

Character and Condition of Geological Resources
of Interest to the Rock Outcrop Management Project
Final Report 2006



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Key Project Data

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Abstract

This project obtained information on geologic resources within Shenandoah National Park (SHEN) that are of interest to the Rock Outcrop Management Project (ROMP). Many geologic factors influence the occurrence and nature of the 50 rock exposure sites selected by the project, including bedrock composition, exposure morphology, regional geologic history, physical stability, and geographic location. The three main bedrock types within SHEN, and their associated geologic structures, create distinctly different rock exposure patterns and habitats that directly affect vegetation growth patterns. There appears to be a direct correlation between ease of visitor access and level of physical impact observed, assessed through the prevalence of social trails, rock graffiti, trash, soil & vegetation damage, and other factors. General-purpose visitation, rather than rock climbing, appears to be the dominant producer of such impacts. Although many of the sites contain features of geologic interest, such as well-formed minerals or structures, none of the features identified appear to be under any direct threat from human activity or physical processes.

Executive Summary

The bedrock geology of Shenandoah National Park directly influences the location, physical character, and soil chemistry of open rock exposures within the park, and thus the vegetation communities that rely upon these exposures. Three fundamentally different rock types (igneous/metamorphic, greenstone, and metasedimentary) occur within discrete areas and elevations of the park, producing unique outcrop patterns and generating physically and chemically distinct landforms and habitats. For example, greenstone lava flows cap many of the highest peaks in the park, tend to produce high-elevation southwest to west facing cliff sites and gentle eastern slopes with deep canyons, create more open ledges than other rock types, and are particularly supportive of diverse vegetation communities due to their mineral/chemical composition. Documenting these patterns allows a deeper understanding of the rare plant and animal communities that rely upon open rock exposures within the park.

Bedrock geology also affects, and is affected by, patterns of human use. For example, rock climbing activity is centered on areas where geologic processes have created suitable exposures, and visitors are drawn to overlooks, vistas, and peaks dominated by open rock. The location, orientation, and physical character of such places are directly related to the geologic processes

that created them. In turn, human activities can have a noticeable impact on open rock areas. Development of social trails, stripping of soils, scratching of graffiti into rock surfaces, collection of minerals or samples, and various climbing impacts all contribute to altering the natural state of geologic resources within the park.

The purpose of this project is to document and interpret the geologic resources and processes that affect sites within the Rock Outcrop Management Project (ROMP). Between April 2005 and September 2006, 50 sites (see Fig. 1 and Tables 1-3) were studied and mapped in detail. Final reports (Appendix F) were produced for each site that document the bedrock composition, exposure morphology, regional geologic history, physical stability, and geographic location.

Collected data and observations support the conclusion that different rock types produce unique outcrop patterns and thus unique ecological habitats. For example, greenstone areas are most likely to contain cliffs and ledges, igneous/metamorphic basement rock areas are most likely to contain rounded faces, and metasedimentary areas are most likely to contain large amounts of talus (see Fig. 2 and Appendix B for definitions). Assessment of the physical condition of ROMP sites (see Fig. 3 and Table 4) shows a direct correlation between ease of visitor access and level of impact observed. Exceptions to this trend occur at certain popular, though difficult to access, sites such as Old Rag Mountain. The majority of impacts appear to be related to general-purpose visitation rather than climbing specifically. Although many of the sites contain features of geologic interest (see Fig. 4 & 5) such as well-formed minerals or structures, none of these features appear to be under any direct threat from human activity or physical processes.

Acknowledgements

Special thanks are due to G. Olson, W. Cass, and S. Bair of the National Park Service (NPS) for their widespread support of this project. J. Young of the United States Geologic Survey (USGS) gave valuable assistance with mapping and field work, as did G. Fleming, A. Belden, K. Heffernan and other cooperating researchers from the Virginia Department of Conservation and Recreation (VADCR). A. Williams (NPS) was instrumental in developing efficient data management tools and methods. S. Southworth (USGS) and L. McClelland (NPS) provided important feedback in developing the study plan.

Significant Findings

- * Bedrock composition, internal structures, and other geologic factors directly affect the location and physical nature of open rock exposures, and thus the natural habitats and recreational opportunities these exposures provide.
- * There is a correlation between ease of visitor access and level of physical impact observed at rock exposure sites, with a few exceptions. Every site with a form of trail access showed some level of impact, while remote sites showed little to no impact.

- * No specific features of geologic interest appear to be under any direct threat from human activity or physical processes, although the general condition of the rock exposures may show significant degradation.

Management Recommendations

- * No specific management tasks are needed to preserve features of significant geologic interest within ROMP sites, beyond the park policies already in place.
- * Existing impacts to geologic or physical features are difficult to mitigate; e.g. graffiti scratched into rock cannot be removed. Any efforts directed this way should focus on prevention rather than mitigation.
- * Efforts to reduce ongoing impact to geologic resources within ROMP sites could include closure of social trails, limitation of access to rock exposure areas through signage or low rope lines, and changes to interpretive literature and/or trail guides.

Introduction

Geologic processes operate over a wide range of time, distance, and rates. While many are no longer active, or operate at time scales not readily intuitive to people, their results continue to influence a wide variety of physical and chemical features within landscapes. For this reason, understanding geologic history is key to a robust investigation of ecological environments dependent on rock exposures.

Geologic studies of the Blue Ridge Mountains, and the Shenandoah area in particular, have been occurring since the turn of the past century. In 1976, Thomas Gathright of the Virginia Department of Mineral Resources published a volume entitled “Geology of the Shenandoah National Park, Virginia”, which provided a comprehensive description of the geologic history and resources of the park as understood at the time. With the development and acceptance of plate tectonic theory (culminating in the 1970s and 1980s), and introduction of new analytical methods, ongoing research provided an increasingly accurate reconstruction of the geologic processes that influenced the bedrock and landscape of SHEN and the surrounding regions (e.g. Badger et al. 2004, Burton and Southworth 2004, Tollo et al. 2004, and Morgan et al. 2004).

