relief	SW VA	No carbonates	Linear	0.87
RMS	Median of raw, mean of joints	Relief	SW VA	No carbonates	Logarithmic	0.89
RMS	Median of raw, mean of joints	Topographic Index	SW VA	No carbonates	Logarithmic	0.82
RMS	Median of raw, mean of joints	Topographic Index	SW VA	No carbonates	Linear	0.78
RMR	Mean of raw, Kidy. UCS, mult. RQD	Slope	SW VA	No carbonates	Logarithmic	0.79
RMR	Mean of raw, Kidy. UCS, mult. RQD	Topographic Index	SW VA	No carbonates	Linear	0.78
RMR	Median of raw, Kidy. UCS, mult. RQD	Topographic Index	SW VA	No carbonates	Logarithmic	0.77
Schmidt	Mean of raw	Topographic Index	SW VA	No carbonates	Logarithmic	0.90
Schmidt	Mean of raw	Topographic Index	SW VA	No carbonates	Linear	0.80
Schmidt	Median of raw	Topographic Index	SW VA	No carbonates	Linear	0.79

Table 3c Table of methods producing top three R^2 values for each rating system tested. Mean/Median of raw refers to which average type was used to process raw data. Kidy/Kahr UCS refers to whether conversion from Schmidt rebound to uniaxial compressive strength was performed with the formula from Kidybinski (1980) or Kahraman (2001). Total/Mult. RQD refers to whether RQD was determined by combining all scanlines or by multiplying the RQD decimal percents of all scanlines together. Mean/Wtd Avg of joints refers to whether multiple joint sets' data were combined with a mean or a weighted average based on fracture frequency.

Rating System	Calculation Techniques	Topographic Metric	Geographic Constraints	Rock Type Constraints	Trendline Type	R^2 value
SMR	Mean of raw, Kidy. UCS, total RQD	Relief	SW VA	No carbonates	Linear	0.87
SMR	Median of raw, Kidy. UCS, total RQD	Relief	SW VA	No carbonates	Linear	0.77
RMS	Mean of raw, mean of joints	Topographic Index	SW VA	No carbonates	Linear	0.80
RMS	Median of raw, mean of joints	Topographic Index	SW VA	No carbonates	Linear	0.78
RMR	Mean of raw, Kidy. UCS, mult. RQD	Topographic Index	SW VA	No carbonates	Linear	0.78
RMR	Median of raw, Kidy. UCS, mult RQD	Topographic Index	SW VA	No carbonates	Linear	0.76
Schmidt	Mean of raw	Topographic Index	SW VA	No carbonates	Linear	0.80
Schmidt	Median of raw	Topographic Index	SW VA	No carbonates	Linear	0.79

Table 3d This table shows the calculation technique that gives the best linear fit for each system, followed by the same calculation technique with only the averaging method for raw data changed. The best linear (rather than logarithmic) fit was used because logarithmic trendlines were only applied to the top few results from each system. Note that R^2 values do not vary much for RMS, RMR, or Schmidt when the average type is changed, but that SMR changed a great deal: SMR has a higher R^2 when the mean of raw data is used.

Rating System	Calculation Techniques	Topographic Metric	Geographic Constraints	Rock Type Constraints	Trendline Type	R^2 value
SMR	Kidy. UCS, mean of raw, mult. RQD	Relief	SW VA	No carbonates	Logarithmic	0.92
SMR	Kahr. UCS, mean of raw, mult. RQD	Relief	SW VA	No carbonates	Logarithmic	0.87
RMR	Kidy. UCS, mean of raw, mult. RQD	Slope	SW VA	No carbonates	Logarithmic	0.79
RMR	Kahr. UCS, mean of raw, mult. RQD	Topographic Index	SW VA	No carbonates	Logarithmic	0.65

Table 3e This table shows the calculation technique that gives the best overall fit for SMR and RMR, followed by the same calculation technique with only the Schmidt rebound to UCS conversion formula changed.

Rating System	Calculation Techniques	Topographic Metric	Geographic Constraints	Rock Type Constraints	Trendline Type	R^2 value
SMR	Kidy. UCS, mean of raw, mult. RQD	Relief	SW VA	No carbonates	Logarithmic	0.92
SMR	Kidy. UCS, mean of raw, total RQD	Relief	SW VA	No carbonates	Logarithmic	0.90
SMR	Kidy. UCS, mean of raw, total RQD	Relief	SW VA	No carbonates	Linear	0.87
SMR	Kidy UCS, mean of raw, mult. RQD	Relief	SW VA	No carbonates	Linear	0.84
RMR	Kidy. UCS, mean of raw, mult. RQD	Slope	SW VA	No carbonates	Logarithmic	0.79
RMR	Kidy. UCS, mean of raw, total RQD	Slope	SW VA	No carbonates	Logarithmic	0.72
RMR	Kidy. UCS, mean of raw, mult. RQD	Topographic Index	SW VA	No carbonates	Linear	0.78
RMR	Kidy. UCS, mean of raw, total RQD	Topographic Index	SW VA	No carbonates	Linear	0.69

Table 3f This table shows the calculation technique that gives the best overall fit for SMR and RMR, followed by the same calculation technique with only RQD calculation technique changed.

Rating Type	Methods Selected	Regression Type	Parameters	Original (Published) Weights	Optimized Weights	R^2 using Original Weights	R^2 using Optimized Weights
RMS	SW VA, no carbonates, mean of raw data, mean of multiple joint sets	Linear, vs. Relief	Schmidt Rebound	20	17.61	0.76	0.94
			Weathering	10	0		
			Joint Spacing	30	16.99		
			Joint Orientation	20	47.80		
			Joint Width	7	0		
			Joint Infill & Continuity	7	17.60		
			Groundwater	6	0		
SMR	SW VA, Mean of raw data, Kidy. UCS, total RQD	Linear, vs. Relief	UCS	15	0	0.87	0.88
			RQD	20	61.47		
			Joint Spacing	20	13.28		
			Joint Persistence	6	0		
			Joint Aperture	6	2.25		
			Joint Roughness	6	0		
			Joint Infilling	6	0		
			Joint Weathering	6	0		
			Groundwater	15	22.98		
			Joint Orientation Adjustment	Subtract up to 60 from score total	Subtract up to 0.27 from score total		
			Excavation Adjustment	Add up to 15 or subtract up to 8 from score total	Add up to 2.62 to score total		
RMS	SW VA, mean of raw data, mean of multiple joint sets	Linear, vs. Relief	Schmidt Rebound	20	23.37	0.08	0.72
			Weathering	10	0		
			Joint Spacing	30	0		
			Joint Orientation	20	30.25		
			Joint Width	7	3.54		
			Joint Infill & Continuity	7	0		
			Groundwater	6	42.83		

Table 3g Results of optimizing the weights of existing parameters in RMS and SMR using carbonate-inclusive and carbonate-exclusive datasets.

Rating Technique	Methods Selected	Regression Type	R^2 with carbonates	R^2 without carbonates	R^2 with carbonates, with adjustment factor	Adj. Factor (to be added to non-carbonates)
SMR	SW VA sites only, mean of raw data, Kidybinski UCS, total RQD	linear, vs. average relief	0.78	0.87	0.78	4
RMS	SW VA sites only, mean of raw data, mean of multiple joint sets	linear, vs. average relief	0.08	0.76	0.51	18

Table 3h Results of optimizing a chemical weatherability adjustment factor for RMS and SMR. The final adjustment factor is a positive amount to be added to rocks that are not particularly susceptible to chemical weathering or dissolution.

Chapter 4: Discussion

4.1 Major Conclusions

After implementing multiple rock mass strength rating indices in various geologic, erosive, and tectonic settings, it seems that such indices do have the potential to accurately characterize the erodibility of a rock mass. SMR and RMS emerged as the best two systems tested, with SMR performing only slightly better; four RMS versions produced $R^2 \geq 0.8$, while 10 SMR versions produced $R^2 \geq 0.8$. SMR showed high correlation to topography in landscapes that are controlled by erodibility, and the greater number of parameters that rely on quantitative, more objective measurements inspired more confidence in the field data collected and the final ratings assigned. SMR also had much better correlations to topography (0.7 higher R^2) than RMS when carbonates were not removed from the dataset. It seems that this performance is due to SMR's weighting groundwater more heavily than RMS, but it is suspected that groundwater being present at carbonate field sites is not a ubiquitous enough occurrence that SMR could be relied upon to perform so well if more carbonate sites were added.

Confidence in SMR measurements was further enhanced by using circular scanlines and windows to measure joint persistence (procedure from Mauldon, 2001) and multiple, intersecting scanlines to measure joint spacing (after Moore et al., 2009). Mauldon's "mean trace length estimator" removes sample bias due to outcrop size or shape while calculating the persistence of joints, and using scanlines to determine joint spacing was found, in practice, to encourage closer examination of all potential joint sets and to yield a dataset that would be easier for another scientist to recreate. Lastly, SMR performs better than RMS (R^2 is 0.1 higher) when all non-carbonate sites are considered. This result may validate SMR's greater range of scores and explain the lack of correlation between SMR and RMS when all non-carbonate sites are included.

The fact that all carbonate field sites tested in southwest Virginia happened to have more groundwater than their non-carbonate counterparts allowed for SMR to (somewhat inadvertently) lower the scores of carbonate rocks. However, none of the rating systems directly addressed the weakness of carbonate rocks, and generally ratings did not correlate to topography when carbonates were included. Therefore, an adjustment factor for chemically weatherable rocks is needed. One of the major results of this study was the calculation of such an adjustment factor for both RMS and SMR. Due to the aforementioned coincidence of carbonates and groundwater, this adjustment factor did not improve SMR ratings for the data used, but it is expected that the addition of dryer carbonate field sites would yield an adjustment factor that significantly improves R^2 values. An improvement was observed with the analogous chemical adjustment factor that was calculated for RMS. The correlation of carbonate-inclusive ratings to topography increased from R^2=0.08 to R^2=0.51 when the adjustment factor was added. With additional field sites in a landscape that is adjusted to erodibility, it seems apparent that these final R^2 values could be even further improved.

Optimization of existing parameters was not successful for SMR, but it was successful for RMS. Optimization using non-carbonate, southwest Virginia data improved RMS ratings' correlation to topography from R^2=0.76 to R^2=0.94. Such a large improvement combined with limited previous calibrations of the system (Selby, 1980) suggests that RMS parameter weightings may need to be altered. However, more data points are needed to ensure that this calibration is accurate.

Despite the finding that SMR and RMS do give a general idea of a rock mass's erodibility, there is a major limitation to this observation. For example, Mt. Owen quartz monzonite in the Tetons received a rating of 97 at one outcrop and 47 at another. Such large differences are generally due to the joint orientation adjustment factor used in SMR, where simply moving to the other side of a hill can show joints dipping steeply out of the slope rather than steeply into it. More typical variations were only around 5-10 points, but the fact that ratings were so often different shows that rating a single field site will not robustly characterize an entire rock mass and could even be misleading.

No technique was able to produce a correlation between coastal Maine sites and topography or between Tetons sites and topography. This lack of correlation was determined both by the highest R^2 values for all systems being obtained when these areas were excluded, and by extremely low correlations to topography when these areas' ratings were separately regressed against topography (all $R^2 \leq 0.05$). With no technique producing a correlation to topography and no other proxy or direct measurement of erodibility, it is not possible to identify an erodibility rating system that works best for coastal or glacial erosive processes. Furthermore, as the only metamorphic and igneous rocks studied were found in these same two regions, this study cannot identify an ideal method for handling these rock types. The study does show, however, that existing methods work well in well-adjusted landscapes consisting of alternating layers of sedimentary rocks when chemically weatherable rocks are excluded or adjustments are made for them.

4.2 Erodibility and Geology

Erodibility has the long-term potential to control the topography of a landscape. Southwest Virginia's Valley and Ridge province displays this adjustment, with hard, sparsely jointed sandstone units comprising ridges, slightly weaker mixed units of siltstone and mudstone comprising flanks, and carbonates comprising valleys. This pattern highlights the major role of chemical weathering in the erodibility of a rock mass, as well as erodibility's ability to govern landscape evolution in certain environments.

In environments with faster erosion rates, this adjustment is not observed. The Teton Range showed extensive variation in the types of rocks comprising various features of the landscape, and examination of geologic and topographic maps lacked the correlation between rock type and topography that was seen in southwest Virginia. This same pattern was observed in the field, where quartz monzonites of the same geologic formation had very different outcrop morphologies depending on where in the mountains they were found. In coastal Maine, where waves are a constant, directed erosive force, all rock types sampled seemed to end up with the same steep cliffs at the most landward end of the surf zone that gave way to flat, underfoot exposures that only emerged at low tide. The variation of outcrop morphology in the Tetons and homogeneity of outcrop morphology in coastal Maine both point to topography and outcrop morphology being controlled by erosive processes rather than the erodibility of rock units.

While a well-adjusted topography does suggest that erodibility ratings would correlate to topography, it is worth noting that the average slopes of all but one formation sampled in southwest Virginia were below the angle of repose. The fact that mass wasting does not relate linearly to slope may be why non-linear trendlines produced better correlations between topography and ratings. Yet, even linear trendlines produced R^2=0.8 or higher for RMS and

SMR. Plots of RMS versus slope from other studies (e.g. Banks, 2005) do not show such a high correlation when only repose or lower slopes are considered; they require the inclusion of slopes above the angle of repose before a better correlation emerges (see Figure 1a). The high correlation of slopes below repose in this study may be due to the smaller data set and the fact that all data were collected by the same researcher, whereas the data in Figure 1a were synthesized from multiple researchers. If so, this result highlights the need for rating systems' results to be more reproducible.

The spatial variability of erodibility does not require great distances between outcrops to be observable. For example, Knox Group dolostone outcrops in southwest Virginia were only about 100 m apart, located within the same quarry, and produced ratings that differed by up to 5 points in SMR. These differences were found in joint infilling, joint weathering, and joint orientation adjustment. In RMS, however, the maximum difference between ratings of these outcrops was only 3 points, stemming from differences in joint spacing. Another southwest Virginia formation, the Rome dolostone, was also studied at two outcrops approximately 75 m apart. SMR values differed by up to 10 points due to differences in groundwater, joint orientation, and RQD. Again, RMS differences were smaller, with a 4-point difference arising from groundwater and joint continuity/infill ratings. This variability was approximately the same, even at greater distance, as seen in Maine outcrops of the Cadillac Mountain granite. Outcrops of this formation were approximately 1.4 km apart and varied in their RMS ratings by up to 7 points and in their SMR ratings by up to 8 points. While even greater variation was seen in the outcrops of the Teton Range, it is suspected that this variation is due more to erosive and tectonic processes rather than actual differences in erodibility.

This spatial variability in erodibility, along with poor correlation between slope or relief and Schmidt hammer rebound values, suggests that rock hardness cannot be used independently of joint characterization to approximate erodibility. Rock hardness is important to erodibility though (Selby, 1980), as evidenced by previous studies (Terzaghi, 1962, via Selby, 1980) and the relative improvement of Schmidt hammer rebound's correlation to topography when the data was limited to only southwest Virginia. It does seem that the relative importance of fractures and rock strength as they contribute to the erodibility of a rock mass depends on the frequency of joints and the rock type. If joints are spaced closely enough, valid rock strength measurements cannot even be taken with a Schmidt hammer, suggesting that rock strength is no longer important beyond a certain frequency of joint spacing. Initial results of the optimization of parameter weightings also indicate that the weighting of joints versus intact strength should be around 3:1, which is consistent with existing weighting schema. However, studies of weak mudstones (Moon et al., 2001; Brook & Hutchinson, 2008) concluded that the relative importance of intact strength is lower when weak lithologies show favorable joint orientation.

4.3 Suggestions for Users of Erodibility Indices

By the end of the study, many techniques and methods had been found or developed and were being implemented regularly. Some were simple or arguably obvious, while others were the result of literature review or data analysis. Overall, however, it was felt that these protocols made measurements more consistent or placed greater confidence in results.

The most general suggestion for fieldwork is to collect as much data in as many different forms as possible. Since some parameters are qualitative or have quantitative but slightly subjective measurements, having additional notes, pictures, samples, and even GPS coordinates can be helpful when reviewing field data, especially months after it was taken. While this is standard practice for collecting field data, the subjectivity of rock mass strength rating systems amplifies the importance of these extra data. Rock descriptions and coordinates were used with geologic maps to confirm field identification of rock type and geologic history. Samples and pictures were used to calibrate the assignment of qualitative parameters such as weathering, joint roughness, and, for RMS, joint continuity. Pictures of circular scanlines/windows and linear scanlines could even be reviewed to determine which joints were counted and which were discounted as weathering products. Again, recording as much as possible may be simply regarded as standard best practice, but when one of the major problems with a system is subjectivity, knowing exactly how each measurement and rating was made can only improve results.

A continuation of the above is the recommendation that all qualitative parameters be internally calibrated. These parameters include joint roughness and weathering for SMR (SMR's verbal descriptions of groundwater were generally specific enough to not require calibration), and joint continuity, infill, groundwater, and weathering for RMS. As was mentioned in previous chapters, a joint roughness determination of "slightly rough," for example, only has meaning as it relates to other levels of roughness that have been observed. Therefore, it is suggested that a preliminary designation for these parameters be given in the field, but that these designations be reviewed after all field work has been completed to ensure that all ratings make relative sense in comparison to one another. Extra notes, pictures, and hand samples were especially helpful for this internal calibration.

Another suggestion for the field is to remain as consistent as possible in the measurement methods used. For example, independent joint spacing measurements should not be mixed with scanline determinations of joint spacing, or if certain Schmidt hammer hits are discounted at one site then the same hits should be discounted at all sites. If these differences are allowed to persist in the dataset, then the comparison of final ratings will not necessarily be representative of true similarities or differences between the rock masses.

Some measurements in erodibility indices are quantitative but lack instruction on how to make said measurements, adding a great deal of subjectivity to the results. Several suggestions are made for improving the objectivity of these parameters. First, the use of several circular scanlines/windows to calculate the average persistence of joints using Mauldon's (2001) formula is suggested as the best method to calculate SMR's persistence parameter. It not only removes sample bias in the outcrop, but it provides a very simple and clear method that can easily be implemented at each outcrop. Another suggestion is to use a series of intersecting scanlines to determine joint spacing measurements. These scanlines are described in greater detail in Chapter 2: Methods, but generally they require joint spacing to be measured in multiple directions and encourage closer examination of all possible joint sets. Scanlines also make measurements easier to reproduce, a very important trait for any scientific procedure.

Another consideration is the history of the outcrop. How a rock mass came to be outcropping at a certain location should be considered when in the field and when comparing the resulting erodibility ratings of various outcrops. Whether the outcrop is natural, a road cut, or a quarry may affect the ratings it yields. This idea is important with respect to weathering parameters, as a rock face in an active quarry will almost always be clean and unweathered, regardless of the rock type or rock mass properties. Likewise, the presence of a natural outcrop in and of itself can, in some landscapes, imply that the rock mass must be fairly strong despite a potentially more weathered appearance. The history of the outcrop may also affect joint spacing, as excavation techniques used on man-made outcrops may be responsible for creating fractures or opening existing ones. As noted previously, some fractures were only found to be emanating from blasting-related drilling scars, suggesting that they are not a consistent, natural feature throughout the rock mass. Determining whether existing fractures were opened by excavation may also improve ratings, but no standard technique to do so was produced. Together, weathering and joint spacing account for up to 40% of potential rating points, making the examination and comparison of outcrop histories worthwhile, especially should there be any unexpected results.

Also of great importance is the data processing side of rating determination. The most conclusive of data processing results was the intact strength calculation method. If a Schmidt hammer is being used to determine uniaxial compressive strength (UCS) for SMR or RMR (rather than lab tests of strength), it is suggested that Kidybinski's formula (1980; via Kahraman, 2001) be used for conversion from rebound value to strength value in MPa. This suggestion is based on the many plots of ratings versus topography, which showed that when ratings were calculated with multiple conversion formulas and all other methods were held equal, the ratings that used Kidybinski's formula consistently yielded higher R^2 values.

Overall, SMR and RMS performed fairly equally, with maximum R^2 values of 0.92 and 0.89, respectively. Likewise, several of the calculation methods tested did not show a conclusive best method (e.g. using the mean or median of raw data). However, a final recommendation for all methods is made based on user experience and confidence in measurements. SMR inspired greater confidence in measurements and their reproducibility when used with the methods previously described. This confidence was due to the greater number of directly measurable parameters. As noted above, Kidybinski's formula (1980; via Kahraman, 2001) is recommended for Schmidt hammer conversions. Multiplying the RQD decimal percentages obtained from multiple scanlines is also recommended, based on the assumption that a rock mass cannot be stronger than its weakest portions. The recommendation of calculating joint orientation deductions using the joint set that produces the greatest deduction is based on this same assumption. It is also recommended that any Schmidt hammer hits that sound hollow or visibly fracture or pulverize the rock be discounted. Finally, using the median of Schmidt hammer measurements is recommended based on the high standard deviation of rebound values and the suspicion that discounting certain hits will not fully account for non-representative rebound values obtained.