SHEN contains three major bedrock units of different age and composition: igneous/metamorphic, greenstone, and metasedimentary (Gathright, 1976). The oldest bedrock is composed of a complex set of igneous and metamorphic rocks formed over 1 billion years ago (the old “Pedlar Formation”, referred to in this report as “basement rocks”. See Appendix C or E for clarification). This classification includes the Old Rag Granite, a distinct rock type within the basement rocks. These rocks are capped by a thick sequence of basaltic lava flows, erupted onto the surface around 570 million years ago (the Catoctin Formation). There is a thin, intermittent layer of sediments between the Catoctin and the basement rocks, known as the Swift Run Formation. The Catoctin is overlain by several thousand feet of mixed sedimentary rocks, mostly

sandstones, siltstones, and shales (the Chilhowee Group). This entire sequence was physically and chemically altered by metamorphic processes generated during the formation of the Appalachian Mountains; thus the basaltic lavas became a related rock called greenstone, and the sedimentary rocks were folded and fused into related metasedimentary rocks such as quartzite and phyllite. Each of the three main bedrock formations (Basement, Catoclin, Chilhowee) have distinct chemical and physical properties that directly influence the surrounding landscape and vegetation communities. For more detail on the geologic formations and history of Shenandoah, see Appendices C and D.

Areas of exposed rock are common on all bedrock types within SHEN. Such exposures are found especially at high elevations, along ridgelines and waterfalls, and in other attractive and dramatic settings. These areas are naturally popular with visitors, as rock exposures tend to provide clear views and obvious recreational opportunities. Visitor use of these areas may range from passive activities such as resting and picnicking to active uses such as scrambling and climbing. The shape and location of any given rock exposure naturally affects if and how it is used by visitors, as does the means of access to the area.

The geologic field work conducted for this project focused on three major factors:

- * Physical characterization of the landscape - What is the actual appearance and nature of the landscape at the site, independent of scientific interpretation?
- * Geological characterization of the bedrock – What is the bedrock composition and structure of the site, and what geologic processes originally formed this rock?
- * Geomorphic interpretation of the landscape – What processes and features combined to create the physical landscape present at the site today?

In addition, several other factors were studied or considered during this project:

- * Mapping for future study – Developing a detailed map of exposure locations and access routes for use by current and future researchers in studying and/or managing the site.
- * Assessment of human impacts – How has human use affected the physical nature of the site?
- * Assessment of access potential – How easy is it for humans to reach and use the site?

Study Area

The ROMP includes 50 study sites, distributed throughout the park (see Figure 1 and Tables 1-3). These sites were selected from a large pool of candidates, initially identified by J. Young (United States Geologic Survey) using a computer algorithm to locate and delineate all possible sites of open rock within the park as visible on satellite and/or aerial imagery. This database was compared with a Digital Elevation Model (DEM)-based slope model of the park in order to further identify possible cliff/outcrop areas that may not have been obvious from overhead imagery. These data were used to confirm and constrain the location of known rock exposure areas, and to select several previously unknown or unvisited sites for possible inclusion in ROMP surveys.

Site selection was based on numerous factors, including perceived or documented threat to vegetation communities, bedrock geology, visitor use history, elevation/aspect, and in some cases the site's remoteness or pristine condition. Final site boundaries were drawn by cooperators from the Virginia Department of Conservation and Recreation using initial GIS data provided by J. Young of the USGS. Of the 50 sites, 32 are located on greenstone bedrock (which tends to support the most ecologic diversity), 10 on granitic/metamorphic (basement) bedrock, 7 on metasedimentary bedrock, and 1 contains exposures of both greenstone and basement rock (C69, Whiteoak Canyon).

Site access ranges from areas adjacent to Skyline Drive to remote sites involving long backcountry hikes and negotiation of significant topography. Most sites include steep, rugged areas of rock exposure, including sheer cliffs and semi-stable boulder fields. Thick vegetation is also common and is often a significant barrier to navigation. The average site covers an area approximately 170m x 460m, though the site boundaries are drawn generously and include a wide buffer of matrix forest adjacent to the rock exposures. In a few cases, site boundaries were altered to reflect the presence or absence of exposure areas near or outside the initial line.

Methods

This study consisted primarily of field mapping and personal observation of open rock exposures within the site boundaries established for the ROMP (for the purposes of this report, "open rock exposures" are those which are largely exposed to the sun, i.e. not covered or shaded by forest). All field work was conducted by geology consultant Eric Butler between April 2005 and September 2006, in cooperation with researchers from the United States Geologic Survey (USGS) and Virginia Department of Conservation and Recreation (VADCR). Field work consisted primarily of visiting each site and exploring the area within and near the established site boundary thoroughly on foot, on and off-trail, in order to fully document the location and nature of rock exposures, and their access routes. Throughout the site visit, observations and data were collected and noted on field data sheets. Later, these data were compiled into a database along with photos, maps, GPS data, and narrative summarized into individual site reports.

Study Design

The ROMP Detailed Implementation Plan summarizes the purpose of the geology survey as follows: "Classify geologic composition and condition of cliff resources". Following this broad guidance, a more detailed study plan was developed to assess the questions discussed above. While other studies of human impact on rock exposure-related vegetation have occurred (e.g. Camp and Knight, 1998), a lack of comparable geologically-focused studies led to a new design process, intended to produce a study uniquely formulated to the needs of the ROMP at SHEN. Several drafts of data sheets were developed and adapted, based on field tests and input from other cooperators including the National Park Service (NPS), United States Geologic Survey (USGS), and Virginia Department of Conservation (VADCR).

Certain types of data were considered but rejected as being less relevant to or realistic for the study, including falling hazard, percent lichen coverage, and soil classifications. Other types of

data were added, including space for geomorphic interpretations (at the request of VADCR researchers) and a five-part classification of rock exposure morphology (see Fig. 2 and Appendix B). This latter effort was designed specifically for Shenandoah rock exposures, in order to identify and distinguish morphologies present within the park that create distinctly different vegetation habitats. Certain data were intended primarily to characterize the conditions at each individual site (such as vegetation thickness and stability), while others were additionally intended to provide useful comparisons between sites (such as geomorphic classification and impacts).

The final data sheet (Appendix A) offers space to note field observations relevant to all questions on a single form, while the attached photo/GPS log sheet offers sufficient space for most sites on another single form. These final formats have not been changed through subsequent field work. See “Field Data Collection” below for more details.

Field Mapping

Each site was initially mapped in the field in conjunction with significant off-trail exploration in order to document the location of open rock exposures, access routes, significant features, and any other necessary geographic information. Initial field maps were drawn on a base map prepared in a GIS, containing the site boundary, topographic information, and existing trails/roads. GPS points were taken in the field to mark the location of important exposures or other features, and other information marked relative to the location of these points. GPS points were given a unique sequential number with the site code as a suffix; thus G059-C02 is the fifty-ninth point taken during the project and relates to C02 (Betty’s Rock). Later, these points were entered into a GIS and used to produce a more complete map, on which the relevant geographic and navigational information was redrawn by hand to ensure accuracy and efficiency. These final maps were then scanned to produce JPG and PDF files. Examples of each stage of map development are given in Appendix A.

Two final maps were prepared for each site. A detailed field map documents the location of all open rock exposures, hazards, routes, and other info within the site boundary, while a broader regional map shows surrounding topography and full access routes from the best point of entry (usually Skyline Drive, occasionally outside roads). These maps were not intended to be truly to-scale, as this was deemed outside the scope and resources of the project. The field maps are reasonable representations of the physical location and nature of open rock exposures within the site. Where practical and meaningful, rough stratigraphic and/or topographic cross-sections were included on the maps to illustrate certain details about the site.

Field Data Collection

A comprehensive data sheet (see Appendix A) was designed to facilitate collection of necessary information. This sheet was divided into five fundamental categories:

- * Geographic Characteristics – Location, elevation, dimensions, access, and other descriptions.
- * Physical Characteristics – General description & nature of the site’s landscape and vegetation.
- * Geologic Characteristics – Bedrock composition, structures, and important resources.

- * Geomorphic Characteristics – Analysis of processes and features that have or continue to influence the landscape at the site.
- * Human Effects – Potential for visitor access, and assessment of human impact on the site.

Whenever possible, data related to these categories were collected using a rating system, allowing for efficient comparison of data among different sites. For example, human impacts were assigned a rating based on a four-point scale from *Pristine-Mild-Moderate-Heavy*, with corresponding definitions (see Fig. 3 and Appendix B). In addition, specific notes were taken to document unique feature at each site. This combination allows for consistent individual assessment of each site as well as overall data analysis.

Five classifications of rock exposure morphology within SHEN were defined for this project (see Fig. 2 and Appendix B). During a site visit, relative amounts of these different morphologies were observed and noted. At the conclusion of mapping, the relative abundance of each morphology was estimated as a percentage of the total open rock exposures (not of the entire site). Thus, a site dominated by tall cliffs capped by narrow ledges and a small band of open talus at the base might be listed as 70% cliff, 20% ledge, and 10% talus. It is important to note that these data are estimates only, as it was not deemed practical or necessary to attempt to measure rock exposure dimensions to a degree that would rigorously distinguish the results from careful estimation. It is also important to note that these data refer only to open rock exposures (e.g. non-forested), as these are the only areas of interest, botanically and ecologically, to the ROMP. Cliffs, outcrops, or other visible bedrock enclosed in forest were not usually included in mapping or morphology estimates, though they were taken into account when studying and describing the overall geology of the site.

Data Management

A Microsoft Access database was developed by the Natural Resources Data Manager (A. Williams) at Shenandoah National Park (SHEN) to manage all project data. Written, numeric, and image data were entered by site number, but are fully searchable by any category. In addition, image information and GPS data within the database are linked to the project GIS file.

Site Reports

The ROMP geologic database generates written site reports by compiling relevant data into a standardized format. These site reports are generally between six and eight pages long, depending on the complexity of the site. The reports contain all written observations and analyses for the site, with associated numerical data and ratings, along with photos, GPS data, and maps. Each report is finalized in PDF format. See Appendix F for copies of all 50 site reports.

Significant Findings or Results

Geologic Influences on Rock Exposures

Many geologic factors interact to affect the location and nature of rock exposures. The bedrock lithology of a site reflects not only the original geologic processes that formed the rock, but any later processes that affected it (such as faulting, metamorphism, or folding). Both the mineral composition of the rock and the physical structures imposed upon it by outside forces (such as faults, jointing, or cleavage) combine to shape specific rock exposures. For example, areas whose bedrock contains more fractures, layering, or other planar features tend to have higher percentages of ledges and talus than areas with more massive (structureless) bedrock, which tend to form more cliffs and rounded faces.

There are significant differences in the nature of rock exposures formed from the different lithologies present within SHEN (see Fig. 6 & 7). Greenstone areas most commonly form significant lines of cliffs and ledges, and open talus areas are not uncommon. In basement rock areas, smooth rock faces are far more common than in the other rock types, isolated outcrops are about as likely as significant cliffs, and ledges are rare. Metasedimentary areas tend to produce a mixture of cliff, outcrop, and ledge, but are often dominated by large, open talus fields. As ROMP sites were not selected as a representative sample of the park, some of the results shown in Figure 6 are admittedly skewed by the selection criteria or nature of certain sites, particularly considering the relatively low number of basement and metasedimentary sites. For example, several metasedimentary sites were chosen specifically because they consisted of large talus fields; in contrast, the expansive cliffs and open faces of Old Rag Mountain pull the basement rock results in that direction. Despite these limitations, the distinctions suggested by these data match up well with observed differences between lithologies both within ROMP sites and throughout SHEN as a whole. For a more thorough discussion of the geologic factors affecting rock exposures, and the typical patterns associated with each geologic formation present in Shenandoah, see Appendix B.

Impacts Assessed

Observed human impacts varied widely between and within ROMP sites. Evidence of impact included social trails, trampled or absent vegetation, compacted or stripped soil, polished or tarnished rock surfaces, unusual lichen patterns (or lack of lichens), rock graffiti, trash, fire rings, and footprints. Impact ratings assigned in this study considered both the worst impact observed and the overall physical condition of the site; even the most impacted sites included areas of lesser or no impact. This study focused on general physical impacts and those related to the geologic resources present, and did not assess specific plants or communities.

Comparison of Results

Comparing results from this and related ROMP studies (Table 4) offers additional insight into the nature of site impact patterns. Impact assessment data were collected between 2005 and 2006 by three sources: a social science team from Virginia Tech (VT), the geology consultant, and a stewardship biologist from the Virginia Department of Conservation and Recreation (VADCR).