4.4 Future Research

Some of the issues addressed in this study still require that additional work be completed in order to fully resolve them. Furthermore, in working to resolve these initial problems, several new potential issues were uncovered as well. While some ideas for addressing these problems are proposed, it does not seem that all problems with using erodibility indices have ideal solutions.

The chemical weatherability adjustment factor that was calculated in this study is functional for RMS but does not improve SMR's correlation to topography when using the existing dataset. This adjustment factor has the potential to greatly improve erodibility ratings while hardly changing the implementation of erodibility rating systems. Therefore, obtaining data for additional field sites in an erodibility-adjusted landscape (e.g. southwest Virginia) and testing or re-optimizing the adjustment factor for SMR is one of the first items that should be addressed in future research. In the meantime, however, the RMS adjustment factor should be tested as-is on other datasets to see if it is as successful in improving the correlation between ratings and topography as it was in this study.

Optimization of parameter weights for rating systems (without chemically weatherable rocks) also requires additional fieldwork. The RMS optimization of parameter weights that was determined with a non-carbonate dataset was very successful in improving correlation to topography, with an increase in R^2 of almost 0.2. More erodibility-adjusted, non-carbonate field sites should be used with this new weighting scheme to determine if it continues to produce better correlations. With these additional non-carbonate field sites, the optimization program could also be run on SMR to test whether the original weightings are ideal.

Internally calibrating qualitative and subjective parameters works when a variety of field sites are being visited and when only one researcher is contributing to the dataset. However, such parameters would ideally be more objective and absolute, not varying based on the types of exposures that a researcher has seen or who is taking the measurements. The joint continuity rating for RMS could be adapted to take persistence measurements instead, and it seems that this would be a worthy undertaking to improve the objectivity of the rating system. As circular scanlines and windows are easy and quick enough to implement with little additional equipment, there does not seem to be a reason to continue using the qualitative, highly subjective scale originally suggested by Selby (1980). Similarly, more detailed descriptions of groundwater beyond “trace” or “moderate” could be used, such as the descriptions used in SMR; these descriptions would also be more useful to a researcher in the field than the flow rate approximations given by Selby (1980). Roughness characterizations in SMR could potentially be improved by using a visual table such as that used by Barton and Choubey (1977) to assign joint roughness coefficients (Figure 4a). With a visual scale, roughness ratings would no longer vary based on the types of outcrops that a researcher had seen, and the scale or wavelength of roughness would be given. If the visual scale shown in Figure 4a were used, every two sketches could replace one roughness designation in the current scale. For example, JRC=16-20 could be used in place of “very rough,” and so on. The drawings of roughness coupled with the appropriate length scale should make it far easier to obtain consistent and reproducible roughness measurements. Weathering parameters are difficult to improve upon without any obvious quantitative measurement technique, and it may simply be best to frequently refer to the detailed descriptions offered in the original rating system manuscripts, or the texts on which they were based (e.g. Dearman, 1974, 1976).

Another issue that this study only addressed to a minor degree was how best to handle multiple discontinuity sets. The issue is likely more complicated than simply whether to treat them equally or to use a weighted average. For example, does the weakest joint set control the strength of the entire rock mass? The most frequently occurring joint set? Or must joint sets be looked at in combination somehow? The extent to which research in this area would actually improve ratings is unknown, but over 50% of possible points in both RMS and SMR ratings are dependent upon joints, suggesting that this issue merits further research.

It may also be beneficial to explore why some erodibility ratings showed a better correlation to certain topographic metrics. SMR, for example, performed best when relief was used, and Schmidt hammer correlations only worked when the topographic index was used. Other studies have generally used slope to calibrate or check erodibility ratings (Selby, 1980; Moon et al., 2001; Brook & Hutchinson, 2008), but it does not seem that extensive work has been done to validate this comparison. Such validation could not be performed in this study, as it is not possible to simultaneously vet a topographic proxy for erodibility while vetting erodibility ratings against topography. Therefore, it may be beneficial to design a separate test to determine the best topographic proxy for erodibility, such as directly comparing topographic metrics (slope, relief, some sort of topographic index) to measured erosion rates of various geologic formations. If such a validation of topographic proxies could be performed, then erodibility indices could be further improved more easily.

Along these same lines, erosion rates could also be compared to erodibility ratings for the most direct calibration of the rating systems. Such a calibration would mean that erodibility ratings could potentially be compared to topography not to validate the ratings themselves, but to determine whether erodibility was the controlling factor in shaping the landscape. It may also be interesting to compare erosion rates and erodibility ratings in landscapes that are not well adjusted to erodibility in order to determine whether there is any discernable difference in erosion rates or whether erosion as well as topography is completely controlled by factors other than erodibility.

Some larger-scale, collaborative research efforts could also add significant results to what is known about rock mass strength rating indices. It seems that many users of these indices informally talk about their subjectivity and the variation in ratings determined by multiple users at the same outcrop. However, it is not readily apparent in the literature that a large-scale study involving multiple field locations and several experienced users of these scales has ever been attempted. If such a study could be performed, we could perhaps finally quantify the extent to which subjectivity and user interpretation really do affect the precision of erodibility indices.

An attempt to map erodibility by geologic formation was initially considered for this study but quickly set aside as the aforementioned spatial variability of erodibility ratings became apparent. This spatial variation seemed to imply that extensive fieldwork would have to be completed in order to get a truly representative map. Yet, slope stability studies that implement GIS models have been successful in characterizing and predicting areas of likely failure without completing a great deal of fieldwork (Pack et al., 1998; Lan et al., 2004). It therefore may be possible to complete basic fieldwork in very few areas and then use GIS tools to account for differences in, for example, joint orientation with respect to slope face or the presence of groundwater. Some studies have already attempted such mapping (e.g. Romana, 2003), but not for use in geomorphology.

The final and most pervasive problem encountered when using erodibility indices was the decision of which joints to count. Between joint spacing, joint persistence, and RQD, much time in the field was spent deciding which discontinuities represented pervasive fractures and which should be disregarded as the results of surface weathering or blasting. This problem has been documented and addressed in the past, especially with respect to RQD core logging (Deere & Deere, 1988). However, even with these suggestions for use, the decision of which joints to count still remains a subjective one. Perhaps the number of years that this issue has persisted indicates that there is no method that can substitute for an educated guess from an experienced researcher.

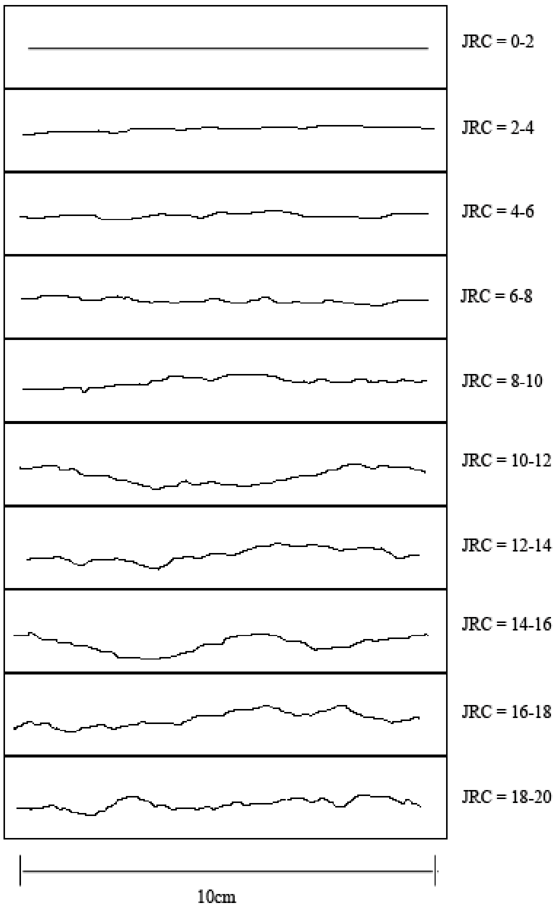


Figure 4a Charts of this type (based on data from Barton & Choubey, 1977) are used in shear strength calculations to approximate the joint roughness coefficient of a fracture plane. Having some sort of similar chart to make joint roughness ratings in SMR may help decrease variability and subjectivity of ratings.

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Statement on Images

All images in this thesis are the original work of R.S. Rodriguez unless otherwise stated.

Appendix A1: Price Formation, Upper Member

Measured September 2010. Blocky sandstone and siltstone with 2 intersecting, near-orthogonal fracture sets.
Approximately 50% fine-grained sandstone, 50% coarse- to medium-grained siltstone.
East wall of Huckleberry Trail, Christiansburg, VA. Excavated early 1900s for railroad.
Window studied: N 37º 10' 40" W 080º 25' 57.2"; 10 m high, 20 m long.
Outcrop strike/dip: 187º/77º W
Fracture set one (bedding planes) ("FS1") strike/dip: 262º/24º S
Fracture set two ("FS2") strike/dip: 201º/84º NW

Fig. A1.1 Outcrop of Upper Member of Price Formation on East side of Huckleberry Trail. Rock hammer at bottom left for scale (~30cm).

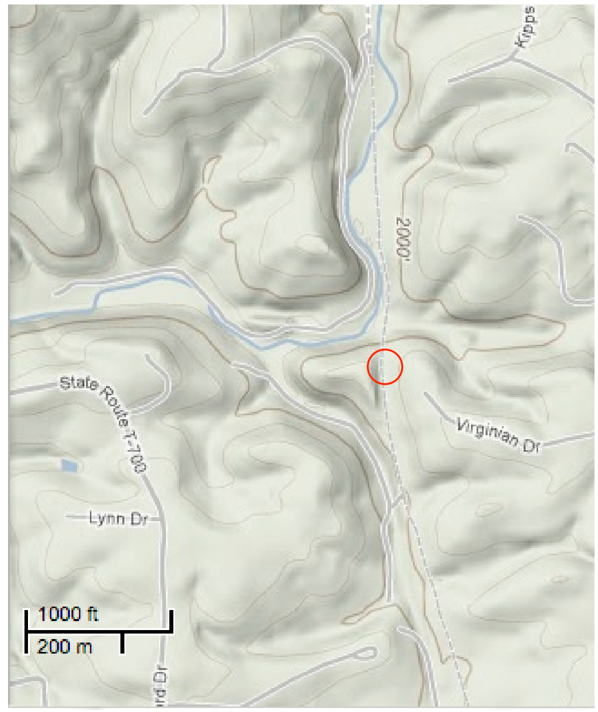

Fig. A1.2 Location of Price Formation outcrop at red circle.

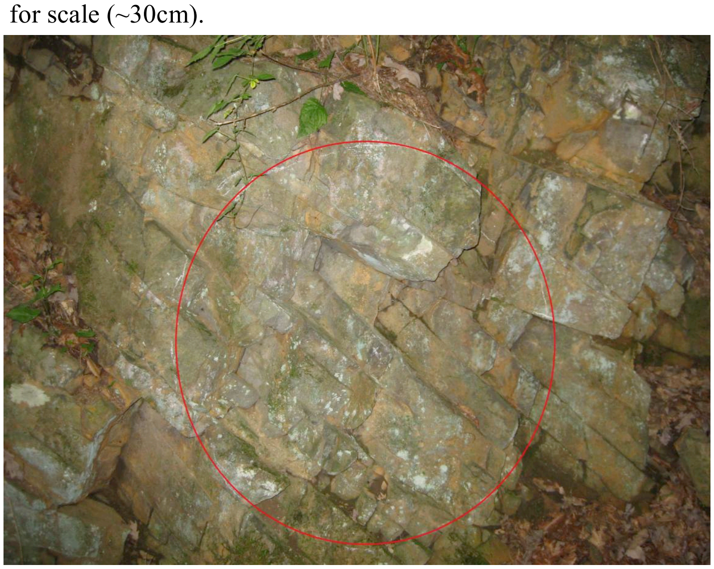

Fig. A1.3 Circular window/scanline on Upper Member of Price Formation. Red circle outlining chalk circle is 110cm in diameter.

Price	ISR (Schmidt rebound)	Weathering	Joint Space Mean (m)	Joint Space Wtd Avg (m)	Joint Dip & Orientation	Joint Width Mean (mm)	Joint Width Wtd Avg (mm)	Continuity/Infill Mean	Groundwater	Mean Total	Wtd Avg Total
mean	45	moderate	1.2	0.4	87º out of slope	8.8	3.9	Continuous/thick or no infill	trace		
median	46.5	moderate	0.9	0.1	87º out of slope	10.8	0.6	Continuous/thick or no infill	trace		
score mean	*14*	*7*	*25*	*18*	*5*	*4*	*5*	*3*	*5*	**63**	**57**
score median	*15*	*7*	*23*	*14*	*5*	*4*	*6*	*3*	*5*	**62**	**55**

Table A1.1 Scoring summary of each parameter and score totals for RMS in the Price Formation. Mean and median rows represent whether the mean or median of raw data was used. Columns that indicate mean or weighted average (“Wtd Avg”) are describing whether data from multiple joint sets was simply averaged together, or whether a weighted average was taken based on the number of joints observed in the window studied.

Price	Kidy. (MPa)	Kahr. (MPa)	Tot RQD	RQD mult	Joint Space (m)	Persistence (m)	Aperture (mm)	Rough	Infill	Weather-ing	Ground-water	Joint adjust.	Excav. adjust.	Totals-Kahr-total RQD	Totals-Kidy-total RQD	Totals-Kahr-RQD mult	Totals-Kidy-RQD mult
mean	44	33.7	0.97	0.9	0.4	3.98	3.93	slightly	Thick hard/ thin soft	moderate	damp/ dry	FS 2, planar	Blasting or mech.				
med.	47.1	35.5	0.97	0.9	0.13	14.1	0.55	slightly	Thick hard/ thin soft	moderate	damp/ dry	FS 2, planar	Blasting or mech.				
score mean	*4*	*4*	*20*	*20*	*10*	*2*	*1*	*4*	*3*	*3*	*13*	*-4.2*	*0*	**55.8**	**55.8**	**55.8**	**55.8**
score med.	*4*	*4*	*20*	*20*	*15*	*1*	*4*	*4*	*3*	*3*	*13*	*-4.2*	*0*	**62.8**	**62.8**	**62.8**	**62.8**

Table A1.2 Scoring summary of each parameter and score totals for SMR in the Price Formation. RMR can be found by removing the Joint Orientation Adjustment (“Joint adjust.”) and Excavation Adjustment (“Excav. adjust.”) from the total score.

Fracture Set	Joint Spacing (m)	Aperture (mm)	Continuity/Infill	Number of Fractures in Window
FS 1 (bedding) (mean/median)	0.15 / 0.13	0.55 / 0.55	Continuous/none	35
FS 2 (mean/median)	2.26 / 1.7	17.1 / 21	Continuous/thick	8

Table A1.3 Selected data by fracture set. The mean or median of raw data is reported as “mean / median.”

Major Elements (Normalized)	**Sandstone Sample (Weight %)**	**Siltstone Sample (Weight %)**
SiO2	83.54	56.16
TiO2	0.567	1.036
Al2O3	9.03	19.00
FeO	2.71	8.96
MnO	0.019	0.307
MgO	0.86	4.29
CaO	0.14	5.11
Na2O	1.64	0.83
K2O	1.41	4.17
P2O5	0.072	0.125
Trace Elements (Unnormalized)	**Sandstone Sample (ppm)**	**Siltstone Sample (ppm)**
Ni	18	38
Cr	32	74
Sc	8	19
V	54	138
Ba	169	508
Rb	44	143
Sr	46	105
Zr	219	164
Y	20	45
Nb	9.2	16.9
Ga	10	21
Cu	5	37
Zn	37	88
Pb	5	9
La	23	49
Ce	47	98
Th	7	13
Nd	22	46
Cs (+/- 5 ppm)	0	5
As (minimum value)	15	9

Table A1.4 XRF/LOI data for Upper Price units studied.

Major Elements (Normalized)	**Shale Sample (Weight %)**
SiO2	58.39
TiO2	1.091
Al2O3	22.51
FeO	8.64
MnO	0.063
MgO	2.53
CaO	0.27
Na2O	1.16
K2O	5.17
P2O5	0.178
Trace Elements (Unnormalized)	**Shale Sample (ppm)**
Ni	44
Cr	86
Sc	20
V	147
Ba	789
Rb	179
Sr	86
Zr	180
Y	41
Nb	20.7
Ga	32
Cu	31
Zn	129
Pb	9
La	42
Ce	96
Th	15
Nd	45
Cs (+/- 5 ppm)	5
As (minimum value)	2

Table A1.5 Additional XRF/LOI data for Upper Price shale unit that was not included within the study window.

Appendix A2: Tuscarora Formation

Measured November 2010. Massive and blocky, fine- to coarse-grained sandstone with 2 intersecting fracture sets.
Northwest side of Cascades Trail (upper arm), Pembroke, VA. Natural outcrop.
Window studied: N 37º 21' 51.0" W 080º 34' 46.7"; 24 m high, 15 m long.
Outcrop strike/dip: 090º/85º S
Fracture set one (bedding planes) ("FS1") strike/dip: 227º/13º E
Fracture set two ("FS2") strike/dip: 090º/85º S

Fig. A2.1 Outcrop of Tuscarora Formation on Northwest side of Cascades trail (upper branch of trail). Note scale bar.

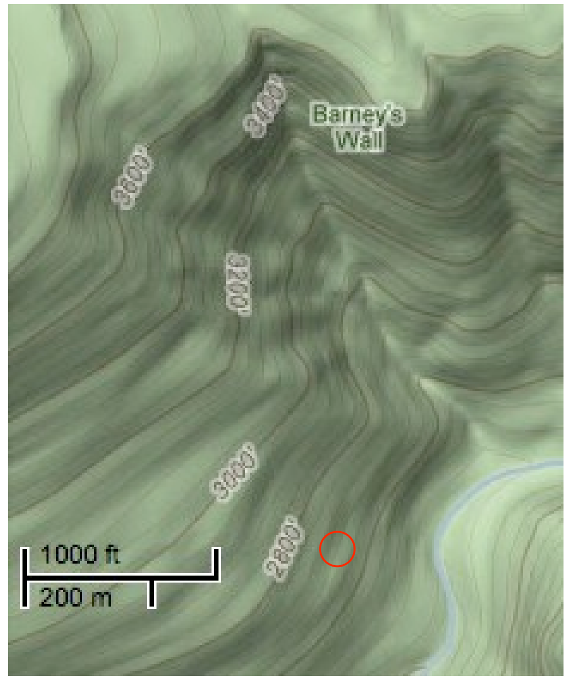

Fig. A2.2 Approximate location of Tuscarora Formation outcrop at red circle.

Fig. A2.3 Circular window/scanline on Tuscarora Formation. Chalk circle on left edge of photo is 110cm in diameter.

Tusca-rora	*ISR (Schmidt rebound)*	*Weathering*	*Joint Space Mean (m)*	*Joint Space Wtd Avg (m)*	*Joint Dip & Orientation*	*Joint Width Mean (mm)*	*Joint Width Wtd Avg (mm)*	*Continuity/Infill Mean*	*Groundwater*	**Mean Total**	**Wtd Avg Total**
mean	58.1	slight	2.125	1.38	13° perpendicular to slope	17.775	7.21	Continuous/no infill	none		
median	59	slight	2	1	13° perpendicular to slope	17.775	0.55	Continuous/no infill	none		
score mean	*19*	*9*	*28*	*25*	*14*	*4*	*4*	*5*	*6*	**85**	**82**
score median	*19*	*9*	*28*	*23*	*14*	*4*	*6*	*5*	*6*	**85**	**82**

Table A2.1 Scoring summary of each parameter and score totals for RMS in the Tuscarora Formation. Mean and median rows represent whether the mean or median of raw data was used. Columns that indicate mean or weighted average ("Wtd Avg") are describing whether data from multiple joint sets was simply averaged together, or whether a weighted average was taken based on the number of joints observed in the window studied.

Tusca-rora	*Kidy. (MPa)*	*Kahr. (MPa)*	*Tot RQD*	*RQD mult*	*Joint Space (m)*	*Persistence (m)*	*Aperture (mm)*	*Rough*	*Infill*	*Weather-ing*	*Ground-water*	*Joint adjust.*	*Excav. adjust.*	**Totals-Kahr-tot RQD**	**Totals-Kidy-tot RQD**	**Totals-Kahr-RQD mult**	**Totals-Kidy-RQD mult**
mean	79.4	53.3	1	1	1.38	1.7	7.21	rough	none	slight	dry	FS 1, planar	Natural				
median	82.7	55	1	1	1	2.02	0.55	rough	none	slight	dry	FS 1, planar	Natural				
score mean	*7*	*7*	*20*	*20*	*15*	*4*	*0*	*5*	*6*	*5*	*15*	*-1.35*	*15*	**90.65**	**90.65**	**90.65**	**90.65**
score median	*7*	*7*	*20*	*20*	*15*	*4*	*4*	*5*	*6*	*5*	*15*	*-1.35*	*15*	**94.65**	**94.65**	**94.65**	**94.65**

Table A2.2 Scoring summary of each parameter and score totals for SMR in the Tuscarora Formation. RMR can be found by removing the Joint Orientation Adjustment ("Joint adjust.") and Excavation Adjustment ("Excav. adjust.") from the total score.