The VT researchers conducted detailed surveys of specific impact evidence, defined as “areas of reduced vegetation cover caused by human trampling”. These included impact zones above and below cliff areas, campsites, and social trails (paths developed through visitor use, not maintained by NPS). The geology consultant gave the sites a more general rating based on the overall physical condition of the rock exposures, considering such elements as rock graffiti, garbage, soil stripping, and social trails. Sites were rated on a 4-point scale from Pristine-Mild-Moderate-Heavy (see Figure 3 and Appendix B for definitions). The potential for visitor access was also rated on a 4-point scale from Remote-Difficult-Moderate-Easy. The VADCR stewardship biologist also rated sites based on a general rating of overall condition, focusing on condition of plant communities and presence of invasive species, but used a 3-point scale from Pristine-Minor-Major.

As of October 2006, complete assessment data from VADCR were not available. Preliminary comparisons are discussed here, and the report will be updated with complete results and discussion when the data become available. To this point, the geologist and VADCR assessments are in close agreement; for the 36 sites rated by both, “Major” generally corresponded to “Heavy” while “Minor” generally straddled the difference between “Moderate” and “Mild”. “Pristine” sites were almost always in agreement between the two studies. In addition, the observed impact level of a site appears to be directly related to its accessibility to visitors. Sites with no trail access were largely pristine, while all sites with easy access were impacted to some degree. Where exceptions occur, other factors such as popularity and terrain are often involved.

Sources of Impact

Most impact identified by this study appeared to be related to general-purpose visitor activities other than rock climbing (hiking, backpacking, vista enjoyment). These impacts were focused on areas directly reached by trail, and consisted largely of scratched graffiti, stripped soil, social trail development, and trash. Signs of climbing impact were found mostly at sites known to be recommended for climbing (e.g. Horst 2001) such as Old Rag Mountain, Little Stony Man, and North Marshall. Examples of climbing-specific impact include trampling and social trail development along cliff bases, equipment left in or near the rock (e.g. bolts, crash pads, and ropes), and cutting or disturbance of vegetation and lichens on and around cliff areas. However, in most areas where these impacts were present, day-use impacts were still the dominant human process observed. One significant exception to this correlation was the north face of Hawksbill Mountain, where apparent ice-climbing impacts (multiple occurrences of deep, parallel scratches in bedrock presumably from crampons) were found in an otherwise remote and pristine area. A subsequent visitor encounter confirmed recent ice-climbing activity in this location.

Impacts/Threats to Geologic Resources

Many sites contained features of geologic interest, such as columnar joints, unusual mineral deposits or formations, cross-bedding or other sedimentary structures, exposures of stratigraphically important units, fossils, and generally attractive rock formations. Most of these features, however, are of primary interest to geologists, and would often not be evident to the average visitor without identification and/or interpretation. In addition, most features are solid enough, large enough, and/or common enough not to warrant specific efforts at preservation in

any one place. The greatest human threat to geologic resources in Shenandoah is probably collection of loose rock samples by visitors, and such activity could not be observed or documented by this study. The general condition of the rock exposures is certainly degraded in places by human actions (graffiti, trampling, etc.) but no evidence of specific threats to individual features of interest was found. It should be noted that features which could require special attention do exist in the park, but not within the sites studied for ROMP.

Discussion and Management Recommendations

The primary factor affecting rock exposure impact appears to be ease of access for visitors. This factor takes two forms; ease of access from a trailhead, and ease of access from along a trail. The former reflects hiking distance and topography; a site several trail miles from the nearest road, with significant topography to negotiate, might reasonably be expected have much lower visitation than one very close to a road. The latter reflects visitors' ability to reach a specific exposure from a trail; a ledge just a few meters from a trail, but blocked by thick vegetation and no obvious access route, may have far less impact than a ledge farther from the trail but with an obvious social trail leading to it. This pattern is particularly common in long, linear sites with repeated exposures, such as North Marshall and South Marshall, where the impact of any individual exposure seems directly related to the presence (or not) of a social trail linking to the Appalachian Trail (which runs through the forest adjacent to the cliffs).

Another important factor appears to be the relative popularity/advertisement of a site. Certain areas within the park are commonly mentioned in hiking or interpretive guides (e.g. Old Rag Mountain), have park signs and/or parking lots devoted to them (e.g. Blackrock South District), or are simply well-known and prominent landmarks (e.g. Mary's Rock). Any of these factors can result in a site receiving a higher visitation rate (as estimated by impact level) than its accessibility might otherwise imply.

These results suggest that most management initiatives related to ROMP should focus primarily on biological resources. No sites studied require any special management attention to geologic resources, beyond general park policies already in place (prohibition of sample collection, alteration of resources, etc.). In most cases, mitigation of existing impacts would be difficult if not futile (rock graffiti cannot be removed, privately collected samples will not be returned, eroded outcrops cannot be rebuilt), and so the focus should be on preventative measures. Any management activity intended to preserve biological resources will likely also serve to protect geologic resources from further impact. Therefore, mitigation efforts might best be focused on affecting how visitors learn about and access rock exposure areas. It is unlikely that the existing popularity and general knowledge of sites could be altered, but lesser-known threatened sites could be excluded from further publications, signage, or otherwise protected from further discovery.

Decisions on prevention/mitigation efforts for individual sites are outside the scope of this study at this time, but the author has observed the successful use of low-cost, low-impact methods (single ropes delineating sensitive areas, small signs with simple symbols or wording) in the Green Mountains (Vermont) and Tettegouchee State Park (Minnesota). Often these methods are

partially self-regulating, as visitors observing others in non-compliance may say something in person, or to park staff, thus assisting the effort.

Conclusions

Geologic factors such as bedrock lithology, structures, and geologic history/processes contribute significantly to the physical location and character of open rock exposures within Shenandoah National Park. Within ROMP sites studied to this date, protection of geologic resources will require no special actions by park resource managers that are not already part of park regulations, or that will not be adopted to protect biological resources. Human impacts on open rock exposures are directly related to the ease of access routes to the site, and are predominately linked to general-purpose visitation, while climbing-specific impacts are found only in a few well-known areas. Therefore, management activities should focus on public education and/or altering visitor use patterns rather than significant closures or restrictions.