Fracture Set	**Joint Spacing (m)**	**Aperture (mm)**	**Continuity/Infill**	**Number of Fractures in Window**
FS 1 (bedding) (mean/median)	1 / 1	0.55 / 0.55	Continuous/none	24
FS 2 (mean/median)	3.25 / 3	35 / 35	Continuous/none	5

Table A2.3 Selected data by fracture set. The mean or median of raw data is reported as "mean / median."

Major Elements (Normalized)	Sandstone Sample (Weight %)
SiO2	98.44
TiO2	0.214
Al2O3	0.97
FeO	0.09
MnO	0.002
MgO	0.02
CaO	0.02
Na2O	0.00
K2O	0.25
P2O5	0.008
Trace Elements (Unnormalized)	**Sandstone Sample (ppm)**
Ni	0
Cr	9
Sc	1
V	8
Ba	23
Rb	5
Sr	7
Zr	317
Y	8
Nb	4.9
Ga	1
Cu	0
Zn	0
Pb	1
La	8
Ce	9
Th	2
Nd	4
Cs (+/- 5 ppm)	0
As (minimum value)	3

Table A2.4 XRF/LOI data for Tuscarora unit studied.

<u>Appendix A3: Rose Hill Formation</u>

Measured November 2010. Blocky, coarse-grained siltstone with 2 intersecting fracture sets.
North side of Cascades Trail (upper branch of trail), Pembroke, VA. Natural outcrop.
Window studied: N 37º 21' 52.2" W 080º 34' 41.7"; 5 m high, 15 m long.
Outcrop strike/dip: 090º/85º S
Fracture set one (bedding planes) ("FS1") strike/dip: 145º/19º NE
Fracture set two ("FS2") strike/dip: 180º/85º W

Fig. A3.1 Outcrop of Rose Hill Formation on North side of Cascades trail (upper branch of trail). White card resting on outcrop is ~15 cm.

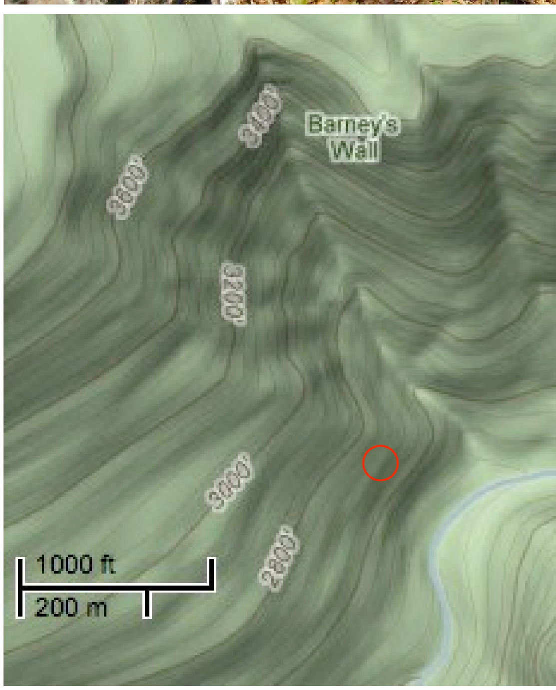

Fig. A3.2 Approximate location of Rose Hill Formation outcrop at red circle.

Fig. A3.3 Close-up of Rose Hill Formation. White card resting on outcrop is ~15 cm.

Rose Hill	ISR (Schmidt rebound)	Weathering	Joint Space Mean (m)	Joint Space Wtd Avg (m)	Joint Dip & Orientation	Joint Width Mean (mm)	Joint Width Wtd Avg (mm)	Continuity/Infill Mean	Groundwater	Mean Total	Wtd Avg Total
mean	54.9	moderate-high	2.1	0.45	19° perpendicular to slope	12	4.8	Continuous/thick or no infill	none		
median	55	moderate-high	2.06	0.12	19° perpendicular to slope	12	3	Continuous/thick or no infill	none		
score mean	*18*	*6*	*28*	*19*	*14*	*4*	*5*	*3*	*6*	**79**	**71**
score median	*18*	*6*	*28*	*14*	*14*	*4*	*5*	*3*	*6*	**79**	**66**

Table A3.1 Scoring summary of each parameter and score totals for RMS in the Rose Hill Formation. Mean and median rows represent whether the mean or median of raw data was used. Columns that indicate mean or weighted average ("Wtd Avg") are describing whether data from multiple joint sets was simply averaged together, or whether a weighted average was taken based on the number of joints observed in the window studied.

Rose Hill	Kidy. (MPa)	Kahr. (MPa)	Tot RQD	RQD mult	Joint Space (m)	Persistence (m)	Aperture (mm)	Rough	Infill	Weather-ing	Ground-water	Joint adjust.	Excav. adjust.	Totals-Kahr-tot RQD	Totals-Kidy-tot RQD	Totals-Kahr-RQD mult	Totals-Kidy-RQD mult
mean	68.7	47.6	0.996	0.98	0.45	5.7	4.8	rough	thick hard/ thin soft	moderate-high	none	FS 1, planar	Natural				
median	69	47.8	0.996	0.98	0.12	5.7	3	rough	thick hard/ thin soft	moderate-high	none	FS 1, planar	Natural				
score mean	*7*	*4*	*20*	*20*	*10*	*2*	*1*	*5*	*3*	*2*	*15*	*-1.35*	*15*	**75.65**	**78.65**	**75.65**	**78.65**
score median	*7*	*4*	*20*	*20*	*8*	*2*	*1*	*5*	*3*	*2*	*15*	*-1.35*	*15*	**73.65**	**76.65**	**73.65**	**76.65**

Table A3.2 Scoring summary of each parameter and score totals for SMR in the Rose Hill Formation. RMR can be found by removing the Joint Orientation Adjustment ("Joint adjust.") and Excavation Adjustment ("Excav. adjust.") from the total score.

Fracture Set	Joint Spacing (m)	Aperture (mm)	Continuity/Infill	Number of Fractures in Window
FS 1 (bedding) (mean/median)	0.12 / 0.12	3 / 3	Continuous/none	35
FS 2 (mean/median)	4.1 / 4	21 / 21	Continuous/thick	3

Table A3.3 Selected data by fracture set. The mean or median of raw data is reported as "mean / median."

Major Elements (Normalized)	Siltstone Sample (Weight %)
SiO2	84.14
TiO2	0.313
Al2O3	2.70
FeO	11.23
MnO	0.005
MgO	0.22
CaO	0.41
Na2O	0.01
K2O	0.57
P2O5	0.387
Trace Elements (Unnormalized)	**Siltstone Sample (ppm)**
Ni	7
Cr	29
Sc	7
V	57
Ba	50
Rb	18
Sr	118
Zr	458
Y	47
Nb	8.7
Ga	4
Cu	1
Zn	6
Pb	2
La	38
Ce	111
Th	9
Nd	52
Cs (+/- 5 ppm)	1
As (minimum value)	0

Table A3.4 XRF/LOI data for Rose Hill unit studied.

Appendix A4: Juniata Formation

Measured November 2010. Bedded medium-grained siltstone.
East side of Cove Road, Wytheville, VA. Road cut excavated most likely in the mid- to late-1900s.
Window studied: N 36º 59' 31.75" W 081º 04' 38.85"; 50 m high, 30 m long.
Outcrop strike/dip: 150º/70º SW
Fracture set one (bedding planes) ("FS1") strike/dip: 273º/45º S

Fig. A4.1 Outcrop of Juniata Formation on East side of Cove Road. Fence is approximately 3 m tall.

Fig. A4.2 Approximate location of Juniata Formation outcrop at red circle.

Fig. A4.3 Close-up of Juniata Formation. Note rock hammer at bottom left for scale (~30cm).

Juniata	ISR (Schmidt rebound)	Weathering	Joint Space Mean (m)	Joint Space Wtd Avg (m)	Joint Dip & Orientation	Joint Width Mean (mm)	Joint Width Wtd Avg (mm)	Continuity/Infill Mean	Groundwater	Mean Total	Wtd Avg Total
mean	52.4	slight-moderate	0.35	0.35	34° out of slope	3	3	Continuous/thin infill	trace		
median	53	slight-moderate	0.35	0.35	34° out of slope	3	3	Continuous/thin infill	trace		
score mean	*17*	*8*	*18*	*18*	*5*	*5*	*5*	*4*	*5*	**62**	**62**
score median	*18*	*8*	*18*	*18*	*5*	*5*	*5*	*4*	*5*	**63**	**63**

Table A4.1 Scoring summary of each parameter and score totals for RMS in the Juniata Formation. Mean and median rows represent whether the mean or median of raw data was used. Columns that indicate mean or weighted average ("Wtd Avg") are describing whether data from multiple joint sets was simply averaged together, or whether a weighted average was taken based on the number of joints observed in the window studied.

Juniata	Kidy. (MPa)	Kahr. (MPa)	Tot RQD	RQD mult	Joint Space (m)	Persistence (m)	Aperture (mm)	Rough	Infill	Weather-ing	Ground-water	Joint adjust.	Excav. adjust.	Totals-Kahr-tot RQD	Totals-Kidy-tot RQD	Totals-Kahr-RQD mult	Totals-Kidy-RQD mult
mean	61.4	43.6	1	1	0.35	infinite	3	rough	Thick hard/ thin soft	slight-moderate	damp	FS 1, planar	smooth blasting				
median	63.1	44.6	1	1	0.35	infinite	3	rough	Thick hard/ thin soft	slight-moderate	damp	FS 1, planar	smooth blasting				
score mean	*7*	*4*	*20*	*20*	*10*	*0*	*1*	*5*	*3*	*4*	*10*	*-7.65*	*8*	**57.35**	**60.35**	**57.35**	**60.35**
score median	*7*	*4*	*20*	*20*	*10*	*0*	*1*	*5*	*3*	*4*	*10*	*-7.65*	*8*	**57.35**	**60.35**	**57.35**	**60.35**

Table A4.2 Scoring summary of each parameter and score totals for SMR in the Juniata Formation. RMR can be found by removing the Joint Orientation Adjustment ("Joint adjust.") and Excavation Adjustment ("Excav. adjust.") from the total score.

Fracture Set	Joint Spacing (m)	Aperture (mm)	Continuity/Infill	Number of Fractures in Window
FS 1 (bedding) (mean/median)	0.35 / 0.35	3 / 3	Continuous/thin	150

Table A4.3 Selected data by fracture set. The mean or median of raw data is reported as "mean / median."

Major Elements (Normalized)	Siltstone Sample 1 (Weight %)	Siltstone Sample 2 (Weight %)
SiO2	83.49	90.51
TiO2	0.701	0.344
Al2O3	8.04	5.27
FeO	3.34	1.04
MnO	0.024	0.009
MgO	0.71	0.33
CaO	0.17	0.06
Na2O	1.35	1.09
K2O	2.08	1.32
P2O5	0.080	0.026
Trace Elements (Unnormalized)	**Siltstone Sample 1 (ppm)**	**Siltstone Sample 2 (ppm)**
Ni	11	6
Cr	25	13
Sc	5	2
V	39	16
Ba	551	194
Rb	58	31
Sr	62	51
Zr	446	328
Y	28	13
Nb	12.7	6.8
Ga	8	6
Cu	13	2
Zn	32	19
Pb	7	4
La	24	11
Ce	49	22
Th	9	5
Nd	23	10
Cs (+/- 5 ppm)	2	1
As (minimum value)	1	2

Table A4.4 XRF/LOI data for Juniata unit studied.

Appendix A5: Clinch Formation

Measured November 2010. Bedded medium- to coarse-grained sandstone.
East side of Cove Road, Wytheville, VA. Road cut excavated most likely in the mid- to late-1900s.
Window studied: N 36º 59' 31.75" W 081º 04' 38.85"; 60 m high, 30 m long.
Outcrop strike/dip: 150º/70º SW
Fracture set one (bedding planes) ("FS1") strike/dip: 255º/45º S

Fig. A5.1 Lighter colored rock is outcrop of Clinch Formation on East side of Cove Road. Fence at bottom is approximately 3 m tall with 2 m spacing between poles.

Fig. A5.2 Approximate location of Clinch Formation outcrop at red circle.

Fig. A5.3 Close-up of Clinch Formation. Note rock hammer at bottom left for scale (~30cm).

Clinch	ISR (Schmidt rebound	Weathering	Joint Space Mean (m)	Joint Space Wtd Avg (m)	Joint Dip & Orientation	Joint Width Mean (mm)	Joint Width Wtd Avg (mm)	Continuity/Infill Mean	Groundwater	Mean Total	Wtd Avg Total
mean	58	slight	0.35	0.35	20° out of slope	0.55	0.55	continuous/no infill	none		
median	60	slight	0.35	0.35	20° out of slope	0.55	0.55	continuous/no infill	none		
score mean	*19*	*9*	*18*	*18*	*9*	*6*	*6*	*5*	*6*	**72**	**72**
score median	*19*	*9*	*18*	*18*	*9*	*6*	*6*	*5*	*6*	**72**	**72**

Table A5.1 Scoring summary of each parameter and score totals for RMS in the Clinch Formation. Mean and median rows represent whether the mean or median of raw data was used. Columns that indicate mean or weighted average ("Wtd Avg") are describing whether data from multiple joint sets was simply averaged together, or whether a weighted average was taken based on the number of joints observed in the window studied.

Clinch	Kidy. (MPa)	Kahr. (MPa)	Tot RQD	RQD mult	Joint Space (m)	Persistence (m)	Aperture (mm)	Rough	Infill	Weathering	Groundwater	Joint adjust.	Excav. adjust.	Totals-Kahr-total RQD	Totals-Kidy-total RQD	Totals-Kahr-RQD mult	Totals-Kidy-RQD mult
mean	79.0	53.1	1	1	0.35	12.1	0.55	slightly	none	slight	dry	FS 1, planar	smooth blasting				
median	86.5	56.9	1	1	0.35	12.1	0.55	slightly	none	slight	dry	FS 1, planar	smooth blasting				
score mean	*7*	*7*	*20*	*20*	*10*	*1*	*4*	*4*	*6*	*5*	*15*	*-7.65*	*8*	**72.35**	**72.35**	**72.35**	**72.35**
score median	*7*	*7*	*20*	*20*	*10*	*1*	*4*	*4*	*6*	*5*	*15*	*-7.65*	*8*	**72.35**	**72.35**	**72.35**	**72.35**

Table A5.2 Scoring summary of each parameter and score totals for SMR in the Clinch Formation. RMR can be found by removing the Joint Orientation Adjustment ("Joint adjust.") and Excavation Adjustment ("Excav. adjust.") from the total score.

Fracture Set	Joint Spacing (m)	Aperture (mm)	Continuity/Infill	Number of Fractures in Window
FS 1 (bedding) (mean/median)	0.35 / 0.35	0.55 / 0.55	Continuous/none	150

Table A5.3 Selected data by fracture set. The mean or median of raw data is reported as "mean / median."

Appendix A6: Huntersville Formation

Measured November 2010. Massive black chert.
East side of Cove Road, Wytheville, VA. Road cut excavated most likely in the mid- to late-1900s.
Window studied: N 36º 59' 31.75" W 081º 04' 38.85"; 10-60 m high, 20 m long.
Outcrop strike/dip: 150º/70º SW
Fracture set one (bedding planes) ("FS1") strike/dip: 268º/48º S
Fracture set two ("FS2") strike/dip: (fractures too high to measure strike)/48º N

Fig. A6.1 Outcrop of Huntersville Formation on East side of Cove Road.

Fig. A6.2 Approximate location of Huntersville Formation outcrop at red circle.

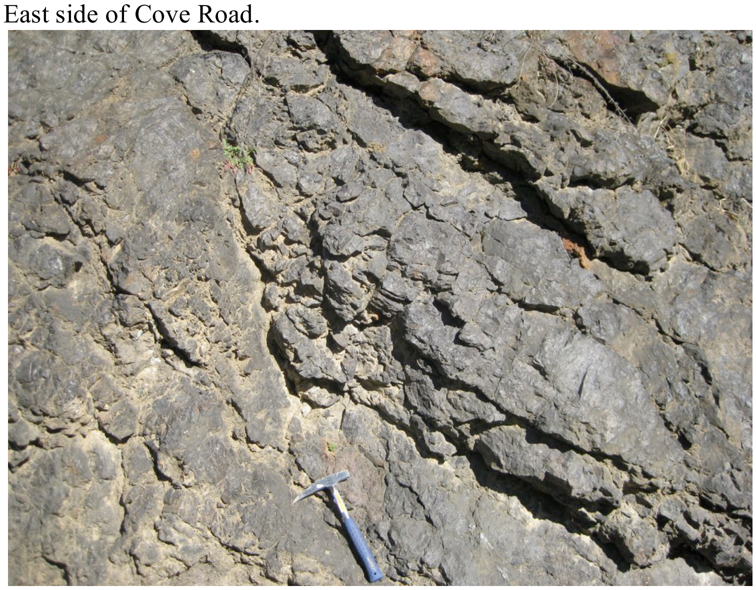

Fig. A6.3 Close-up of Huntersville Formation. Note rock hammer at bottom for scale (~30cm).

Hunters-ville	ISR (Schmidt rebound)	Weathering	Joint Space Mean (m)	Joint Space Wtd Avg (m)	Joint Dip & Orientation	Joint Width Mean (mm)	Joint Width Wtd Avg (mm)	Continuity/Infill Mean	Groundwater	Mean Total	Wtd Avg Total
mean	54	moderate	5.75	7.16	15° out of slope	12.5	12.5	Continuous/thick infill	trace		
median	54	moderate	5.75	10	15° out of slope	12.5	12.5	Continuous/thick infill	trace		
score mean	*18*	*7*	*30*	*30*	*9*	*4*	*4*	*1*	*5*	**74**	**74**
score median	*18*	*7*	*30*	*30*	*9*	*4*	*4*	*1*	*5*	**74**	**74**

Table A6.1 Scoring summary of each parameter and score totals for RMS in the Huntersville Formation. Mean and median rows represent whether the mean or median of raw data was used. Columns that indicate mean or weighted average ("Wtd Avg") are describing whether data from multiple joint sets was simply averaged together, or whether a weighted average was taken based on the number of joints observed in the window studied.

Hunters-ville	Kidy. (MPa)	Kahr. (MPa)	Tot RQD	RQD mult	Joint Space (m)	Persistence (m)	Aperture (mm)	Rough	Infill	Weather-ing	Ground-water	Joint adjust.	Excav. adjust.	Totals-Kahr-tot RQD	Totals-Kidy-tot RQD	Totals-Kahr-RQD mult	Totals-Kidy-RQD mult
mean	76.7	51.7	1	1	7.16	5.6	12.5	rough	Thick hard/ thin soft	moderate	damp	FS 1, planar	smooth blasting				
median	76.7	51.7	1	1	10	5.6	12.5	rough	Thick hard/ thin soft	moderate	damp	FS 1, planar	smooth blasting				
score mean	*7*	*7*	*20*	*20*	*20*	*2*	*0*	*5*	*3*	*3*	*10*	*-9*	*8*	**69**	**69**	**69**	**69**
score median	*7*	*7*	*20*	*20*	*20*	*2*	*0*	*5*	*3*	*3*	*10*	*-9*	*8*	**69**	**69**	**69**	**69**

Table A6.2 Scoring summary of each parameter and score totals for SMR in the Huntersville Formation. RMR can be found by removing the Joint Orientation Adjustment ("Joint adjust.") and Excavation Adjustment ("Excav. adjust.") from the total score.

Fracture Set	Joint Spacing (m)	Aperture (mm)	Continuity/Infill	Number of Fractures in Window
FS 1 (bedding) (mean/median)	10 / 10	12.5 / 12.5	Continuous/thick	3
FS 2 (mean/median)	1.5 / 1.5	12.5 / 12.5	Continuous/thick	2

Table A6.3 Selected data by fracture set. The mean or median of raw data is reported as "mean / median."

Major Elements (Normalized)	Chert Sample 1 (Weight %)
SiO2	91.69
TiO2	0.067
Al2O3	1.45
FeO	1.18
MnO	0.191
MgO	0.59
CaO	4.28
Na2O	0.08
K2O	0.37
P2O5	0.105
Trace Elements (Unnormalized)	**Chert Sample 1 (ppm)**
Ni	4
Cr	10
Sc	3
V	16
Ba	51
Rb	10
Sr	48
Zr	20
Y	11
Nb	1.3
Ga	2
Cu	2
Zn	368
Pb	8
La	11
Ce	16
Th	0
Nd	10
Cs (+/- 5 ppm)	1
As (minimum value)	0

Table A6.4 XRF/LOI data for Huntersville unit studied.

<u>Appendix A7: Millboro Formation</u>

Measured November 2010. Weathered, finely bedded, blocky, black shale.
East side of Cove Road, Wytheville, VA. Road cut excavated most likely in the mid- to late-1900s.
Window studied: N 36º 59' 31.75" W 081º 04' 38.85"; 10-20 m high, 10 m long.
Outcrop strike/dip: 150º/70º SW
Fracture set one (bedding planes) ("FS1") strike/dip: 265º/40º S
Fracture set two ("FS2") strike/dip: 265/40º N

Fig. A7.1 Outcrop of Millboro Formation on East side of Cove Road.

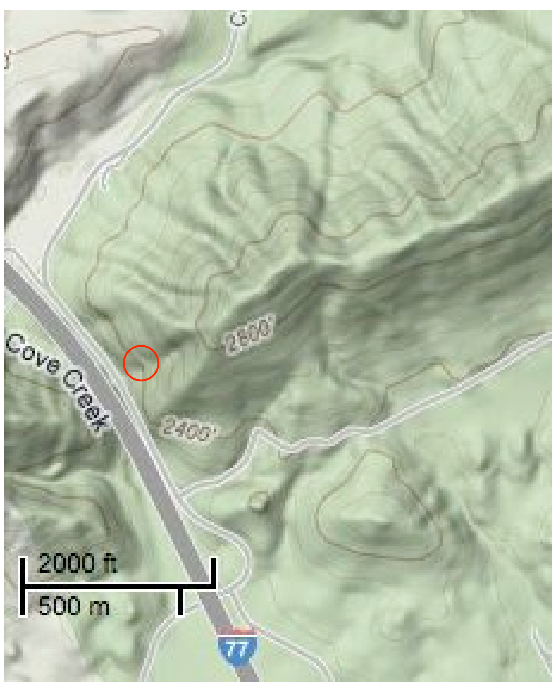

Fig. A7.2 Approximate location of Millboro Formation outcrop at red circle.

Fig. A7.3 Close-up of Millboro Formation. Note rock hammer at bottom for scale (~30cm).

Millboro	ISR (Schmidt rebound)	Weathering	Joint Space Mean (m)	Joint Space Wtd Avg (m)	Joint Dip & Orientation	Joint Width Mean (mm)	Joint Width Wtd Avg (mm)	Continuity/Infill Mean	Groundwater	Mean Total	Wtd Avg Total
mean	12	moderate-high	0.12	0.08	15º out of slope	0.55	0.55	Continuous/no infill	none		
median	11	moderate-high	0.12	0.04	15º out of slope	0.55	0.55	Continuous/no infill	none		
score mean	*5*	*6*	*14*	*13*	*9*	*6*	*6*	*5*	*6*	**51**	**50**
score median	*5*	*6*	*14*	*11*	*9*	*6*	*6*	*5*	*6*	**51**	**48**

Table A7.1 Scoring summary of each parameter and score totals for RMS in the Millboro Formation. Mean and median rows represent whether the mean or median of raw data was used. Columns that indicate mean or weighted average ("Wtd Avg") are describing whether data from multiple joint sets was simply averaged together, or whether a weighted average was taken based on the number of joints observed in the window studied.

Millboro	Kidy. (MPa)	Kahr. (MPa)	Tot RQD	RQD mult	Joint Space (m)	Persistence (m)	Aperture (mm)	Rough	Infill	Weathering	Groundwater	Joint adjust.	Excav. adjust.	Totals-Kahr-tot RQD	Totals-Kidy-tot RQD	Totals-Kahr-RQD mult	Totals-Kidy-RQD mult
mean	11.0	10.8	0.64	0.29	0.08	8.9	0.55	smooth	none	moderate-high	none	FS 1, planar	smooth blasting				
median	10.5	10.4	0.64	0.29	0.04	8.9	0.55	smooth	none	moderate-high	none	FS 1, planar	smooth blasting				
score mean	*2*	*2*	*13*	*8*	*8*	*2*	*4*	*1*	*6*	*2*	*15*	*-7.65*	*8*	**53.35**	**53.35**	**48.35**	**48.35**
score median	*2*	*2*	*13*	*8*	*5*	*2*	*4*	*1*	*6*	*2*	*15*	*-7.65*	*8*	**50.35**	**50.35**	**45.35**	**45.35**

Table A7.2 Scoring summary of each parameter and score totals for SMR in the Millboro Formation. RMR can be found by removing the Joint Orientation Adjustment ("Joint adjust.") and Excavation Adjustment ("Excav. adjust.") from the total score.

Fracture Set	Joint Spacing (m)	Aperture (mm)	Continuity/Infill	Number of Fractures in Window
FS 1 (bedding) (mean/median)	0.04 / 0.04	0.55 / 0.55	Continuous/none	2-3 times as many as FS 2 (too many to count)
FS 2 (mean/median)	0.2 / 0.2	0.55 / 0.55	Continuous/none	1/3-1/2 as many as FS 1 (too many to count)

Table A7.3 Selected data by fracture set. The mean or median of raw data is reported as "mean / median."

Major Elements (Normalized)	Chert Sample 1 (Weight %)
SiO2	77.51
TiO2	0.820
Al2O3	14.03
FeO	1.65
MnO	0.004
MgO	0.72
CaO	0.02
Na2O	0.23
K2O	4.98
P2O5	0.042
Trace Elements (Unnormalized)	**Chert Sample 1 (ppm)**
Ni	11
Cr	73
Sc	15
V	172
Ba	597
Rb	145
Sr	55
Zr	166
Y	29
Nb	14.3
Ga	18
Cu	27
Zn	21
Pb	63
La	39
Ce	69
Th	10
Nd	34
Cs (+/- 5 ppm)	6
As (minimum value)	8

Table A7.4 XRF/LOI data for Millboro unit studied.

Appendix A8: Knox Group: North Cut

Measured February 2011. Dolostone with 0.1-3 cm calcite nodules.
North cut of Hokie Stone Quarry, Blacksburg, VA. Contemporary excavation.
Window studied: N 37º 13' 28" W 080º 23' 05"; 6 m high, 20 m long.
Outcrop strike/dip: 090º/90º S
Fracture set one (bedding planes) ("FS1") strike/dip: 168º/20º NE
Fracture set two ("FS2") strike/dip: 078/85º SE

Fig. A8.1 Outcrop of Knox Group Formation on the North cut of the Hokie Stone Quarry. Note red scale bar.

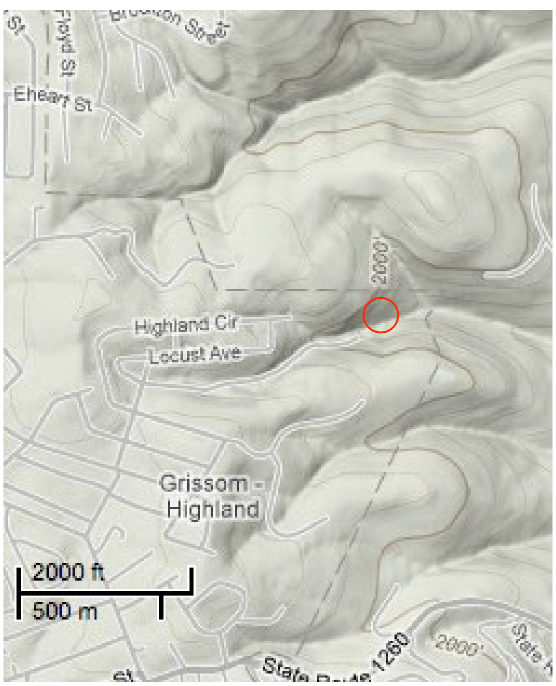

Fig. A8.2 Approximate location of Knox Formation outcrop at red circle.

Fig. A8.3 Close-up of Knox Formation.

Knox Group-North	ISR (Schmidt rebound)	Weathering	Joint Space Mean (m)	Joint Space Wtd Avg (m)	Joint Dip & Orientation	Joint Width Mean (mm)	Joint Width Wtd Avg (mm)	Continuity/Infill Mean	Groundwater	Mean Total	Wtd Avg Total
mean	56	slight	8	1.66	0° out/in	1.5	2.67	Continuous/no infill	moderate		
median	56	slight	7.95	1	0° out/in	1.5	0.32	Continuous/no infill	moderate		
score mean	*18*	*9*	*30*	*27*	*14*	*5*	*5*	*5*	*3*	**84**	**81**
score median	*18*	*9*	*30*	*23*	*14*	*5*	*6*	*5*	*3*	**84**	**78**

Table A8.1 Scoring summary of each parameter and score totals for RMS in the Knox Formation. Mean and median rows represent whether the mean or median of raw data was used. Columns that indicate mean or weighted average ("Wtd Avg") are describing whether data from multiple joint sets was simply averaged together, or whether a weighted average was taken based on the number of joints observed in the window studied.

Knox Group-North	Kidy. (MPa)	Kahr. (MPa)	Tot RQD	RQD mult	Joint Space (m)	Persistence (m)	Aperture (mm)	Rough	Infill	Weather-ing	Ground-water	Joint adjust.	Excav. adjust.	Totals-Kahr-tot RQD	Totals-Kidy-tot RQD	Totals-Kahr-RQD mult	Totals-Kidy-RQD mult
mean	79.8	53.5	1	1	1.66	infinite	2.67	slightly	none	slight	wet	FS 1, planar	Blasting or mech.				
median	79.8	53.5	1	1	1	infinite	0.32	slightly	none	slight	wet	FS 1, planar	Blasting or mech.				
score mean	*7*	*7*	*20*	*20*	*15*	*0*	*1*	*3*	*6*	*5*	*7*	*-1.35*	*0*	**62.65**	**62.65**	**62.65**	**62.65**
score median	*7*	*7*	*20*	*20*	*15*	*0*	*4*	*3*	*6*	*5*	*7*	*-1.35*	*0*	**65.65**	**65.65**	**65.65**	**65.65**

Table A8.2 Scoring summary of each parameter and score totals for SMR in the Knox Formation. RMR can be found by removing the Joint Orientation Adjustment ("Joint adjust.") and Excavation Adjustment ("Excav. adjust.") from the total score.

Fracture Set	Joint Spacing (m)	Aperture (mm)	Continuity/Infill	Number of Fractures in Window
FS 1 (bedding) (mean/median)	0.98 / 0.9	0.43 / 0.32	Continuous/none	20
FS 2 (mean/median)	15 / 15	2.5 / 2.5	Few continuous	2

Table A8.3 Selected data by fracture set. The mean or median of raw data is reported as "mean / median."

Major Elements (Normalized)	Dolostone Sample 1 (Weight %)
SiO_2	17.03
TiO_2	0.108
Al_2O_3	2.52
FeO	1.14
MnO	0.019
MgO	31.31
CaO	46.04
Na_2O	0.03
K_2O	1.76
P_2O_5	0.040
Trace Elements (Unnormalized)	**Dolostone Sample 1 (ppm)**
Ni	4
Cr	10
Sc	0
V	14
Ba	39
Rb	13
Sr	62
Zr	16
Y	4
Nb	1.2
Ga	2
Cu	2
Zn	2
Pb	1
La	4
Ce	6
Th	1
Nd	6
Cs (+/- 5 ppm)	0
As (minimum value)	2

Table A8.4 XRF/LOI data for Knox units studied (only one sample used for the entire quarry).

<u>Appendix A9: Knox Group: South Cut</u>

Measured February 2011. Dolostone with 0.1-3 cm calcite nodules.
South cut of Hokie Stone Quarry, Blacksburg, VA. Contemporary excavation.
Window studied: N 37º 13' 28" W 080º 23' 05"; 6 m high, 30 m long.
Outcrop strike/dip: 090º/90º S
Fracture set one (bedding planes) ("FS1") strike/dip: 168º/20º NE
Fracture set two ("FS2") strike/dip: 078/85º SE

Fig. A9.1 Outcrop of Knox Group Formation on the South cut of the Hokie Stone Quarry. Note current excavation at far end of outcrop.

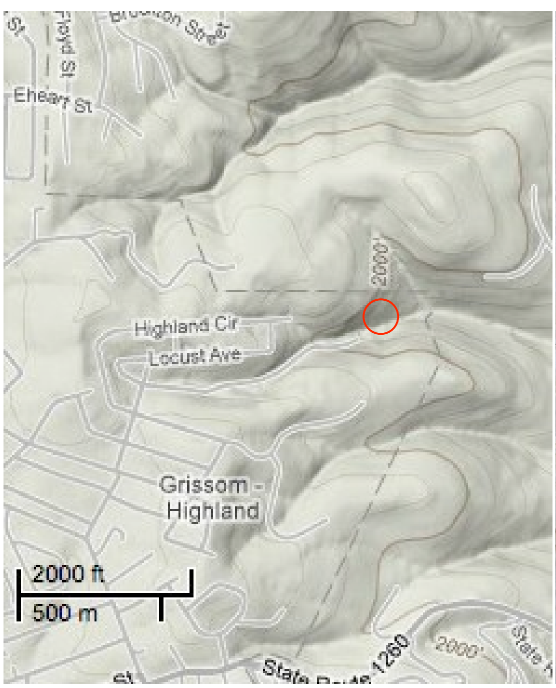

Fig. A9.2 Approximate location of Knox Formation outcrop at red circle.

Fig. A9.3 Close-up of Knox Formation on South cut. Note signs of dissolution and precipitation in upper end of fracture.

Knox Group-South	*ISR (Schmidt rebound)*	*Weathering*	*Joint Space Mean (m)*	*Joint Space Wtd Avg (m)*	*Joint Dip & Orientation*	*Joint Width Mean (mm)*	*Joint Width Wtd Avg (mm)*	*Continuity/Infill Mean*	*Groundwater*	**Mean Total**	**Wtd Avg Total**
mean	56	slight-moderate	15.75	3.54	0 out/in	2.02375	1.15	Continuous/no infill	Moderate		
median	57	slight-moderate	15.75	1.5	0 out/in	1.775	0.55	Continuous/no infill	Moderate		
score mean	*18*	*8*	*30*	*30*	*14*	*5*	*5*	*5*	*3*	**83**	**83**
score median	*19*	*8*	*30*	*26*	*14*	*5*	*6*	*5*	*3*	**84**	**81**

Table A9.1 Scoring summary of each parameter and score totals for RMS in the Knox Formation. Mean and median rows represent whether the mean or median of raw data was used. Columns that indicate mean or weighted average ("Wtd Avg") are describing whether data from multiple joint sets was simply averaged together, or whether a weighted average was taken based on the number of joints observed in the window studied.

Knox Group-South	*Kidy. (MPa)*	*Kahr. (MPa)*	*Tot RQD*	*RQD mult*	*Joint Space (m)*	*Persistence (m)*	*Aperture (mm)*	*Rough*	*Infill*	*Weather-ing*	*Ground-water*	*Joint adjust.*	*Excav. adjust.*	**Totals-Kahr-tot RQD**	**Totals-Kidy-tot RQD**	**Totals-Kahr-RQD mult**	**Totals-Kidy-RQD mult**
mean	79.8	53.5	1	1	3.54	infinite	1.15	slightly	thin/ hard	slight-moderate	wet	FS 1, planar	Blasting or mech.				
median	83.5	55.5	1	1	1.5	infinite	0.55	slightly	thin/ hard	slight-moderate	wet	FS 1, planar	Blasting or mech.				
score mean	*7*	*7*	*20*	*20*	*20*	*0*	*1*	*3*	*4*	*4*	*7*	*-3.6*	*0*	**62.4**	**62.4**	**62.4**	**62.4**
score median	*7*	*7*	*20*	*20*	*15*	*0*	*4*	*3*	*4*	*4*	*7*	*-3.6*	*0*	**60.4**	**60.4**	**60.4**	**60.4**

Table A9.2 Scoring summary of each parameter and score totals for SMR in the Knox Formation. RMR can be found by removing the Joint Orientation Adjustment ("Joint adjust.") and Excavation Adjustment ("Excav. adjust.") from the total score.

Fracture Set	**Joint Spacing (m)**	**Aperture (mm)**	**Continuity/Infill**	**Number of Fractures in Window**
FS 1 (bedding) (mean/median)	1.5 / 1.5	1.1 / 0.55	Continuous/thin	13
FS 2 (mean/median)	30 / 30	3 / 3	Few continuous	1

Table A9.3 Selected data by fracture set. The mean or median of raw data is reported as "mean / median."

Major Elements (Normalized)	Dolostone Sample 1 (Weight %)
SiO_2	17.03
TiO_2	0.108
Al_2O_3	2.52
FeO	1.14
MnO	0.019
MgO	31.31
CaO	46.04
Na_2O	0.03
K_2O	1.76
P_2O_5	0.040
Trace Elements (Unnormalized)	**Dolostone Sample 1 (ppm)**
Ni	4
Cr	10
Sc	0
V	14
Ba	39
Rb	13
Sr	62
Zr	16
Y	4
Nb	1.2
Ga	2
Cu	2
Zn	2
Pb	1
La	4
Ce	6
Th	1
Nd	6
Cs (+/- 5 ppm)	0
As (minimum value)	2

Table A9.4 XRF/LOI data for Knox units studied (only one sample used for the entire quarry).

Appendix A10: Rome Group: Northern Exposure
Measured May 2011. Bedded dolostone and fine-grained siltstone.
Approximately 70% dolostone, 30% siltstone.
East wall of 94S near Bishop Rd, Ivanhoe, VA. Road cut excavated most likely in the mid- to late-1900s.
Window studied: N 36º 51' 40.7" W 080º 58' 57.6"; 20 m high, 30 m long.
Outcrop strike/dip: 150º/85º SW
Fracture set one (bedding planes) ("FS1") strike/dip: 250º/50º SE

Fig. A10.1 Northern outcrop of Rome Group Formation on the East side of 94S.

Fig. A10.2 Approximate location of Rome Formation outcrop at red circle.

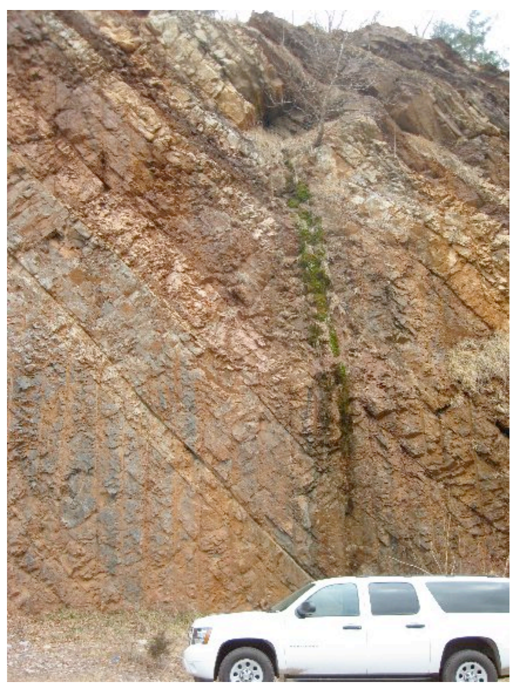

Fig. A10.3 Close-up of Rome Formation on North cut. Moss & algae correspond to a regular groundwater flow path.

Rome-North	ISR (Schmidt rebound)	Weathering	Joint Space Mean (m)	Joint Space Wtd Avg (m)	Joint Dip & Orientation	Joint Width Mean (mm)	Joint Width Wtd Avg (mm)	Continuity/Infill Mean	Groundwater	Mean Total	Wtd Avg Total
mean	57.5	slight	4.7684	2.708461538	50º into slope	41.3	1	Continuous/thick	great		
median	57	slight	3.8	0.6	50º into slope	15.5	1	Continuous/thick	great		
score mean	*19*	*9*	*30*	*29*	*20*	*2*	*5*	*1*	*1*	**82**	**84**
score median	*19*	*9*	*30*	*20*	*20*	*4*	*5*	*1*	*1*	**84**	**75**

Table A10.1 Scoring summary of each parameter and score totals for RMS in the Rome Formation. Mean and median rows represent whether the mean or median of raw data was used. Columns that indicate mean or weighted average (“Wtd Avg”) are describing whether data from multiple joint sets was simply averaged together, or whether a weighted average was taken based on the number of joints observed in the window studied.

Rome-North	Kidy. (MPa)	Kahr. (MPa)	Tot RQD	RQD mult	Joint Space (m)	Persistence (m)	Aperture (mm)	Rough	Infill	Weathering	Ground-water	Joint adjust.	Excav. adjust.	Totals-Kahr-total RQD	Totals-Kidy-total RQD	Totals-Kahr-RQD mult	Totals-Kidy-RQD mult
mean	85.4	56.5	0.94	0.78	0.21	2.36	1	Rough-slight	none	unweathered	flowing	FS 1, planar	smooth blasting				
median	83.5	55.5	0.94	0.78	0.17	2.36	1	Rough-slight	none	unweathered	flowing	FS 1, planar	smooth blasting				
score mean	*7*	*7*	*20*	*17*	*10*	*4*	*1*	*4*	*6*	*6*	*0*	*-9*	*8*	**57**	**57**	**54**	**54**
score median	*7*	*7*	*20*	*17*	*15*	*4*	*1*	*4*	*6*	*6*	*0*	*-9*	*8*	**62**	**62**	**59**	**59**

Table A10.2 Scoring summary of each parameter and score totals for SMR in the Rome Formation. RMR can be found by removing the Joint Orientation Adjustment (“Joint adjust.”) and Excavation Adjustment (“Excav. adjust.”) from the total score.