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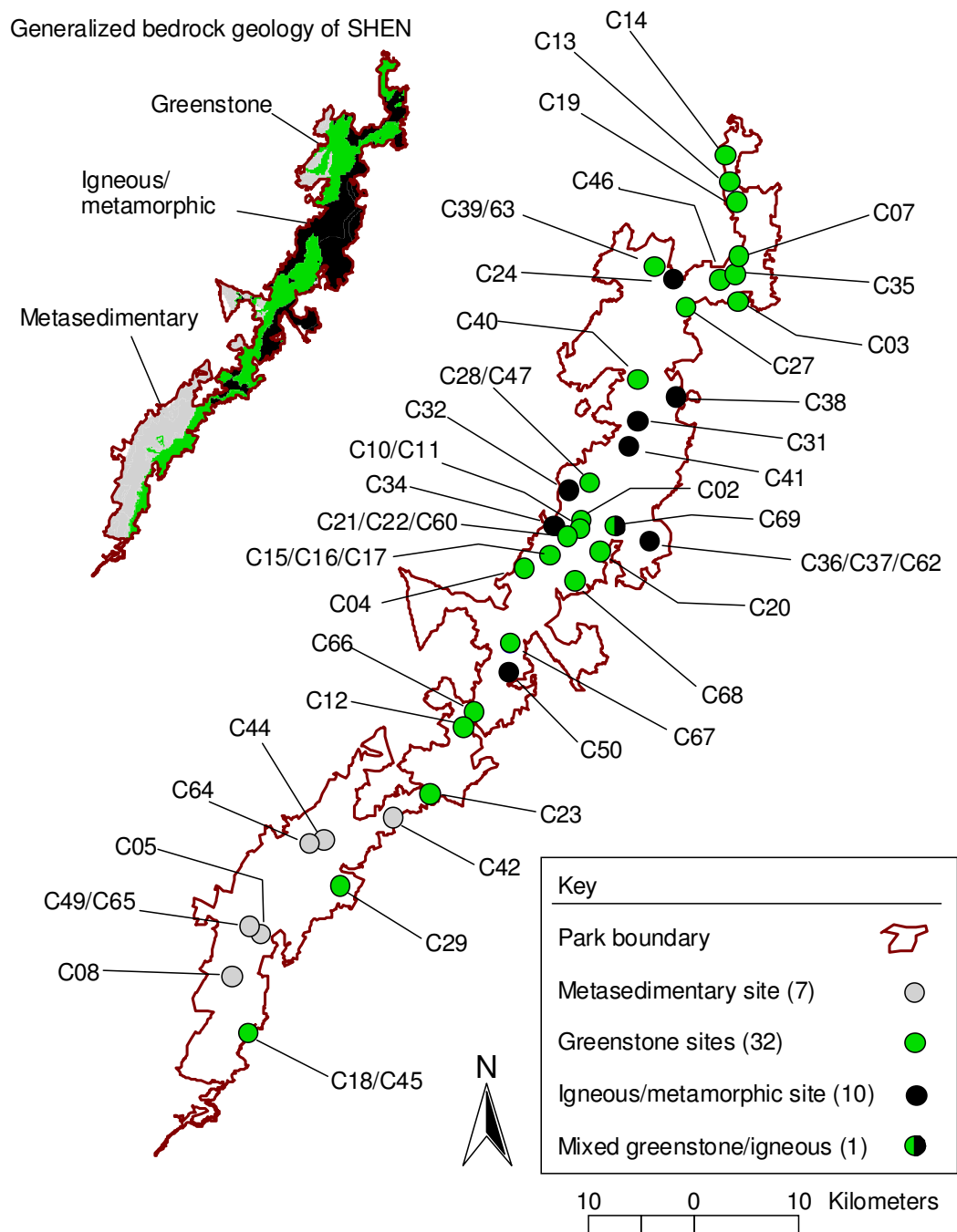


Figure 1. ROMP site locations and bedrock composition.

 Cliff	Cliff – Near-vertical exposure that dominates or creates surrounding topography. Usually continuous across slope, though may be interrupted by talus slopes or other erosional features. Generally sheer, with minor ledges along the vertical drop. Face – Continuous, rounded, gently sloping exposure (<45°) of smoothly weathered rock. Not steep enough to be a cliff, too continuous and smooth to be an outcrop, and too sloping and rounded to be a ledge. Outcrop – Intermittent exposures that stand out from surrounding topography but do not influence it. Most commonly sloping, rugged exposures with many associated ledges. May also consist of intermittent protruding rock ribs that are not continuous or wide enough to be a cliff. Ledge – Near-horizontal exposure along top or sides of cliffs and outcrops, where a local break in slope occurs, but trees and thick soil have not yet accumulated. Often hosts vegetation. Talus – Continuous to scattered rock debris with little to no soil development, covering general topography. May or may not be associated with in-place bedrock exposures.
 Face	 Outcrop
 Ledge	 Talus

Figure 2. Photographic key to rock exposure classifications used for the ROMP at SHEN.

 Heavy impact (C31, Mary's Rock) Definition: ubiquitous impacts; trails and compaction are prevalent, rocks are carved, polished, or otherwise obviously impacted, trash or other debris may be common, vegetation severely diminished.	 Moderate impact (C02, Betty's Rock) Definition: significant impacts; trails and compaction are common, areas of use are clearly visible, vegetation clearly affected and diminished.
 Mild impact (C11, Crescent Rock South) Definition: minor impacts; minor trails, slight compaction, vegetation sporadically affected, most of site is untouched.	 Pristine (C40, Pass Mountain) Definition: no impacts; trails/compaction nonexistent, absolutely no signs of human use or visitation.

Figure 3. Photographic key to physical impact ratings used for the ROMP at SHEN.

	(a) Joints – Large, planar, parallel fractures with a consistent orientation, generally more widely spaced than fractures or cleavage. (b) Foliation – This is a banded texture within an igneous/ metamorphic rock that is formed by planar zones of minerals segregated by individual type. (c) Fractures – These are random cracks within the rock, not uniformly planar and parallel like joints, and not related to mineral orientations like foliation or cleavage.	
	(d) Dike – This is an intrusion of dark igneous rock that generally follows a joint and forms a thin, planar body within the host rock. (e) Cleavage – This creates a thin, platy set of fractures oriented in a roughly similar direction, and related to orientation of minerals such as chlorite. Much more densely occurring than joints, and more aligned than fractures. (f) Layering – A planar structure internal to the rock, formed by deposition of sediment, and not segregated by mineral type & orientation as in foliation. May cut across older layers at different angles, forming cross-bedding (as seen here).	
		

(a) Joints (Mary's Rock)	(b) Foliation (Pinnacles)
(c) Fractures (Calvary Rocks)	(d) Dike (Old Rag Mountain)
(e) Cleavage (Betty's Rock)	(f) Layering (Brown Mountain)

Figure 4. Examples of common geological structures found within SHEN.

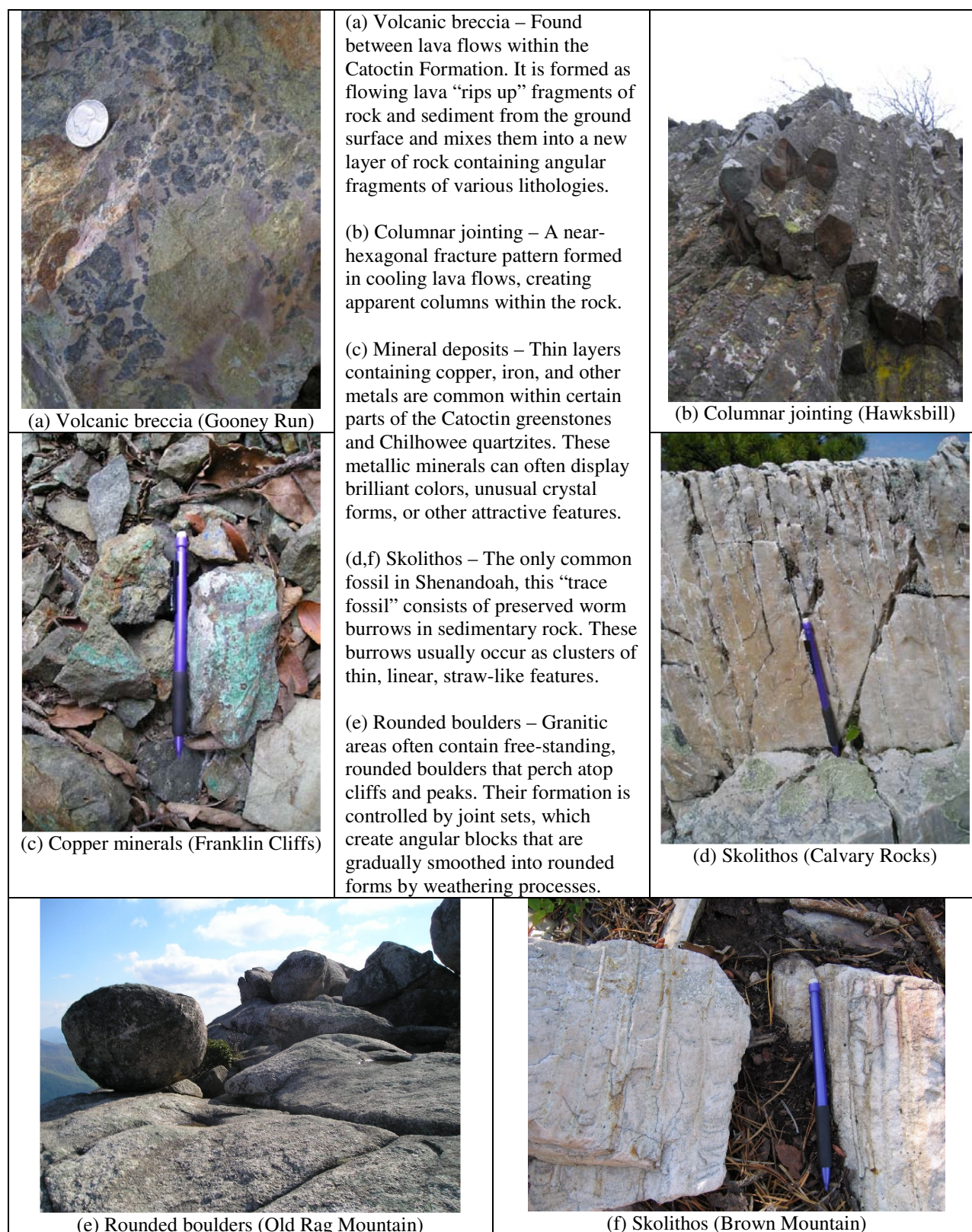


Figure 5. Examples of common features of geologic interest found in SHEN.

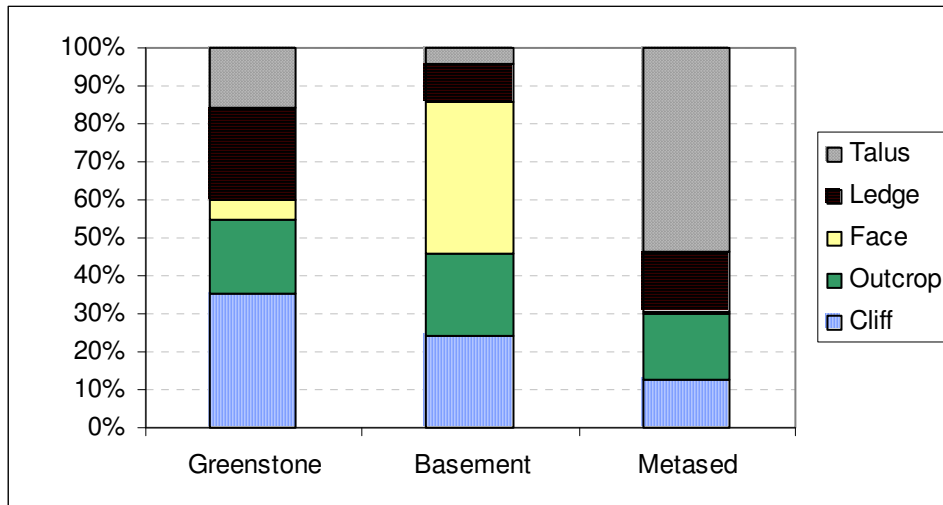


Figure 6. Average exposure morphologies by bedrock lithology.