Fracture Set	Joint Spacing (m)	Aperture (mm)	Continuity/Infill	Number of Fractures in Window
FS 1 (bedding) (mean/median)	2.5 / 0.6	1 / 1	Continuous/thick	72
FS 2 (mean/median)	7 / 7	81.7 / 30	Continuous/thick	1

Table A10.3 Selected data by fracture set. The mean or median of raw data is reported as “mean / median.”

Major Elements (Normalized)	Dolostone Sample (Weight %)	Siltstone Sample (Weight %)
SiO_2	9.17	57.26
TiO_2	0.042	0.869
Al_2O_3	0.94	13.17
FeO	0.34	4.73
MnO	0.014	0.054
MgO	8.93	6.63
CaO	80.20	6.83
Na_2O	0.01	0.18
K_2O	0.33	9.71
P_2O_5	0.018	0.570
Trace Elements (Unnormalized)	**Dolostone Sample (ppm)**	**Siltstone Sample (ppm)**
Ni	6	25
Cr	5	39
Sc	0	10
V	7	62
Ba	26	572
Rb	7	123
Sr	276	117
Zr	4	282
Y	3	57
Nb	0.0	11.8
Ga	1	17
Cu	5	1
Zn	6	62
Pb	1	11
La	8	35
Ce	4	80
Th	2	8
Nd	0	39
Cs (+/- 5 ppm)	1	3
As (minimum value)	0	4

Table A10.4 XRF/LOI data for Rome units studied (samples not distinguished by Northern or Southern Exposure).

Appendix A11: Rome Group: Southern Exposure

Measured February 2011. Bedded dolostone and fine-grained siltstone.
Approximately 90% dolostone, 10% siltstone.
East wall of 94S near Bishop Rd, Ivanhoe, VA. Road cut excavated most likely in the mid- to late-1900s.
Window studied: N 36º 51' 38" W 080º 58' 54.7"; 10 m high, 30 m long.
Outcrop strike/dip: 325º/90º SW
Fracture set one (bedding planes) ("FS1") strike/dip: 240º/32º SE

Fig. A11.1 Southern outcrop of Rome Group Formation on the East side of 94S.

Fig. A11.2 Approximate location of Rome Formation outcrop at red circle.

Fig. A11.3 Close-up of Rome Formation on South cut. Red scale bar at left is 2 m.

Rome-South	*ISR (Schmidt rebound)*	*Weathering*	*Joint Space Mean (m)*	*Joint Space Wtd Avg (m)*	*Joint Dip & Orientation*	*Joint Width Mean (mm)*	*Joint Width Wtd Avg (mm)*	*Continuity/Infill Mean*	*Groundwater*	**Mean Total**	**Wtd Avg Total**
mean	56	slight-moderate	22.8	2.5	32° perpendicular to slope	58.6	17.6	Continuous/thick or no infill	trace		
median	57	slight-moderate	22.7	0.4	32° perpendicular to slope	52.3	5	Continuous/thick or no infill	trace		
score mean	*18*	*8*	*30*	*29*	*14*	*2*	*4*	*3*	*5*	**80**	**81**
score median	*19*	*8*	*30*	*18*	*14*	*2*	*4*	*3*	*5*	**81**	**71**

Table A11.1 Scoring summary of each parameter and score totals for RMS in the Rome Formation. Mean and median rows represent whether the mean or median of raw data was used. Columns that indicate mean or weighted average (“Wtd Avg”) are describing whether data from multiple joint sets was simply averaged together, or whether a weighted average was taken based on the number of joints observed in the window studied.

Rome-South	*Kidy. (MPa)*	*Kahr. (MPa)*	*Tot RQD*	*RQD mult*	*Joint Space (m)*	*Persistence (m)*	*Aperture (mm)*	*Rough*	*Infill*	*Weathering*	*Ground-water*	*Joint adjust.*	*Excav. adjust.*	**Totals-Kahr-total RQD**	**Totals-Kidy-total RQD**	**Totals-Kahr-RQD mult**	**Totals-Kidy-RQD mult**
mean	79.8	53.5	0.9	0.7	0.21	1.67	17.6	rough-slightly	none	slight	damp	FS 1, planar	smooth blasting				
median	83.5	55.5	0.9	0.7	0.16	1.67	5	rough-slightly	none	slight	damp	FS 1, planar	smooth blasting				
score mean	*7*	*7*	*20*	*13*	*10*	*4*	*0*	*4*	*6*	*5*	*10*	*-6.3*	*8*	**67.7**	**67.7**	**60.7**	**60.7**
score median	*7*	*7*	*20*	*13*	*8*	*4*	*1*	*4*	*6*	*5*	*10*	*-6.3*	*8*	**66.7**	**66.7**	**59.7**	**59.7**

Table A11.2 Scoring summary of each parameter and score totals for SMR in the Rome Formation. RMR can be found by removing the Joint Orientation Adjustment (“Joint adjust.”) and Excavation Adjustment (“Excav. adjust.”) from the total score.

Fracture Set	**Joint Spacing (m)**	**Aperture (mm)**	**Continuity/Infill**	**Number of Fractures in Window**
FS 1 (bedding) (mean/median)	0.53 / 0.35	17.2 / 5	Continuous/none	25
FS 2 (mean/median)	45 / 45	100 / 100	Continuous/thick	1

Table A11.3 Selected data by fracture set. The mean or median of raw data is reported as “mean / median.”

Major Elements (Normalized)	Dolostone Sample (Weight %)	Siltstone Sample (Weight %)
SiO2	9.17	57.26
TiO2	0.042	0.869
Al2O3	0.94	13.17
FeO	0.34	4.73
MnO	0.014	0.054
MgO	8.93	6.63
CaO	80.20	6.83
Na2O	0.01	0.18
K2O	0.33	9.71
P2O5	0.018	0.570
Trace Elements (Unnormalized)	**Dolostone Sample (ppm)**	**Siltstone Sample (ppm)**
Ni	6	25
Cr	5	39
Sc	0	10
V	7	62
Ba	26	572
Rb	7	123
Sr	276	117
Zr	4	282
Y	3	57
Nb	0.0	11.8
Ga	1	17
Cu	5	1
Zn	6	62
Pb	1	11
La	8	35
Ce	4	80
Th	2	8
Nd	0	39
Cs (+/- 5 ppm)	1	3
As (minimum value)	0	4

Table A11.4 XRF/LOI data for Rome units studied (samples not distinguished by Northern or Southern Exposure).

Appendix A12: Kittery Formation

Measured July 2011. Blocky, layered phyllite and quartz-rich granofels.
Coastal exposure at Two Lights State Park, ME. Natural outcrop.
Window studied: N 43º 33' 33" W 070º 12' 14"; 10 m high, 40 m long.
Outcrop strike/dip: 235º/85º E
Fracture set one (foliations) ("FS1") strike/dip: 151º/9º E
Fracture set two ("FS2") strike/dip: 235º/55º W
Fracture set three ("FS3") strike/dip: 145º/88º S

Fig. A12.1 Outcrop of Kittery Formation on the coast of Two Lights State Park.

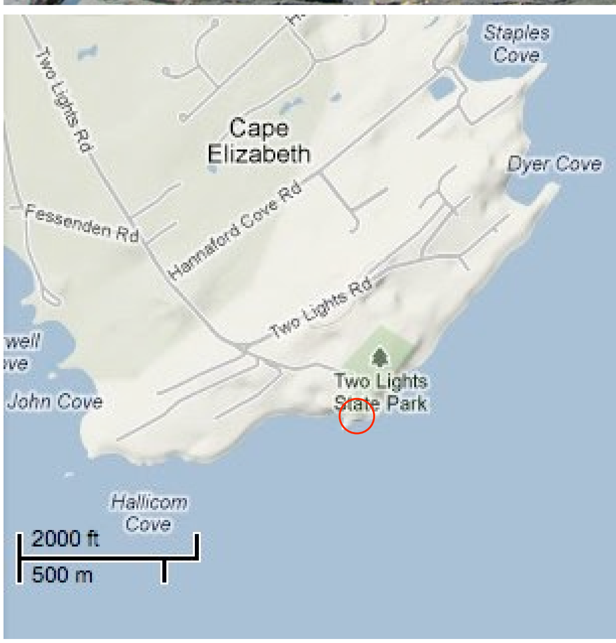

Fig. A12.2 Approximate location of Kittery Formation outcrop at red circle.

Fig. A12.3 Close-up of Kittery Formation. Field notebook is ~20 cm.

Kittery	*ISR (Schmidt rebound)*	*Weathering*	*Joint Space Mean (m)*	*Joint Space Wtd Avg (m)*	*Joint Dip & Orientation*	*Joint Width Mean (mm)*	*Joint Width Wtd Avg (mm)*	*Continuity/Infill Mean*	*Groundwater*	**Mean Total**	**Wtd Avg Total**
mean	56.2	slight-moderate	0.3	0.3	88º perpendicular to slope	11	8.9	Continuous/no infill	waves/tides		
median	58	slight-moderate	0.2	0.17	88º perpendicular to slope	3	3	Continuous/no infill	waves/tides		
score mean	*18*	*8*	*18*	*17*	*14*	*4*	*4*	*5*	*1*	**68**	**67**
score median	*19*	*8*	*15*	*15*	*14*	*5*	*5*	*5*	*1*	**67**	**67**

Table A12.1 Scoring summary of each parameter and score totals for RMS in the Kittery Formation. Mean and median rows represent whether the mean or median of raw data was used. Columns that indicate mean or weighted average ("Wtd Avg") are describing whether data from multiple joint sets was simply averaged together, or whether a weighted average was taken based on the number of joints observed in the window studied.

Kittery	*Kidy. (MPa)*	*Kahr. (MPa)*	*Tot RQD*	*RQD mult*	*Joint Space (m)*	*Persistence (m)*	*Aperture (mm)*	*Rough*	*Infill*	*Weathering*	*Ground-water*	*Joint adjust.*	*Excav. adjust.*	**Totals-Kahr-total RQD**	**Totals-Kidy-total RQD**	**Totals-Kahr-RQD mult**	**Totals-Kidy-RQD mult**
mean	98.4	63.1	0.95	0.67	0.3	4.57	8.86	very rough	none	moderate-high	waves/ tides	FS 2, toppling	natural				
median	106.7	67.7	0.95	0.67	0.17	12.1	3	very rough	none	moderate-high	waves/ tides	FS 2, toppling	natural				
score mean	*7*	*7*	*20*	*13*	*10*	*2*	*0*	*6*	*6*	*2*	*0*	*-25*	*15*	**43**	**43**	**36**	**36**
score median	*12*	*7*	*20*	*13*	*8*	*1*	*1*	*6*	*6*	*2*	*0*	*-25*	*15*	**41**	**46**	**34**	**39**

Table A12.2 Scoring summary of each parameter and score totals for SMR in the Kittery Formation. RMR can be found by removing the Joint Orientation Adjustment ("Joint adjust.") and Excavation Adjustment ("Excav. adjust.") from the total score.

Fracture Set	**Joint Spacing (m)**	**Aperture (mm)**	**Continuity/Infill**	**Number of Fractures in Window**
FS 1 (foliations) (mean/median)	0.15 / 0.1	17 / 4	Continuous/none	22
FS 2 (mean/median)	0.34 / 0.21	5 / 2	Continuous/thick	11
FS 3 (mean/median)	0.48 / 0.29	5 / 2	Continuous/thick	13

Table A12.3 Selected data by fracture set. The mean or median of raw data is reported as "mean / median."

Appendix A13: Cushing Formation

Measured July 2011. Quartz-feldspar-biotite gneiss.
Coastal exposure at Fort Williams Municipal Park, ME. Natural outcrop.
Window studied: N 43º 37' 36" W 070º 12' 46"; 5 m high, 15 m long.
Outcrop strike/dip: 058º/85º S
Fracture set one (foliations) ("FS1") strike/dip: 055º/67º S
Fracture set two ("FS2") strike/dip: 145º/70º E

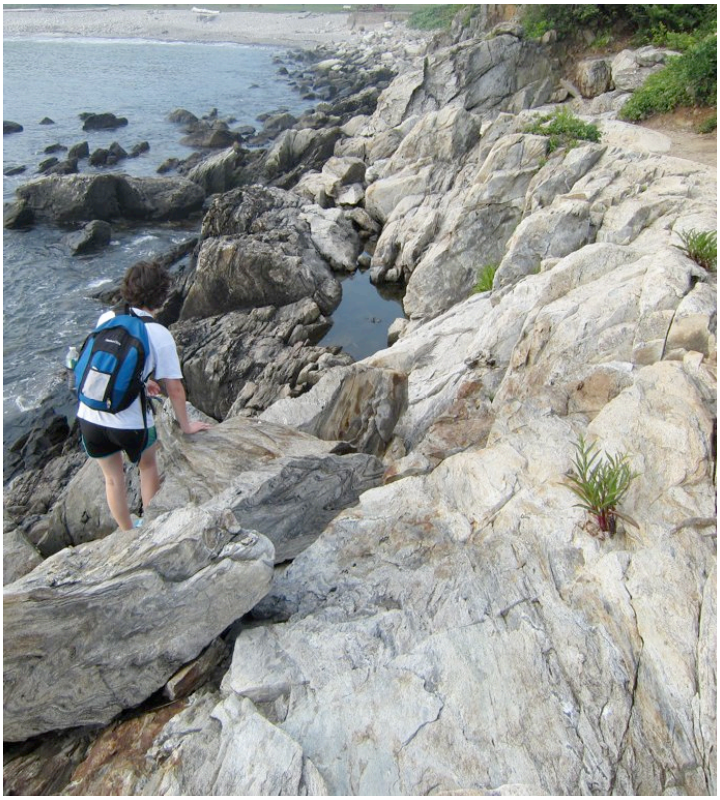

Fig. A13.1 Outcrop of Cushing Formation on the coast of Fort Williams Municipal Park.

Fig. A13.2 Approximate location of Cushing Formation outcrop at red circle.

Fig. A13.3 Close-up of Cushing Formation. White chalk circle is 110 cm in diameter.

Cushing	ISR (Schmidt rebound)	Weathering	Joint Space Mean (m)	Joint Space Wtd Avg (m)	Joint Dip & Orientation	Joint Width Mean (mm)	Joint Width Wtd Avg (mm)	Continuity/Infill Mean	Groundwater	Mean Total	Wtd Avg Total
mean	58.1	slight-moderate	0.21	0.19	67° out of slope	4.6	4.7	Continuous/no infill	waves/tides		
median	59	slight-moderate	0.18	0.12	67° out of slope	2.3	2	Continuous/no infill	waves/tides		
score mean	*19*	*8*	*16*	*15*	*5*	*5*	*5*	*5*	*1*	**59**	**58**
score median	*19*	*8*	*15*	*14*	*5*	*5*	*5*	*5*	*1*	**58**	**57**

Table A13.1 Scoring summary of each parameter and score totals for RMS in the Cushing Formation. Mean and median rows represent whether the mean or median of raw data was used. Columns that indicate mean or weighted average ("Wtd Avg") are describing whether data from multiple joint sets was simply averaged together, or whether a weighted average was taken based on the number of joints observed in the window studied.

Cushing	Kidy. (MPa)	Kahr. (MPa)	Tot RQD	RQD mult	Joint Space (m)	Persistence (m)	Aperture (mm)	Rough	Infill	Weathering	Ground-water	Joint adjust.	Excav. adjust.	Totals-Kahr-total RQD	Totals-Kidy-total RQD	Totals-Kahr-RQD mult	Totals-Kidy-RQD mult
mean	107.2	68.0	0.89	0.52	0.19	2.5	4.7	very rough	none	slight-moderate	waves/tides	FS 1, planar	natural				
median	111.6	70.4	0.89	0.52	0.12	2.5	2	very rough	none	slight-moderate	waves/tides	FS 1, planar	natural				
score mean	*12*	*7*	*17*	*13*	*8*	*4*	*1*	*6*	*6*	*4*	*0*	*-60*	*15*	**8**	**13**	**4**	**9**
score median	*12*	*7*	*17*	*13*	*8*	*4*	*1*	*6*	*6*	*4*	*0*	*-60*	*15*	**8**	**13**	**4**	**9**

Table A13.2 Scoring summary of each parameter and score totals for SMR in the Cushing Formation. RMR can be found by removing the Joint Orientation Adjustment ("Joint adjust.") and Excavation Adjustment ("Excav. adjust.") from the total score.

Fracture Set	Joint Spacing (m)	Aperture (mm)	Continuity/Infill	Number of Fractures in Window
FS 1 (foliations) (mean/median)	0.12 / 0.09	6.7 / 3.5	Continuous/none	24
FS 2 (mean/median)	0.29 / 0.26	2.5 / 1	Continuous/none	15

Table A13.3 Selected data by fracture set. The mean or median of raw data is reported as "mean / median."

<u>Appendix A14: Cadillac Mountain Formation: Blackwoods</u>

Measured July 2011. Coarse-grained, pink, hornblende granite.
Coastal exposure at Blackwoods Campground, Acadia National Park, ME. Natural outcrop.
Window studied: N 44º 18' 22" W 068º 12' 05"; 15 m high, 15 m long.
Outcrop strike/dip: 223º/57º SE
Fracture set one ("FS1") strike/dip: 222º/25º SE
Fracture set two ("FS2") strike/dip: 130º/64º W

Fig. A14.1 Outcrop of Cadillac Mtn Formation at Blackwoods Campground.

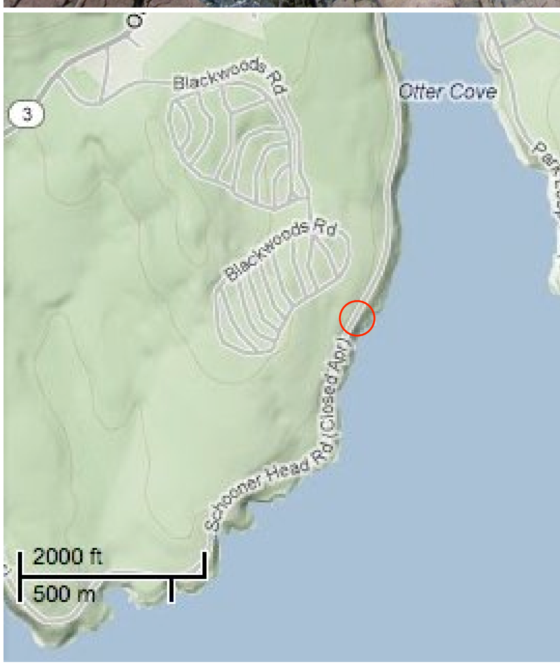

Fig. A14.2 Approximate location of Cadillac Mtn Formation outcrop at red circle.

Fig. A14.3 Close-up of Cadillac Mtn Formation.

Cadillac-Blackwoods	ISR (Schmidt rebound)	Weathering	Joint Space Mean (m)	Joint Space Wtd Avg (m)	Joint Dip & Orientation	Joint Width Mean (mm)	Joint Width Wtd Avg (mm)	Continuity/Infill Mean	Groundwater	Mean Total	Wtd Avg Total
mean	58.2	slight	0.43	0.38	25° out of slope	2.8	3.15	Continuous/no infill	waves/tides		
median	58.5	slight	0.31	0.21	25° out of slope	2	2	Continuous/no infill	waves/tides		
score mean	*19*	*9*	*19*	*18*	*9*	*5*	*5*	*5*	*1*	**67**	**66**
score median	*19*	*9*	*18*	*16*	*9*	*5*	*5*	*5*	*1*	**66**	**64**

Table A14.1 Scoring summary of each parameter and score totals for RMS in the Cadillac Mtn Formation. Mean and median rows represent whether the mean or median of raw data was used. Columns that indicate mean or weighted average ("Wtd Avg") are describing whether data from multiple joint sets was simply averaged together, or whether a weighted average was taken based on the number of joints observed in the window studied.

Cadillac-Blackwoods	Kidy. (MPa)	Kahr. (MPa)	Tot RQD	RQD mult	Joint Space (m)	Persistence (m)	Aperture (mm)	Rough	Infill	Weathering	Ground-water	Joint adjust.	Excav. adjust.	Totals-Kahr-total RQD	Totals-Kidy-total RQD	Totals-Kahr-RQD mult	Totals-Kidy-RQD mult
mean	97.4	62.9	0.97	0.9	0.38	3.46	3.15	rough	none	slight	waves/ tides	FS 1, planar	natural				
median	98.7	63.6	0.97	0.9	0.21	3.46	2	rough	none	slight	waves/ tides	FS 1, planar	natural				
score mean	*7*	*7*	*20*	*20*	*10*	*2*	*1*	*5*	*6*	*5*	*0*	*-24*	*15*	**47**	**47**	**47**	**47**
score median	*7*	*7*	*20*	*20*	*10*	*2*	*1*	*5*	*6*	*5*	*0*	*-24*	*15*	**47**	**47**	**47**	**47**

Table A14.2 Scoring summary of each parameter and score totals for SMR in the Cadillac Mtn Formation. RMR can be found by removing the Joint Orientation Adjustment ("Joint adjust.") and Excavation Adjustment ("Excav. adjust.") from the total score.