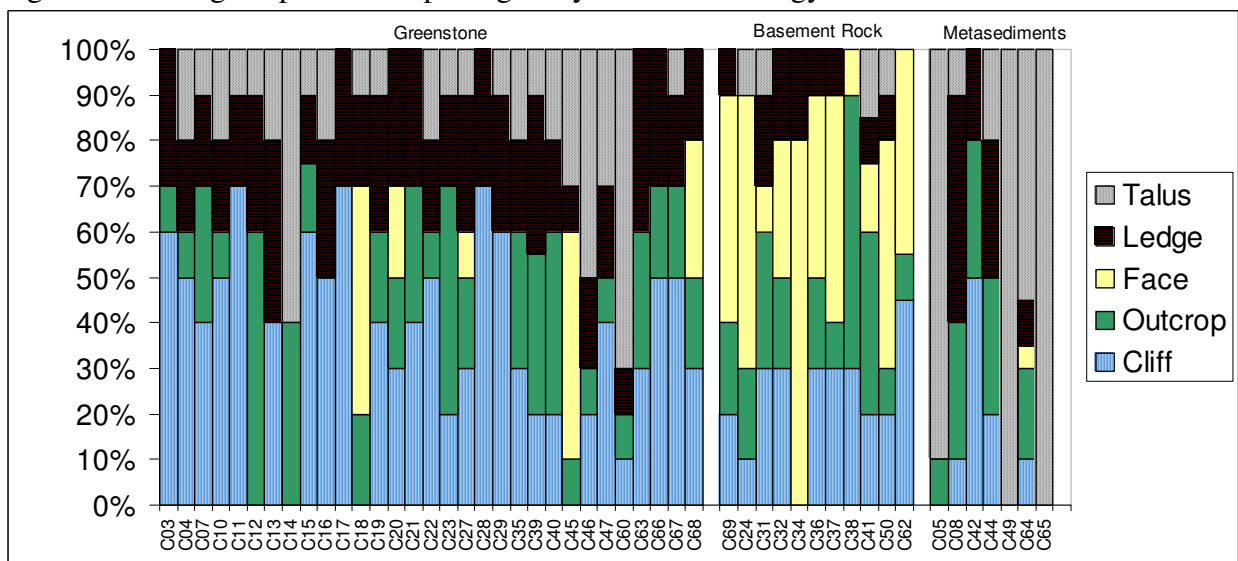


Figure 7. Morphologic compositions of individual ROMP sites.

Figures 6 and 7 are based on the five distinct bedrock exposure morphologies defined for this project (see Fig. 2 for definitions and photos). At each site, the percentage of total open rock exposure composed of each morphology was estimated and recorded (Fig. 7). When these figures are averaged (Fig. 6) the impact of bedrock composition on the physical nature of rock exposures is clear. For the purposes of these comparisons, the only site with two lithologies present (Whiteoak Canyon, C69) was included within Basement Rock as the granitic exposures within the site were far more extensive and open than the Greenstone exposures.

Table 1. ROMP study sites and associated bedrock, sorted by site number

Site ID #	SHEN District	Site Name	Site Bedrock
C02	Central	Bettys Rock	Greenstone (Catoclin)
C03	North	Big Devils Stairs	Greenstone (Catoclin)
C04	Central	Blackrock Central District	Greenstone (Catoclin)
C05	South	Blackrock South District	Quartzite (Chilhowee)
C07	North	Browtown Valley Overlook	Greenstone (Catoclin)
C08	South	Calvary Rocks / Chimney Rock	Quartzite (Chilhowee)
C10	Central	Crescent Rock Overlook	Greenstone (Catoclin)
C11	Central	Crescent Rock South	Greenstone (Catoclin)
C12	Central	Dean Mountain Ridge	Greenstone (Catoclin)
C13	North	Dickey Hill	Greenstone (Catoclin)
C14	North	Dickey Ridge	Greenstone (Catoclin)
C15	Central	Franklin Cliffs North	Greenstone (Catoclin)
C16	Central	Franklin Cliffs Overlook	Greenstone (Catoclin)
C17	Central	Franklin Cliffs South	Greenstone (Catoclin)
C18	South	Goat Ridge	Greenstone (Catoclin)
C19	North	Gooney Manor Overlook	Greenstone (Catoclin)
C20	Central	Halfmile Cliff	Greenstone (Catoclin)
C21	Central	Hawksbill N slope outcrops	Greenstone (Catoclin)
C22	Central	Hawksbill summit	Greenstone (Catoclin)
C23	South	Hightop	Greenstone (Catoclin)
C24	North	Hogback Mtn spur	Basement rock
C27	North	Little Devils Stairs	Greenstone (Catoclin)
C28	Central	Little Stony Man	Greenstone (Catoclin)
C29	South	Loft Mountain summit	Greenstone (Catoclin)
C31	Central	Marys Rock	Basement rock
C32	Central	Millers Head	Basement rock
C34	Central	Nakedtop Upper East Slope	Basement rock
C35	North	North Marshall summit	Greenstone (Catoclin)
C36	Central	Old Rag southside	Old Rag granite
C37	Central	Old Rag summit east	Old Rag granite
C38	North	Oventop	Old Rag granite
C39	North	Overall Run Falls south	Greenstone (Catoclin)
C40	North	Pass Mountain	Greenstone (Catoclin)
C41	Central	Pinnacles	Basement rock
C42	South	Powell Gap cliff	Metasediments (Swift Run)
C44	South	Rocky Mountain	Quartzite (Chilhowee)
C45	South	Sawlog Ridge	Greenstone (Catoclin)
C46	North	South Marshall cliff	Greenstone (Catoclin)
C47	Central	Stony Man summit	Greenstone (Catoclin)
C49	South	Trayfoot Saddle boulderfields E	Quartzite (Chilhowee)
C50	Central	Upper Devils Ditch	Basement rock
C60	Central	Hawksbill N slope talus	Greenstone (Catoclin)
C62	Central	Old Rag summit west	Old Rag granite
C63	North	Overall Run Falls north	Greenstone (Catoclin)
C64	South	Brown Mountain	Quartzite (Chilhowee)
C65	South	Trayfoot Saddle boulderfields W	Quartzite (Chilhowee)
C66	Central	Field Hollow Cliff	Greenstone (Catoclin)
C67	Central	Bearfence	Greenstone (Catoclin)
C68	Central	Rose River	Greenstone (Catoclin)
C69	Central	Whiteoak Canyon	Greenstone/Basement