Fracture Set	Joint Spacing (m)	Aperture (mm)	Continuity/Infill	Number of Fractures in Window
FS 1 (mean/median)	0.28 / 0.15	4.3 / 3	Continuous/none	15
FS 2 (mean/median)	0.57 / 0.46	1.2 / 1	Continuous/none	8

Table A14.3 Selected data by fracture set. The mean or median of raw data is reported as "mean / median."

<u>Appendix A15: Cadillac Mountain Formation: Pebble Beach</u>

Measured July 2011. Coarse-grained, pink, hornblende granite.
Coastal exposure at Pebble Beach, Acadia National Park, ME. Natural outcrop.
Window studied: N 44º 19' 5" W 068º 11' 24"; 10 m high, 15 m long.
Outcrop strike/dip: 292º/90º SW
Fracture set one ("FS1") strike/dip: 190º/15º E
Fracture set two ("FS2") strike/dip: 035º/80º NW
Fracture set three ("FS3") strike/dip: 152º/80º SW
Fracture set four ("FS4") strike/dip: 292º/90º SW

Fig. A15.1 Outcrop of Cadillac Mtn Formation at Pebble Beach.

Fig. A15.2 Approximate location of Cadillac Mtn Formation outcrop at red circle.

Fig. A15.3 Close-up of Cadillac Mtn Formation.

Cadillac-Pebble Beach	***ISR (Schmidt rebound)***	***Weathering***	***Joint Space Mean (m)***	***Joint Space Wtd Avg (m)***	***Joint Dip & Orientation***	***Joint Width Mean (mm)***	***Joint Width Wtd Avg (mm)***	***Continuity/Infill Mean***	***Groundwater***	**Mean Total**	**Wtd Avg Total**
mean	58.3	slight-moderate	0.29	0.3	90° out of slope	12.8	12.8	Continuous/no infill	waves/tides		
median	59	slight-moderate	0.21	0.17	90° out of slope	4	4	Continuous/no infill	waves/tides		
score mean	*19*	*8*	*17*	*17*	*5*	*4*	*4*	*5*	*1*	**59**	**59**
score median	*19*	*8*	*16*	*15*	*5*	*5*	*5*	*5*	*1*	**59**	**58**

Table A15.1 Scoring summary of each parameter and score totals for RMS in the Cadillac Mtn Formation. Mean and median rows represent whether the mean or median of raw data was used. Columns that indicate mean or weighted average ("Wtd Avg") are describing whether data from multiple joint sets was simply averaged together, or whether a weighted average was taken based on the number of joints observed in the window studied.

Cadillac-Pebble Beach	***Kidy. (MPa)***	***Kahr. (MPa)***	***Tot RQD***	***RQD mult***	***Joint Space (m)***	***Persistence (m)***	***Aperture (mm)***	***Rough***	***Infill***	***Weathering***	***Ground-water***	***Joint adjust.***	***Excav. adjust.***	**Totals-Kahr-total RQD**	**Totals-Kidy-total RQD**	**Totals-Kahr-RQD mult**	**Totals-Kidy-RQD mult**
mean	124.7	77.4	0.94	0.78	0.3	36.4	12.8	rough	none	slight-moderate	waves/ tides	FS 4, planar	natural				
median	126.4	78.3	0.94	0.78	0.17	6.9	4	rough	none	slight-moderate	waves/ tides	FS 4, planar	natural				
score mean	*12*	*7*	*20*	*17*	*10*	*0*	*0*	*5*	*6*	*4*	*0*	*-25*	*15*	**42**	**47**	**39**	**44**
score median	*12*	*7*	*20*	*17*	*8*	*2*	*1*	*5*	*6*	*4*	*0*	*-25*	*15*	**43**	**48**	**40**	**45**

Table A15.2 Scoring summary of each parameter and score totals for SMR in the Cadillac Mtn Formation. RMR can be found by removing the Joint Orientation Adjustment ("Joint adjust.") and Excavation Adjustment ("Excav. adjust.") from the total score.

Fracture Set	**Joint Spacing (m)**	**Aperture (mm)**	**Continuity/Infill**	**Number of Fractures in Window**
FS 1 (mean/median)	0.22 / 0.19	12.8 / 4	Continuous/none	11
FS 2&3 (mean/median)	0.31 / 0.11	12.8 / 4	Continuous/none	29
FS 4 (mean/median)	0.34 / 0.33	12.8 / 4	Continuous/none	21

Table A15.3 Selected data by fracture set. The mean or median of raw data is reported as "mean / median."

Appendix A16: Shatter Zone

Measured July 2011. Shatter zone of Cadillac Mtn. Granite and Devonian gabbrod-diorite (country rock).
Coastal exposure at Newport Cove, Acadia National Park, ME. Natural outcrop.
Window studied: N 44º 19' 41" W 068º 10' 48"; 8 m high, 10 m long.
Outcrop strike/dip: 173º/34º W
Fracture set one ("FS1") strike/dip: 036º/19º E
Fracture set two ("FS2") strike/dip: 002º/83º E
Fracture set three ("FS3") strike/dip: 099º/77º S

Fig. A16.1 Outcrop of Shatter Zone at Newport Cove.

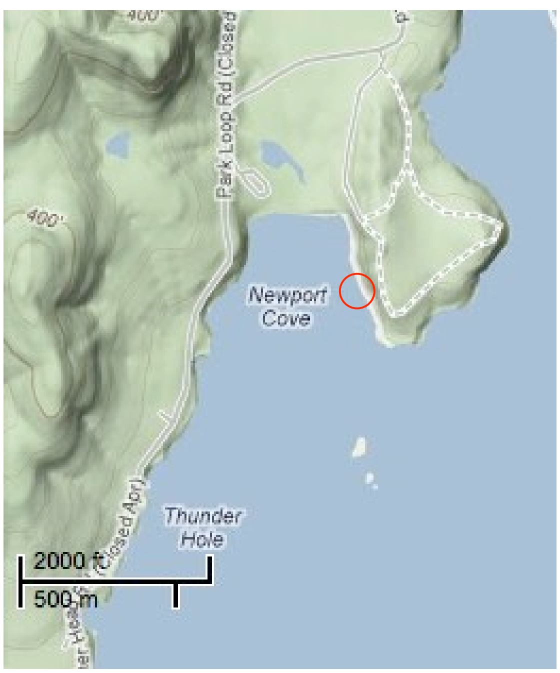

Fig. A16.2 Approximate location of Shatter Zone Formation outcrop at red circle.

Fig. A16.3 Close-up of Shatter Zone.

Shatter Zone	ISR (Schmidt rebound)	Weathering	Joint Space Mean (m)	Joint Space Wtd Avg (m)	Joint Dip & Orientation	Joint Width Mean (mm)	Joint Width Wtd Avg (mm)	Continuity/Infill Mean	Groundwater	Mean Total	Wtd Avg Total
mean	63.7	slight-moderate	0.33	0.32	19º out of slope	1.6	1.6	Continuous/no infill	waves/tides		
median	64	slight-moderate	0.21	0.31	19º out of slope	1	1	Continuous/no infill	waves/tides		
score mean	*19*	*8*	*18*	*18*	*9*	*5*	*5*	*5*	*1*	**65**	**65**
score median	*19*	*8*	*16*	*18*	*9*	*5*	*5*	*5*	*1*	**63**	**65**

Table A16.1 Scoring summary of each parameter and score totals for RMS in the Shatter Zone Formation. Mean and median rows represent whether the mean or median of raw data was used. Columns that indicate mean or weighted average ("Wtd Avg") are describing whether data from multiple joint sets was simply averaged together, or whether a weighted average was taken based on the number of joints observed in the window studied.

Shatter Zone	Kidy. (MPa)	Kahr. (MPa)	Tot RQD	RQD mult	Joint Space (m)	Persistence (m)	Aperture (mm)	Rough	Infill	Weathering	Ground-water	Joint adjust.	Excav. adjust.	Totals-Kahr-total RQD	Totals-Kidy-total RQD	Totals-Kahr-RQD mult	Totals-Kidy-RQD mult
mean	137.9	84.7	0.97	0.92	0.32	1.32	1.6	rough-slightly	none	slight	waves/ tides	FS 1, planar	natural				
median	139.7	85.7	0.97	0.92	0.31	1.94	1	rough-slightly	none	slight	waves/ tides	FS 1, planar	natural				
score mean	*12*	*7*	*20*	*20*	*10*	*4*	*1*	*4*	*6*	*5*	*0*	*-9*	*15*	**63**	**68**	**63**	**68**
score median	*12*	*7*	*20*	*20*	*10*	*4*	*1*	*4*	*6*	*5*	*0*	*-9*	*15*	**63**	**68**	**63**	**68**

Table A16.2 Scoring summary of each parameter and score totals for SMR in the Shatter Zone Formation. RMR can be found by removing the Joint Orientation Adjustment ("Joint adjust.") and Excavation Adjustment ("Excav. adjust.") from the total score.

Fracture Set	Joint Spacing (m)	Aperture (mm)	Continuity/Infill	Number of Fractures in Window
FS 1 (mean/median)	0.32 / 0.2	1.6 / 1	Continuous/none	19
FS 2 &3 (mean/median)	0.34 / 0.22	1.6 / 1	Continuous/none	23

Table A16.3 Selected data by fracture set. The mean or median of raw data is reported as "mean / median."

Appendix A17: Archean Gneiss: Death Canyon

Measured August 2011. Layered biotite and hornblende gneiss.
Exposure on Northeast wall of Death Canyon, Teton, WY. Natural outcrop.
Window studied: N 43º 39' 30" W 111º 49' 16"; 10 m high, 8 m long.
Outcrop strike/dip: 105º/32º S
Fracture set one ("FS1") strike/dip: 255º/44º S

Fig. A17.1 Outcrop of Archean Gneiss at Death Canyon.

Fig. A17.2 Approximate location of Archean Gneiss outcrop at red circle.

Fig. A17.3 Close-up of Archean Gneiss. White chalk circle is 110cm in diameter.

Archean Gneiss-Death Canyon	*ISR (Schmidt rebound)*	*Weathering*	*Joint Space Mean (m)*	*Joint Space Wtd Avg (m)*	*Joint Dip & Orientation*	*Joint Width Mean (mm)*	*Joint Width Wtd Avg (mm)*	*Continuity/Infill Mean*	*Groundwater*	**Mean Total**	**Wtd Avg Total**
mean	54.2	moderate	0.33	0.34	44º out	3.3	3.3	Continuous/thin	trace		
median	54	moderate	0.28	0.27	44º out	0.75	0.75	Continuous/thin	trace		
score mean	*18*	*7*	*18*	*18*	*5*	*5*	*5*	*4*	*5*	**62**	**62**
score median	*18*	*7*	*17*	*17*	*5*	*6*	*6*	*4*	*5*	**62**	**62**

Table A17.1 Scoring summary of each parameter and score totals for RMS in the Archean Gneiss Formation. Mean and median rows represent whether the mean or median of raw data was used. Columns that indicate mean or weighted average ("Wtd Avg") are describing whether data from multiple joint sets was simply averaged together, or whether a weighted average was taken based on the number of joints observed in the window studied.

Archean Gneiss-Death Canyon	*Kidy. (MPa)*	*Kahr. (MPa)*	*Tot RQD*	*RQD mult*	*Joint Space (m)*	*Persistence (m)*	*Aperture (mm)*	*Rough*	*Infill*	*Weathering*	*Ground-water*	*Joint adjust.*	*Excav. adjust.*	**Totals-Kahr-total RQD**	**Totals-Kidy-total RQD**	**Totals-Kahr-RQD mult**	**Totals-Kidy-RQD mult**
mean	85.5	56.2	0.95	0.88	0.34	1.99	3.3	slight-smooth	Thin soft	slight-moderate	wet	FS 1, planar	natural				
median	84.8	55.7	0.95	0.88	0.27	1.72	0.75	slight-smooth	Thin soft	slight-moderate	wet	FS 1, planar	natural				
score mean	*7*	*7*	*20*	*17*	*10*	*4*	*1*	*2*	*2*	*4*	*7*	*0*	*15*	**72**	**72**	**69**	**69**
score median	*7*	*7*	*20*	*17*	*10*	*4*	*4*	*2*	*2*	*4*	*7*	*0*	*15*	**75**	**75**	**72**	**72**

Table A17.2 Scoring summary of each parameter and score totals for SMR in the Archean Gneiss Formation. RMR can be found by removing the Joint Orientation Adjustment ("Joint adjust.") and Excavation Adjustment ("Excav. adjust.") from the total score.

Fracture Set	**Joint Spacing (m)**	**Aperture (mm)**	**Continuity/Infill**	**Number of Fractures in Window**
FS 1 (mean/median)	0.3 / 0.26	3.3 / 0.75	Continuous/thin	25

Table A17.3 Selected data by fracture set. The mean or median of raw data is reported as "mean / median."

<u>Appendix A18: Archean Gneiss: Paintbrush Canyon</u>

Measured August 2011. Layered biotite and hornblende gneiss.
Exposure on valley floor of Paintbrush Canyon, Teton, WY. Natural outcrop.
Window studied: N 43º 47' 51" W 110º 46' 25"; 2 m high, 12 m long.
Outcrop strike/dip: 170º/39º E
Fracture set one ("FS1") strike/dip: 168º/41º E

Fig. A18.1 Outcrop of Archean Gneiss at Paintbrush Canyon.

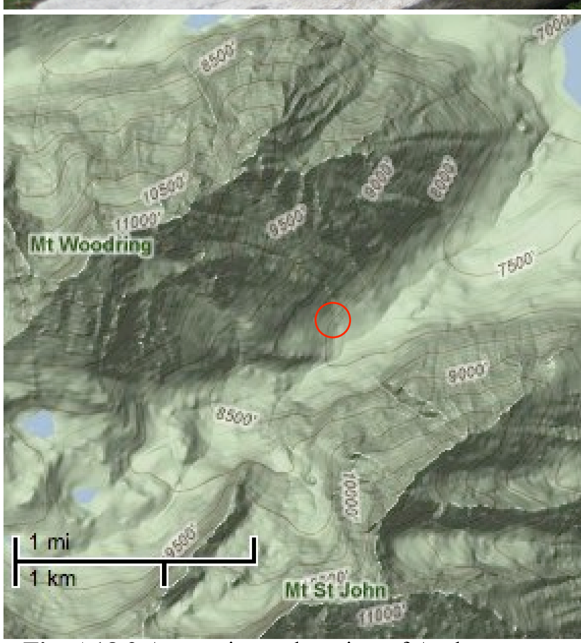

Fig. A18.2 Approximate location of Archean Gneiss outcrop at red circle.

Fig. A18.3 Close-up of Archean Gneiss. White chalk circle is 110cm in diameter.

Archean Gneiss-Paintbrush Canyon	ISR (Schmidt rebound)	Weathering	Joint Space Mean (m)	Joint Space Wtd Avg (m)	Joint Dip & Orientation	Joint Width Mean (mm)	Joint Width Wtd Avg (mm)	Continuity/Infill Mean	Groundwater	Mean Total	Wtd Avg Total
mean	55.9	slight-moderate	0.47	0.47	41° out of slope	3.6	3.6	few	none		
median	57	slight-moderate	0.36	0.36	41° out of slope	1	1	few	none		
score mean	*18*	*8*	*19*	*19*	*5*	*5*	*5*	*6*	*6*	**67**	**67**
score median	*19*	*8*	*18*	*18*	*5*	*5*	*5*	*6*	*6*	**67**	**67**

Table A18.1 Scoring summary of each parameter and score totals for RMS in the Archean Gneiss Formation. Mean and median rows represent whether the mean or median of raw data was used. Columns that indicate mean or weighted average ("Wtd Avg") are describing whether data from multiple joint sets was simply averaged together, or whether a weighted average was taken based on the number of joints observed in the window studied.

Archean Gneiss-Paintbrush Canyon	Kidy. (MPa)	Kahr. (MPa)	Tot RQD	RQD mult	Joint Space (m)	Persistence (m)	Aperture (mm)	Rough	Infill	Weathering	Ground-water	Joint adjust.	Excav. adjust.	Totals-Kahr-total RQD	Totals-Kidy-total RQD	Totals-Kahr-RQD mult	Totals-Kidy-RQD mult
mean	92.3	60.0	0.99	0.93	0.47	1.34	3.6	rough	thick/ soft	moderate	none	FS 1, planar	natural				
median	97.0	62.6	0.99	0.93	0.36	1.34	1	rough	thick/ soft	moderate	none	FS 1, planar	natural				
score mean	*7*	*7*	*20*	*20*	*10*	*4*	*1*	*5*	*0*	*3*	*15*	*-5.1*	*15*	**74.9**	**74.9**	**74.9**	**74.9**
score median	*7*	*7*	*20*	*20*	*10*	*4*	*1*	*5*	*0*	*3*	*15*	*-5.1*	*15*	**74.9**	**74.9**	**74.9**	**74.9**

Table A18.2 Scoring summary of each parameter and score totals for SMR in the Archean Gneiss Formation. RMR can be found by removing the Joint Orientation Adjustment ("Joint adjust.") and Excavation Adjustment ("Excav. adjust.") from the total score.

Fracture Set	Joint Spacing (m)	Aperture (mm)	Continuity/Infill	Number of Fractures in Window
FS 1 (mean/median)	0.47 / 0.36	3.6 / 1	Few continuous	15

Table A18.3 Selected data by fracture set. The mean or median of raw data is reported as "mean / median."

Appendix A19: Archean Gneiss: South Fork of Cascade Canyon

Measured August 2011. Layered biotite and hornblende gneiss.
Exposure on West side of trail in South Fork of Cascade Canyon, Teton, WY. Natural outcrop.
Window studied: N 43º 44' 6" W 110º 50' 12"; 2 m high, 8 m long.
Outcrop strike/dip: 165º/85º E
Fracture set one ("FS1") strike/dip: 083º/16º N

Fig. A19.1 Outcrop of Archean Gneiss at South Fork of Cascade Canyon.

Fig. A19.2 Approximate location of Archean Gneiss outcrop at red circle.

Archean Gneiss-Cascade Canyon	ISR (Schmidt rebound)	Weathering	Joint Space Mean (m)	Joint Space Wtd Avg (m)	Joint Dip & Orientation	Joint Width Mean (mm)	Joint Width Wtd Avg (mm)	Continuity/Infill Mean	Groundwater	Mean Total	Wtd Avg Total
mean	56.4	moderate	0.3	0.31	16° perpendicular to slope	5.2	5.16	Few continuous	trace		
median	57	moderate	0.25	0.24	16° perpendicular to slope	3	3	Few continuous	trace		
score mean	*18*	*7*	*17*	*18*	*14*	*4*	*4*	*6*	*5*	**71**	**72**
score median	*19*	*7*	*16*	*16*	*14*	*5*	*5*	*6*	*5*	**72**	**72**

Table A19.1 Scoring summary of each parameter and score totals for RMS in the Archean Gneiss Formation. Mean and median rows represent whether the mean or median of raw data was used. Columns that indicate mean or weighted average ("Wtd Avg") are describing whether data from multiple joint sets was simply averaged together, or whether a weighted average was taken based on the number of joints observed in the window studied.

Archean Gneiss-Cascade Canyon	Kidy. (MPa)	Kahr. (MPa)	Tot RQD	RQD mult	Joint Space (m)	Persistence (m)	Aperture (mm)	Rough	Infill	Weathering	Ground-water	Joint adjust.	Excav. adjust.	Totals-Kahr-total RQD	Totals-Kidy-total RQD	Totals-Kahr-RQD mult	Totals-Kidy-RQD mult
mean	94.4	61.1	0.98	0.84	0.31	0.86	5.16	smooth	thin-thick/ soft	high	damp	FS 1, planar	natural				
median	97.0	62.6	0.98	0.84	0.24	0.86	3	smooth	thin-thick/ soft	high	damp	FS 1, planar	natural				
score mean	*7*	*7*	*20*	*17*	*10*	*6*	*0*	*1*	*1*	*1*	*10*	*-1.35*	*15*	**69.65**	**69.65**	**66.65**	**66.65**
score median	*7*	*7*	*20*	*17*	*10*	*6*	*1*	*1*	*1*	*1*	*10*	*-1.35*	*15*	**70.65**	**70.65**	**67.65**	**67.65**

Table A19.2 Scoring summary of each parameter and score totals for SMR in the Archean Gneiss Formation. RMR can be found by removing the Joint Orientation Adjustment ("Joint adjust.") and Excavation Adjustment ("Excav. adjust.") from the total score.

Fracture Set	Joint Spacing (m)	Aperture (mm)	Continuity/Infill	Number of Fractures in Window
FS 1 (mean/median)	0.21 / 0.18	5.2 / 3	Few continuous	15

Table A19.3 Selected data by fracture set. The mean or median of raw data is reported as "mean / median."

Appendix A20: Mt Owen Formation: Delta Lake

Measured August 2011. Massive quartz monzonite.
Exposure above Delta Lake up Glacier Gulch, Teton, WY. Natural outcrop.
Window studied: N 43º 43' 56" W 110º 46' 14"; 10 m by 10 m.
Outcrop strike/dip: (rounded dome)
No pervasive or regular fractures.

Fig. A20.1 Outcrop of Mt Owen Formation above Delta Lake.

Fig. A20.2 Approximate location of Mt Owen Formation outcrop at red circle.

Fig. A20.3 Close-up of Mt Owen Formation. White chalk circle is 110cm in diameter.

Mt Owen-Delta Lake	*ISR (Schmidt rebound)*	*Weathering*	*Joint Space Mean (m)*	*Joint Space Wtd Avg (m)*	*Joint Dip & Orientation*	*Joint Width Mean (mm)*	*Joint Width Wtd Avg (mm)*	*Continuity/Infill Mean*	*Groundwater*	**Mean Total**	**Wtd Avg Total**
mean	62.1	slight	0.71	0.58	n/a	1.2	1.2	Few continuous	none		
median	62	slight	0.67	0.38	n/a	0.5	0.5	Few continuous	none		
score mean	*19*	*9*	*22*	*20*	*14*	*5*	*5*	*6*	*6*	**81**	**79**
score median	*19*	*9*	*21*	*18*	*14*	*6*	*6*	*6*	*6*	**81**	**78**

Table A20.1 Scoring summary of each parameter and score totals for RMS in the Mt Owen Formation. Mean and median rows represent whether the mean or median of raw data was used. Columns that indicate mean or weighted average ("Wtd Avg") are describing whether data from multiple joint sets was simply averaged together, or whether a weighted average was taken based on the number of joints observed in the window studied.

Mt Owen-Delta Lake	*Kidy. (MPa)*	*Kahr. (MPa)*	*Tot RQD*	*RQD mult*	*Joint Space (m)*	*Persistence (m)*	*Aperture (mm)*	*Rough*	*Infill*	*Weathering*	*Ground-water*	*Joint adjust.*	*Excav. adjust.*	**Totals-Kahr-total RQD**	**Totals-Kidy-total RQD**	**Totals-Kahr-RQD mult**	**Totals-Kidy-RQD mult**
mean	116.1	72.9	0.98	0.93	0.58	1.22	1.2	rough	none	moderate-slight	none	n/a	natural				
median	115.6	72.6	0.98	0.93	0.38	0.86	0.5	rough	none	moderate-slight	none	n/a	natural				
score mean	*12*	*7*	*20*	*20*	*10*	*4*	*1*	*5*	*6*	*4*	*15*	*0*	*15*	**87**	**92**	**87**	**92**
score median	*12*	*7*	*20*	*20*	*10*	*6*	*4*	*5*	*6*	*4*	*15*	*0*	*15*	**92**	**97**	**92**	**97**

Table A20.2 Scoring summary of each parameter and score totals for SMR in the Mt Owen Formation. RMR can be found by removing the Joint Orientation Adjustment ("Joint adjust.") and Excavation Adjustment ("Excav. adjust.") from the total score.

Appendix A21: Mt Owen Formation: Garnet Canyon

Measured August 2011. Massive quartz monzonite.
Exposure on valley floor of Paintbrush Canyon, Teton, WY. Natural outcrop.
Window studied: N 43º 47' 51" W 110º 46' 25"; 2 m high, 12 m long.
Outcrop strike/dip: 180º/56º E
Fracture set one ("FS1") strike/dip: 174º/32º E
Fracture set two ("FS2") strike/dip: 080º/55º S

Fig. A21.1 Outcrop of Mt Owen Formation at Garnet Canyon.

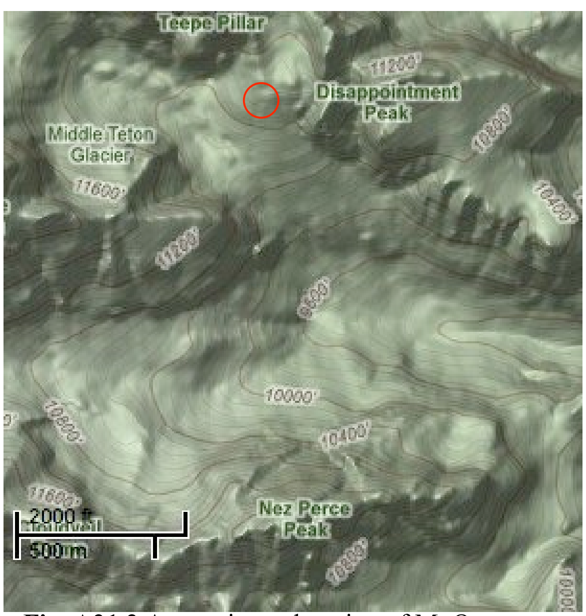

Fig. A21.2 Approximate location of Mt Owen Formation outcrop at red circle.

Fig. A21.3 Close-up of Mt Owen Formation. White chalk circle is 110cm in diameter.

Mt Owen-Garnet Canyon	*ISR (Schmidt rebound)*	*Weathering*	*Joint Space Mean (m)*	*Joint Space Wtd Avg (m)*	*Joint Dip & Orientation*	*Joint Width Mean (mm)*	*Joint Width Wtd Avg (mm)*	*Continuity/Infill Mean*	*Groundwater*	**Mean Total**	**Wtd Avg Total**
mean	59.9	moderate	0.92	0.67	32° out of slope	9.5	9.5	Continuous/thick	none		
median	61.5	moderate	0.885	0.49	32° out of slope	5	5	Continuous/thick	none		
score mean	*19*	*7*	*23*	*21*	*5*	*4*	*4*	*1*	*6*	**65**	**63**
score median	*19*	*7*	*23*	*19*	*5*	*5*	*4*	*1*	*6*	**66**	**61**

Table A21.1 Scoring summary of each parameter and score totals for RMS in the Mt Owen Formation. Mean and median rows represent whether the mean or median of raw data was used. Columns that indicate mean or weighted average ("Wtd Avg") are describing whether data from multiple joint sets was simply averaged together, or whether a weighted average was taken based on the number of joints observed in the window studied.

Mt Owen-Garnet Canyon	*Kidy. (MPa)*	*Kahr. (MPa)*	*Tot RQD*	*RQD mult*	*Joint Space (m)*	*Persistence (m)*	*Aperture (mm)*	*Rough*	*Infill*	*Weathering*	*Ground-water*	*Joint adjust.*	*Excav. adjust.*	**Totals-Kahr-total RQD**	**Totals-Kidy-total RQD**	**Totals-Kahr-RQD mult**	**Totals-Kidy-RQD mult**
mean	105.1	67.1	0.99	0.96	0.67	2.59	9.5	rough-slight	thick/soft	moderate-high	none	FS 1, planar	natural				
median	113.0	71.3	0.99	0.96	0.49	2.59	5	rough-slight	thick/soft	moderate-high	none	FS 1, planar	natural				
score mean	*12*	*7*	*20*	*20*	*15*	*4*	*0*	*4*	*0*	*2*	*15*	*-35.7*	*15*	**46.3**	**51.3**	**46.3**	**51.3**
score median	*12*	*7*	*20*	*20*	*10*	*4*	*1*	*4*	*0*	*2*	*15*	*-35.7*	*15*	**42.3**	**47.3**	**42.3**	**47.3**

Table A21.2 Scoring summary of each parameter and score totals for SMR in the Mt Owen Formation. RMR can be found by removing the Joint Orientation Adjustment ("Joint adjust.") and Excavation Adjustment ("Excav. adjust.") from the total score.

Fracture Set	**Joint Spacing (m)**	**Aperture (mm)**	**Continuity/Infill**	**Number of Fractures in Window**
FS 1 (mean/median)	0.49 / 0.49	9.5 / 5	Continuous/thick	6
FS 2 (mean/median)	2.2 / 2.2	9.5 / 5	Continuous/thick	4

Table A21.3 Selected data by fracture set. The mean or median of raw data is reported as "mean / median."

Appendix A22: Mt Owen Formation: South Fork of Cascade Canyon

Measured August 2011. Massive, glacially polished quartz monzonite.
Exposure on Western wall of trail in South Fork of Cascade Canyon, Teton, WY. Natural outcrop.
Window studied: N 43º 44' 20" W 110º 50' 17"; 8 m high, 15 m long.
Outcrop strike/dip: 154º/84º E
Fracture set one ("FS1") strike/dip: 080º/73º N
Fracture set two ("FS2") strike/dip: 154º/84º E

Fig. A22.1 Outcrop of Mt Owen Formation at Cascade Canyon.

Fig. A22.2 Approximate location of Mt Owen Formation outcrop at red circle.

Fig. A22.3 Close-up of Mt Owen Formation. White chalk circle is 110cm in diameter.

Mt Owen-Cascade Canyon	*ISR (Schmidt rebound)*	*Weathering*	*Joint Space Mean (m)*	*Joint Space Wtd Avg (m)*	*Joint Dip & Orientation*	*Joint Width Mean (mm)*	*Joint Width Wtd Avg (mm)*	*Continuity/Infill Mean*	*Groundwater*	Mean Total	Wtd Avg Total
mean	65.1	slight	0.19	0.17	84º out of slope	10.2	10.2	Continuous/none	none		
median	65.5	slight	0.15	0.12	84º out of slope	4.5	4.5	Continuous/none	none		
score mean	*19*	*9*	*15*	*15*	*5*	*4*	*4*	*5*	*6*	**63**	**63**
score median	*19*	*9*	*14*	*14*	*5*	*5*	*5*	*5*	*6*	**63**	**63**

Table A22.1 Scoring summary of each parameter and score totals for RMS in the Mt Owen Formation. Mean and median rows represent whether the mean or median of raw data was used. Columns that indicate mean or weighted average ("Wtd Avg") are describing whether data from multiple joint sets was simply averaged together, or whether a weighted average was taken based on the number of joints observed in the window studied.

Mt Owen-Cascade Canyon	*Kidy. (MPa)*	*Kahr. (MPa)*	*Tot RQD*	*RQD mult*	*Joint Space (m)*	*Persistence (m)*	*Aperture (mm)*	*Rough*	*Infill*	*Weathering*	*Ground-water*	*Joint adjust.*	*Excav. adjust.*	Totals-Kahr-total RQD	Totals-Kidy-total RQD	Totals-Kahr-RQD mult	Totals-Kidy-RQD mult
mean	132.9	81.6	0.87	0.58	0.17	4.07	10.2	smooth	little to none	slight	none	FS 2, planar	natural				
median	135.3	82.9	0.87	0.58	0.12	4.07	4.5	smooth	little to none	slight	none	FS 2, planar	natural				
score mean	*12*	*7*	*17*	*13*	*8*	*2*	*0*	*1*	*5*	*5*	*15*	*-25*	*15*	**50**	**55**	**46**	**51**
score median	*12*	*7*	*17*	*13*	*8*	*2*	*1*	*1*	*5*	*5*	*15*	*-25*	*15*	**51**	**56**	**47**	**52**

Table A22.2 Scoring summary of each parameter and score totals for SMR in the Mt Owen Formation. RMR can be found by removing the Joint Orientation Adjustment ("Joint adjust.") and Excavation Adjustment ("Excav. adjust.") from the total score.

Fracture Set	**Joint Spacing (m)**	**Aperture (mm)**	**Continuity/Infill**	**Number of Fractures in Window**
FS 1 (mean/median)	0.16 / 0.11	10.2 / 4.5	Continuous/none	13
FS 2 (mean/median)	0.19 / 0.15	10.2 / 4.5	Continuous/none	13

Table A22.3 Selected data by fracture set. The mean or median of raw data is reported as "mean / median."

Appendix A23: Madison Group Formation

Measured August 2011. Massive limestone.
Exposure Blacktail Butte, WY. Natural outcrop.
Window studied: N 43º 39' 41" W 110º 41' 50"; 10 m high, 10 m long.
Outcrop strike/dip: 322º/71º SW
Fracture set one (bedding planes) ("FS1") strike/dip: 322º/71º SW
Fracture set two ("FS2") strike/dip: 052º/85º SE
Fracture set three ("FS3") strike/dip: 232º/75º NW

Fig. A23.1 Outcrop of Madison Group at Blacktail Butte.

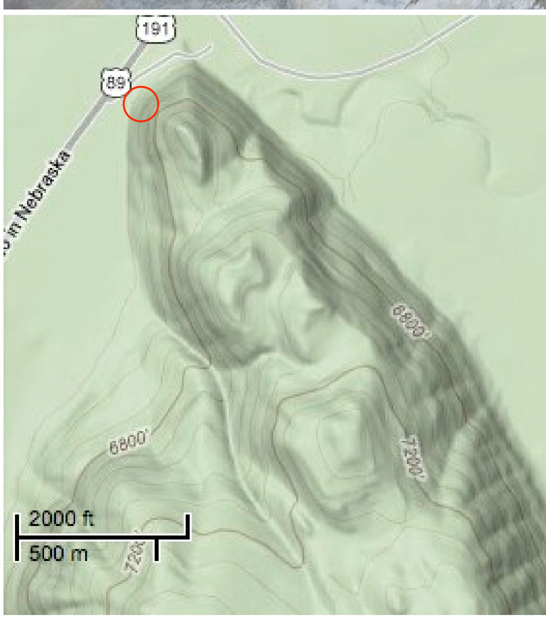

Fig. A23.2 Approximate location of Madison Group Formation outcrop at red circle.

Fig. A23.3 Close-up of Madison Group Formation. White chalk circle is 110cm in diameter.

Madison	ISR (Schmidt rebound)	Weathering	Joint Space Mean (m)	Joint Space Wtd Avg (m)	Joint Dip & Orientation	Joint Width Mean (mm)	Joint Width Wtd Avg (mm)	Continuity/Infill Mean	Groundwater	Mean Total	Wtd Avg Total
mean	58.3	slight	0.32	0.32	71° out of slope	10.2	10.2	Continuous/none	none		
median	59	slight	0.24	0.23	71° out of slope	5.5	5.5	Continuous/none	none		
score mean	*19*	*9*	*18*	*18*	*5*	*4*	*4*	*5*	*6*	**66**	**66**
score median	*19*	*9*	*16*	*16*	*5*	*4*	*4*	*5*	*6*	**64**	**64**

Table A23.1 Scoring summary of each parameter and score totals for RMS in the Madison Formation. Mean and median rows represent whether the mean or median of raw data was used. Columns that indicate mean or weighted average ("Wtd Avg") are describing whether data from multiple joint sets was simply averaged together, or whether a weighted average was taken based on the number of joints observed in the window studied.

Madison	Kidy. (MPa)	Kahr. (MPa)	Tot RQD	RQD mult	Joint Space (m)	Persistence (m)	Aperture (mm)	Rough	Infill	Weathering	Ground-water	Joint adjust.	Excav. adjust.	Totals-Kahr-total RQD	Totals-Kidy-total RQD	Totals-Kahr-RQD mult	Totals-Kidy-RQD mult
mean	88.5	58.2	0.98	0.95	0.32	2.59	10.2	slight-smooth	none or thin/ hard	slight	none	FS 1, planar	natural				
median	91.4	59.7	0.98	0.95	0.23	2.59	5.5	slight-smooth	none or thin/ hard	slight	none	FS 1, planar	natural				
score mean	*7*	*7*	*20*	*20*	*10*	*4*	*0*	*2*	*5*	*5*	*15*	*-25*	*15*	**58**	**58**	**58**	**58**
score median	*7*	*7*	*20*	*20*	*10*	*4*	*0*	*2*	*5*	*5*	*15*	*-25*	*15*	**58**	**58**	**58**	**58**

Table A23.2 Scoring summary of each parameter and score totals for SMR in the Madison Formation. RMR can be found by removing the Joint Orientation Adjustment ("Joint adjust.") and Excavation Adjustment ("Excav. adjust.") from the total score.

Fracture Set	Joint Spacing (m)	Aperture (mm)	Continuity/Infill	Number of Fractures in Window
FS 1 (bedding, outcrop face) (mean/median)	n/a	n/a	n/a	n/a
FS 2 (mean/median)	0.28 / 0.21	10.2 / 5.5	Continuous/none	18
FS 3 (mena/median)	0.35 / 0.26	10.2 / 5.5	Continuous/thick	5

Table A23.3 Selected data by fracture set. The mean or median of raw data is reported as "mean / median."

Appendix B

Score Type	Data Set	Topo. Metric	R2 value
RMS	SW VA, no carbonates, median of meas., mean of joints, 2ord log fit	avg. relief	0.8943
RMS	SW VA, no carbonates, mean of meas, mean of joints, 2ord log fit	topo score	0.8428
RMS	SW VA, no carbonates, median of meas., mean of joints, 2ord log fit	topo score	0.8236
RMS	SW VA, no carbonates, mean of meas, mean of joints	topo score	0.7973
RMS	SW VA, no carbonates, median of meas., mean of joints	topo score	0.7798
RMS	SW VA, no carbonates, mean of meas, wt avg of joints, 2ord log fit	avg. slope	0.766
RMS	SW VA, no carbonates, median of meas., mean of joints	avg. relief	0.7651
RMS	SW VA, no carbonates, mean of meas., mean of joints	avg. relief	0.7567
RMS	SW VA, no carbonates, mean of meas, wt avg of joints	avg. slope	0.7102
RMS	SW VA, no carbonates, median of meas., mean of joints	avg. slope	0.7053
RMS	SW VA, no carbonates, median of meas., mean of joints, 2ord log fit	topo score	0.7034
RMS	SW VA, no carbonates, median of meas, wt avg of joints	avg. slope	0.6914
RMS	East coast, no carbonates, mean of joints, median of meas	avg. relief	0.6627
RMS	East coast, no carbonates, mean of joints, mean of meas	avg. relief	0.6384
RMS	SW VA, no carbonates, mean of joints, mean of meas	topo score	0.6318
RMS	SW VA, no carbonates, mean of meas, wt avg of joints	avg. relief	0.5927
RMS	SW VA, no carbonates, mean of meas., mean of joints	avg. slope	0.5173
RMS	East coast, no carbonates, wt avg of joints, mean of meas	avg. relief	0.4875
RMS	SW VA, no carbonates, wt avg of joints, mean of meas	topo score	0.4802
RMS	East coast, no carbonates, mean of joints, mean of meas	topo score	0.4596
RMS	SW VA, no carbonates, median of meas, wt avg of joints	avg. relief	0.4546
RMS	SW VA, no carbonates, wt avg of joints, median of meas	topo score	0.408
RMS	East coast, no carbonates, wt avg of joints, mean of meas	avg. slope	0.3837
RMS	East coast, no carbonates, mean of joints, mean of meas	avg. slope	0.3625
RMS	East coast, no carbonates, wt avg of joints, median of meas	avg. relief	0.3612
RMS	East coast, no carbonates, wt avg of joints, median of meas	avg. slope	0.3566
RMS	East coast, no carbonates, mean of joints, median of meas	avg. slope	0.352
RMS	East coast, no carbonates, wt avg of joints, mean of meas	topo score	0.3424
RMS	no carbonates, wt avg of joints, mean of meas	topo score	0.2588
RMS	no carbonates, mean of joints, mean of meas	topo score	0.2567
RMS	All sites, no carbonates, mean of meas, wt avg of joints	avg. relief	0.2454
RMS	All sites, no carbonates, median of meas, mean of joints	avg. relief	0.241
RMS	no carbonates, wt avg of joints, median of meas	topo score	0.2286
RMS	All sites, no carbonates, median of meas, wt avg of joints	avg. slope	0.2221
RMS	All sites, no carbonates, mean of meas, wt avg of joints	avg. slope	0.2163
RMS	All sites, no carbonates, median of meas, wt avg of joints	avg. relief	0.2129
RMS	All sites, no carbonates, mean of meas, mean of joints	avg. relief	0.2084
RMS	All sites, no carbonates, median of meas, mean of joints	avg. slope	0.1497
RMS	All sites, no carbonates, mean of meas, mean of joints	avg. slope	0.1333
RMS	East coast, mean of joints, mean of meas	topo score	0.0872
RMS	All SW VA, mean of measurements, mean of joints	avg. relief	0.0822
RMS	All SW VA, median of measurements, mean of joints	avg. relief	0.0683
RMS	All SW VA, median of measurements, wt avg of joints	avg. slope	0.0466
RMS	All SW VA, median of measurements, wt avg of joints	avg. relief	0.0437

RMS	Maine, no carbonates, median of meas., mean of joints	avg. relief	0.0434
RMS	All SW VA, mean of measurements, mean of joints	avg. slope	0.0325
RMS	All SW VA, median of measurements, mean of joints	avg. slope	0.0269
RMS	all sites, mean of joints, median of meas	topo score	0.0259
RMS	Tetons, no carbonates, median of meas., mean of joints	avg. relief	0.0241
RMS	All SW VA, mean of joints, mean of meas	topo score	0.0216
RMS	all sites, mean of joints, mean of meas	topo score	0.0215
RMS	all sites, wt avg of joints, median of meas	topo score	0.0204
RMS	all sites, wt avg of joints, mean of meas	topo score	0.0183
RMS	All SW VA, mean of measurements, wt avg of joints	avg. relief	0.0179
RMS	All SW VA, mean of measurements, wt avg of joints	avg. slope	0.0142
SMR	SW VA, no carbonates, mult RQD, mean of meas, kidy ucs, 2ord log fit	avg. relief	0.9221
SMR	SW VA, no carbonates, total RQD, mean of meas, kidy ucs, 2ord log fit	avg. relief	0.9022
SMR	SW VA, no carbonates, total RQD, mean of meas, kidy ucs	avg. relief	0.8654
SMR	SW VA, no carbonates, mult RQD, mean of meas, kahr ucs, 2ord log fit	avg. relief	0.865
SMR	SW VA, no carbonates, mult RQD, mean of meas, kidy ucs, 2ord log fit	avg. slope	0.8584
SMR	SW VA, no carbonates, mult RQD, mean of meas, kidy ucs	avg. slope	0.8441
SMR	SW VA, no carbonates, mult RQD, mean of meas, kidy ucs	avg. relief	0.8412
SMR	SW VA, no carbonates, total RQD, mean of meas, kahr ucs, 2ord log fit	avg. relief	0.835
SMR	SW VA, no carbonates, total RQD, mean of meas, kahr ucs	avg. relief	0.8045
SMR	SW VA, no carbonates, mult RQD, median of meas, kidy ucs, 2ord log fit	avg. relief	0.8004
SMR	SW VA, no carbonates, total RQD, median of meas, kidy ucs, 2ord log fit	avg. relief	0.7923
SMR	SW VA, no carbonates, mult RQD, mean of meas, kahr ucs	avg. relief	0.7911
SMR	SW VA, total RQD, mean of meas, kidy meas	avg. relief	0.7844
SMR	SW VA, mult RQD, mean of meas, kidy meas	avg. relief	0.7835
SMR	SW VA, no carbonates, total RQD, median of meas, kidy ucs	avg. relief	0.7678
SMR	SW VA, no carbonates, mult RQD, mean of meas, kidy ucs, 2pd exp	topo score	0.7405
SMR	SW VA, no carbonates, mult RQD, median of meas, kahr ucs, 2ord log fit	avg. relief	0.738
SMR	SW VA, no carbonates, mult RQD, median of meas, kidy ucs	avg. relief	0.7369
SMR	SW VA, no carbonates, total RQD, median of meas, kahr ucs, 2ord log fit	avg. relief	0.7193
SMR	SW VA, no carbonates, total RQD, median of meas, kahr ucs	avg. relief	0.7005
SMR	SW VA, no carbonates, mult RQD, median of meas, kahr ucs	avg. relief	0.6814
SMR	SW VA, no carbonates, mult RQD, mean of meas, kidy ucs	topo score	0.6802
SMR	SW VA, no carbonates, mult RQD, mean of meas, kidy ucs, 2ord log fit	topo score	0.5711
SMR	East coast, no carbonates, mult RQD, mean of meas, kidy ucs	avg. relief	0.4964
SMR	East coast, no carbonates, total RQD, mean of meas, kidy ucs	avg. relief	0.4931
SMR	East coast, no carbonates, mult RQD, mean of meas, kahr ucs	avg. relief	0.478
SMR	East coast, no carbonates, mult RQD, median of meas, kidy ucs	avg. relief	0.4763
SMR	East coast, no carbonates, total RQD, median of meas, kidy ucs	avg. relief	0.4717
SMR	East coast, no carbonates, total RQD, mean of meas, kahr ucs	avg. relief	0.471
SMR	East coast, no carbonates, mult RQD, median of meas, kahr ucs	avg. relief	0.4657
SMR	no carbonates, total RQD, median of meas, kahr ucs	topo score	0.4621
SMR	East coast, no carbonates, total RQD, median of meas, kahr ucs	avg. relief	0.4619
SMR	no carbonates, total RQD, median of meas, kidy ucs	topo score	0.4546
SMR	no carbonates, total RQD, mean of meas, kidy ucs	topo score	0.4497
SMR	no carbonates, total RQD, mean of meas, kahr ucs	topo score	0.4356

SMR	All sites, no carbonates, total RQD, mean of meas, kidy ucs	avg. relief	0.3485
SMR	all sites, total RQD, median of meas, kidy ucs	topo score	0.3377
SMR	All sites, no carbonates, mult RQD, mean of meas, kidy ucs	avg. relief	0.3372
SMR	all sites, mult RQD, median of meas, kidy ucs	topo score	0.337
SMR	all sites, total RQD, mean of meas, kidy ucs	topo score	0.3298
SMR	all sites, mult RQD, mean of meas, kidy ucs	topo score	0.329
SMR	all sites, mult RQD, median of meas, kahr ucs	topo score	0.3282
SMR	all sites, total RQD, median of meas, kahr ucs	topo score	0.3275
SMR	All sites, no carbonates, total RQD, median of meas, kidy ucs	avg. relief	0.3192
SMR	All sites, no carbonates, mult RQD, median of meas, kidy ucs	avg. relief	0.3121
SMR	All sites, no carbonates, total RQD, mean of meas, kahr ucs	avg. relief	0.3116
SMR	all sites, mult RQD, mean of meas, kahr ucs	topo score	0.3051
SMR	All sites, no carbonates, mult RQD, mean of meas, kahr ucs	avg. relief	0.305
SMR	all sites, total RQD, mean of meas, kahr ucs	topo score	0.3025
SMR	All sites, no carbonates, total RQD, median of meas, kahr ucs	avg. relief	0.2972
SMR	All sites, no carbonates, mult RQD, median of meas, kahr ucs	avg. relief	0.2917
SMR	All sites, no carbonates, total RQD, mean of meas, kidy ucs	avg. slope	0.1495
SMR	All sites, no carbonates, total RQD, median of meas, kidy ucs	avg. slope	0.1492
SMR	All sites, no carbonates, mult RQD, median of meas, kidy ucs	avg. slope	0.1451
SMR	All sites, no carbonates, mult RQD, mean of meas, kidy ucs	avg. slope	0.1444
SMR	All sites, no carbonates, total RQD, median of meas, kahr ucs	avg. slope	0.134
SMR	All sites, no carbonates, mult RQD, median of meas, kahr ucs	avg. slope	0.131
SMR	All sites, no carbonates, total RQD, mean of meas, kahr ucs	avg. slope	0.1282
SMR	All sites, no carbonates, mult RQD, mean of meas, kahr ucs	avg. slope	0.1255
SMR	East coast, no carbonates, mult RQD, median of meas, kidy ucs	avg. slope	0.1168
SMR	East coast, no carbonates, mult RQD, median of meas, kahr ucs	avg. slope	0.1113
SMR	East coast, no carbonates, total RQD, median of meas, kidy ucs	avg. slope	0.1103
SMR	East coast, no carbonates, total RQD, median of meas, kahr ucs	avg. slope	0.1051
SMR	East coast, no carbonates, mult RQD, mean of meas, kidy ucs	avg. slope	0.1044
SMR	East coast, no carbonates, mult RQD, mean of meas, kahr ucs	avg. slope	0.0984
SMR	East coast, no carbonates, total RQD, mean of meas, kidy ucs	avg. slope	0.0971
SMR	East coast, no carbonates, total RQD, mean of meas, kahr ucs	avg. slope	0.0907
SMR	Tetons, no carbonates, total RQD, mean of meas, kidy ucs	avg. relief	0.0513
SMR	Maine, no carbonates, total RQD, mean of meas, kidy ucs	avg. relief	0.0481
RMR	SW VA, no carbonates, mult RQD, mean of meas, kidy ucs, 2ord log fit	avg. slope	0.7891
RMR	SW VA, no carbonates, mult RQD, mean of meas, kidy ucs	topo score	0.7783
RMR	SW VA, no carbonates, mult RQD, median of meas, kidy ucs, 2ord log fit	topo score	0.7676
RMR	SW VA, no carbonates, mult RQD, median of meas, kidy ucs	topo score	0.7627
RMR	SW VA, no carbonates, mult RQD, mean of meas, kahr ucs, 2ord log fit	topo score	0.7608
RMR	SW VA, no carbonates, total RQD, median of meas, kidy ucs, 2ord log fit	topo score	0.7491
RMR	SW VA, no carbonates, mult RQD, median of meas, kahr ucs, 2ord log fit	topo score	0.7456
RMR	SW VA, no carbonates, mult RQD, mean of meas, kidy ucs, 2ord log fit	topo score	0.7434
RMR	SW VA, no carbonates, total RQD, mean of meas, kidy ucs, 2ord log fit	avg. slope	0.7209
RMR	SW VA, no carbonates, mult RQD, mean of meas, kahr ucs	topo score	0.7122
RMR	SW VA, no carbonates, mult RQD, mean of meas, kidy ucs	avg. slope	0.7108
RMR	SW VA, no carbonates, mult RQD, median of meas, kidy ucs, 2ord log fit	avg. slope	0.7079

RMR	SW VA, no carbonates, mult RQD, median of meas, kahr ucs	topo score	0.6931
RMR	SW VA, no carbonates, total RQD, mean of meas, kidy ucs	topo score	0.6871
RMR	SW VA, no carbonates, mult RQD, mean of meas, kahr ucs, 2ord log fit	avg. slope	0.6469
RMR	SW VA, no carbonates, mult RQD, median of meas, kidy ucs	avg. slope	0.6439
RMR	SW VA, no carbonates, mult RQD, mean of meas, kidy ucs, 2ord log fit	avg. relief	0.6409
RMR	SW VA, no carbonates, total RQD, mean of meas, kidy ucs, 2ord log fit	avg. relief	0.6278
RMR	SW VA, no carbonates, mult RQD, mean of meas, kahr ucs, 2ord log fit	avg. relief	0.5292
RMR	no carbonates, total RQD, median of meas, kahr ucs	topo score	0.4903
RMR	SW VA, no carbonates, total RQD, mean of meas, kahr ucs, 2ord log fit	avg. relief	0.4864
RMR	SW VA, no carbonates, mult RQD, median of meas, kidy ucs, 2ord log fit	avg. relief	0.4509
RMR	SW VA, no carbonates, total RQD, mean of meas, kidy ucs	avg. relief	0.4325
RMR	no carbonates, total RQD, mean of meas, kahr ucs	topo score	0.4283
RMR	SW VA, no carbonates, total RQD, median of meas, kidy ucs, 2ord log fit	avg. relief	0.4276
RMR	SW VA, no carbonates, mult RQD, mean of meas, kidy ucs	avg. relief	0.4192
RMR	no carbonates, total RQD, median of meas, kidy ucs	topo score	0.408
RMR	no carbonates, total RQD, mean of meas, kidy ucs	topo score	0.3764
RMR	SW VA, no carbonates, mult RQD, median of meas, kahr ucs, 2ord log fit	avg. relief	0.3677
RMR	SW VA, no carbonates, mult RQD, mean of meas, kahr ucs	avg. relief	0.3399
RMR	SW VA, no carbonates, total RQD, mean of meas, kahr ucs	avg. relief	0.3294
RMR	SW VA, no carbonates, total RQD, median of meas, kahr ucs, 2ord log fit	avg. relief	0.3284
RMR	SW VA, no carbonates, total RQD, median of meas, kidy ucs	avg. relief	0.2993
RMR	SW VA, no carbonates, mult RQD, median of meas, kidy ucs	avg. relief	0.2988
RMR	all sites, total RQD, median of meas, kahr ucs	topo score	0.2679
RMR	no carbonates, total RQD, mean of meas, kidy ucs	avg. relief	0.2646
RMR	all sites, mult RQD, median of meas, kahr ucs	topo score	0.2534
RMR	no carbonates, total RQD, mean of meas, kahr ucs	avg. relief	0.2422
RMR	SW VA, no carbonates, mult RQD, median of meas, kahr ucs	avg. relief	0.2394
RMR	all sites, total RQD, median of meas, kidy ucs	topo score	0.238
RMR	no carbonates, mult RQD, mean of meas, kidy ucs	avg. relief	0.2379
RMR	all sites, mult RQD, median of meas, kidy ucs	topo score	0.2294
RMR	SW VA, no carbonates, total RQD, median of meas, kahr ucs	avg. relief	0.2262
RMR	no carbonates, total RQD, median of meas, kidy ucs	avg. relief	0.2232
RMR	no carbonates, total RQD, median of meas, kahr ucs	avg. relief	0.2204
RMR	no carbonates, mult RQD, mean of meas, kahr ucs	avg. relief	0.2202
RMR	all sites, total RQD, mean of meas, kidy ucs	topo score	0.2121
RMR	no carbonates, mult RQD, median of meas, kidy ucs	avg. relief	0.211
RMR	no carbonates, mult RQD, median of meas, kahr ucs	avg. relief	0.2057
RMR	All sites, total RQD, mean of meas, kidy ucs	avg. relief	0.2051
RMR	all sites, mult RQD, mean of meas, kidy ucs	topo score	0.205
RMR	all sites, total RQD, mean of meas, kahr ucs	topo score	0.2018
RMR	All sites, mult RQD, mean of meas, kidy ucs	avg. relief	0.1984
RMR	all sites, mult RQD, mean of meas, kahr ucs	topo score	0.1984
RMR	All sites, total RQD, median of meas, kidy ucs	avg. relief	0.1832
RMR	All sites, mult RQD, median of meas, kidy ucs	avg. relief	0.1829
RMR	no carbonates, total RQD, median of meas, kidy ucs	avg. slope	0.1804
RMR	no carbonates, total RQD, mean of meas, kidy ucs	avg. slope	0.1778
RMR	no carbonates, total RQD, median of meas, kahr ucs	avg. slope	0.1625

RMR	no carbonates, mult RQD, median of meas, kidy ucs	avg. slope	0.1587
RMR	All sites, mult RQD, mean of meas, kahr ucs	avg. relief	0.1552
RMR	no carbonates, mult RQD, mean of meas, kidy ucs	avg. slope	0.1515
RMR	no carbonates, total RQD, mean of meas, kahr ucs	avg. slope	0.1513
RMR	All sites, total RQD, mean of meas, kahr ucs	avg. relief	0.1508
RMR	no carbonates, mult RQD, median of meas, kahr ucs	avg. slope	0.1426
RMR	All sites, mult RQD, median of meas, kahr ucs	avg. relief	0.1403
RMR	All sites, total RQD, median of meas, kahr ucs	avg. relief	0.134
RMR	no carbonates, mult RQD, mean of meas, kahr ucs	avg. slope	0.131
RMR	All sites, total RQD, median of meas, kidy ucs	avg. slope	0.1189
RMR	All sites, mult RQD, median of meas, kidy ucs	avg. slope	0.1102
RMR	All sites, total RQD, mean of meas, kidy ucs	avg. slope	0.0992
RMR	All sites, mult RQD, mean of meas, kidy ucs	avg. slope	0.0926
RMR	All sites, mult RQD, median of meas, kahr ucs	avg. slope	0.0632
RMR	All sites, total RQD, median of meas, kahr ucs	avg. slope	0.0623
RMR	All sites, mult RQD, mean of meas, kahr ucs	avg. slope	0.0578
RMR	All sites, total RQD, mean of meas, kahr ucs	avg. slope	0.0558
SchmidtHam	SW VA, no carbonates, mean of meas, 2ord log fit	topo score	0.8999
SchmidtHam	SW VA, no carbonates, mean of meas	topo score	0.797
SchmidtHam	SW VA, no carbonates, median of meas	topo score	0.7942
SchmidtHam	SW VA, no carbonates, median of meas, 2ord log fit	topo score	0.7827
SchmidtHam	SW VA, no carbonates, mean of meas, 2ord log fit	avg. relief	0.5538
SchmidtHam	SW VA, no carbonates, no shale, mean of meas, 2ord log fit	avg. relief	0.5351
SchmidtHam	SW VA, no carbonates, median of meas, 2ord log fit	avg. relief	0.5217
SchmidtHam	SW VA, no carbonates, mean of Schmidt rebounds	avg. slope	0.4129
SchmidtHam	SW VA, no carbonates, no shale, median of meas, 2ord log fit	avg. relief	0.4119
SchmidtHam	SW VA, no carbonates, median of Schmidt rebounds	avg. slope	0.3976
SchmidtHam	SW VA, no carbonates, no shale, mean of meas, 2ord log fit	avg. slope	0.39
SchmidtHam	no carbonates, mean of meas, 2nd degree poly fit	avg. slope	0.2934
SchmidtHam	SW VA, no carbonates, mean of Schmidt rebounds	avg. relief	0.284
SchmidtHam	SW VA, no carbonates, median of Schmidt rebounds	avg. relief	0.2559
SchmidtHam	no carbonates, no shale, mean of meas, 2nd degree poly fit	avg. slope	0.1728
SchmidtHam	All SW VA, median of Schmid hammer rebounds	avg. slope	0.1049
SchmidtHam	All SW VA, mean of Schmidt hammer rebounds	avg. slope	0.1
SchmidtHam	All SW VA, mean of Schmidt hammer rebounds	avg. relief	0.077
SchmidtHam	All SW VA, median of Schmid hammer rebounds	avg. relief	0.0752

Appendix C

The following code was written for use in MATLAB and consists of Version 1, which optimizes the weights of parameters in rating systems to maximize the correlation to topography, and Version 2, which optimizes an adjustment factor to be added to rocks that are not chemically susceptible to weathering, also to maximize the correlation of ratings to topography. Both versions consist of a script and a function.

Version 1: Parameter Weight Optimization

Script:

```
smrW = load('SMRWeights.txt'); %SMR weights does not include joint
orientation adjustment or slope excavation adjustment

ucs = (load('SMRwtdUCSmean.txt'))/smrW(1);

RQD = (load('SMRwtdRQD.txt'))/smrW(2);

jspace = (load('SMRwtdJSpace.txt'))/smrW(3);

pers = (load('SMRwtdPers.txt'))/smrW(4);

aper = (load('SMRwtdAper.txt'))/smrW(5);

rough = (load('SMRwtdRough.txt'))/smrW(6);

infil = (load('SMRwtdInfill.txt'))/smrW(7);

jweath = (load('SMRwtdJWeath.txt'))/smrW(8);

gw = (load('SMRwtdGW.txt'))/smrW(9);

f1f2 = (load('f1f2.txt')); %this parameter is not "de-weighted"

excav = (load('excav.txt')); %this parameter is not "de-weighted"

topo = load('MeanReliefSWVA.txt'); %this parameter is not "de-weighted"

initW = 100*rand(11,1);

Aeq = [ones(1,9) zeros(1,2)];

Beq = 100;
```

```
lb = [zeros(9,1); -100; -100; 0];

ub = [100*(ones(9,1)); 0; 100; 100];


options = optimset('Display', 'iter', 'algorithm', 'interior-point');


[Wopt negRsq] = fmincon(@(W)SMRcalcnegRsquared(W, jspace, ucs, aper,
rough, pers, infil, jweath, RQD, gw, f1f2, excav, topo), initW, [], [],
Aeq, Beq, lb, ub, [], options)
```

Function:

```
function [ negRsq ] = SMRcalcnegRsquared( W, jspace, ucs, aper, rough,
pers, infil, jweath, RQD, gw, f1f2, excav, topo )


SMR = W(1)*ucs + W(2)*RQD + W(3)*jspace + W(4)*pers + W(5)*aper +
W(6)*rough + W(7)*infil + W(8)*jweath + W(9)*gw + W(10)*f1f2 +
W(11)*excav;

SMR_ones = [SMR, ones(length(SMR), 1)];


[temp1, temp2, temp3, temp4, stats] = regress(topo, SMR_ones);

negRsq = -stats(1);

end
```

Version 2: Chemical Weatherability Adjustment Factor Optimization

Script:

```
selbyW = load('SelbyWeights.txt');

isr = (load('WeightedISRmean.txt'))/selbyW(1);

weath = (load('WeightedWeath.txt'))/selbyW(2);

js = (load('WeightedJSmean.txt'))/selbyW(3);

jo = (load('WeightedJO.txt'))/selbyW(4);

jw = (load('WeightedJWmean.txt'))/selbyW(5);

jic = (load('WeightedJIC.txt'))/selbyW(6);

gw = (load('WeightedGW.txt'))/selbyW(7);

carbo = (load('carbo.txt'));

topo = load('MeanReliefSWVA.txt');


W_fixed = selbyW;

initW = 50*randn(1,1);

% initW = [100;0;0;0;0;0;0];

% initW = selbyW;

Aeq = [];

Beq = [];

lb = -100;

ub = 100;


options = optimset('Display', 'iter', 'algorithm', 'interior-point');


[Wopt negRsq] = fmincon(@(W_carb)RMScalcnegRsquared_carb(W_carb,
W_fixed, isr, jo, jw, js, jic, gw, weath, topo, carbo), initW, [], [],
Aeq, Beq, lb, ub, [], options)
```

Function:

```
function [ negRsq ] = RMScalcnegRsquared_carb( W_carb, W_fixed, isr,
jo, jw, js, jic, gw, weath, topo, carbo )


RMS = W_fixed(1)*isr + W_fixed(2)*jo + W_fixed(3)*jw + W_fixed(4)*js +
W_fixed(5)*jic + W_fixed(6)*gw + W_fixed(7)*weath + W_carb*carbo;

RMS_ones = [RMS, ones(length(RMS), 1)];



[temp1, temp2, temp3, temp4, stats] = regress(topo, RMS_ones);

negRsq = -stats(1);


end
```