Table 2. ROMP study sites and associated bedrock, sorted by park district

Site ID #	SHEN District	Site Name	Site Bedrock
C03	North	Big Devils Stairs	Greenstone (Catoclin)
C07	North	Browntown Valley Overlook	Greenstone (Catoclin)
C13	North	Dickey Hill	Greenstone (Catoclin)
C14	North	Dickey Ridge	Greenstone (Catoclin)
C19	North	Gooney Manor Overlook	Greenstone (Catoclin)
C24	North	Hogback Mtn spur	Basement rock
C27	North	Little Devils Stairs	Greenstone (Catoclin)
C35	North	North Marshall summit	Greenstone (Catoclin)
C38	North	Oventop	Old Rag granite
C39	North	Overall Run Falls south	Greenstone (Catoclin)
C40	North	Pass Mountain	Greenstone (Catoclin)
C46	North	South Marshall cliff	Greenstone (Catoclin)
C63	North	Overall Run Falls north	Greenstone (Catoclin)
C02	Central	Bettys Rock	Greenstone (Catoclin)
C04	Central	Blackrock Central District	Greenstone (Catoclin)
C10	Central	Crescent Rock Overlook	Greenstone (Catoclin)
C11	Central	Crescent Rock South	Greenstone (Catoclin)
C12	Central	Dean Mountain Ridge	Greenstone (Catoclin)
C15	Central	Franklin Cliffs North	Greenstone (Catoclin)
C16	Central	Franklin Cliffs Overlook	Greenstone (Catoclin)
C17	Central	Franklin Cliffs South	Greenstone (Catoclin)
C20	Central	Halfmile Cliff	Greenstone (Catoclin)
C21	Central	Hawksbill N slope outcrops	Greenstone (Catoclin)
C22	Central	Hawksbill summit	Greenstone (Catoclin)
C28	Central	Little Stony Man	Greenstone (Catoclin)
C31	Central	Marys Rock	Basement rock
C32	Central	Millers Head	Basement rock
C34	Central	Nakedtop Upper East Slope	Basement rock
C36	Central	Old Rag southside	Old Rag granite
C37	Central	Old Rag summit east	Old Rag granite
C41	Central	Pinnacles	Basement rock
C47	Central	Stony Man summit	Greenstone (Catoclin)
C50	Central	Upper Devils Ditch	Basement rock
C60	Central	Hawksbill N slope talus	Greenstone (Catoclin)
C62	Central	Old Rag summit west	Old Rag granite
C66	Central	Field Hollow Cliff	Greenstone (Catoclin)
C67	Central	Bearfence	Greenstone (Catoclin)
C68	Central	Rose River	Greenstone (Catoclin)
C69	Central	Whiteoak Canyon	Greenstone/Basement
C05	South	Blackrock South District	Quartzite (Chilhowee)
C08	South	Calvary Rocks / Chimney Rock	Quartzite (Chilhowee)
C18	South	Goat Ridge	Greenstone (Catoclin)
C23	South	Hightop	Greenstone (Catoclin)
C29	South	Loft Mountain summit	Greenstone (Catoclin)
C42	South	Powell Gap cliff	Metasediments (Swift Run)
C44	South	Rocky Mountain	Quartzite (Chilhowee)
C45	South	Sawlog Ridge	Greenstone (Catoclin)
C49	South	Trayfoot Saddle boulderfields E	Quartzite (Chilhowee)
C64	South	Brown Mountain	Quartzite (Chilhowee)
C65	South	Trayfoot Saddle boulderfields W	Quartzite (Chilhowee)

Table 3. ROMP study sites and park district, sorted by bedrock type

Site ID #	SHEN District	Site Name	Site Bedrock
C03	North	Big Devils Stairs	Greenstone (Catoclin)
C07	North	Browntown Valley Overlook	Greenstone (Catoclin)
C13	North	Dickey Hill	Greenstone (Catoclin)
C14	North	Dickey Ridge	Greenstone (Catoclin)
C19	North	Gooney Manor Overlook	Greenstone (Catoclin)
C27	North	Little Devils Stairs	Greenstone (Catoclin)
C35	North	North Marshall summit	Greenstone (Catoclin)
C39	North	Overall Run Falls south	Greenstone (Catoclin)
C40	North	Pass Mountain	Greenstone (Catoclin)
C46	North	South Marshall cliff	Greenstone (Catoclin)
C63	North	Overall Run Falls north	Greenstone (Catoclin)
C02	Central	Bettys Rock	Greenstone (Catoclin)
C04	Central	Blackrock Central District	Greenstone (Catoclin)
C10	Central	Crescent Rock Overlook	Greenstone (Catoclin)
C11	Central	Crescent Rock South	Greenstone (Catoclin)
C12	Central	Dean Mountain Ridge	Greenstone (Catoclin)
C15	Central	Franklin Cliffs North	Greenstone (Catoclin)
C16	Central	Franklin Cliffs Overlook	Greenstone (Catoclin)
C17	Central	Franklin Cliffs South	Greenstone (Catoclin)
C20	Central	Halfmile Cliff	Greenstone (Catoclin)
C21	Central	Hawksbill N slope outcrops	Greenstone (Catoclin)
C22	Central	Hawksbill summit	Greenstone (Catoclin)
C28	Central	Little Stony Man	Greenstone (Catoclin)
C47	Central	Stony Man summit	Greenstone (Catoclin)
C60	Central	Hawksbill N slope talus	Greenstone (Catoclin)
C66	Central	Field Hollow Cliff	Greenstone (Catoclin)
C67	Central	Bearfence	Greenstone (Catoclin)
C68	Central	Rose River	Greenstone (Catoclin)
C18	South	Goat Ridge	Greenstone (Catoclin)
C23	South	Hightop	Greenstone (Catoclin)
C29	South	Loft Mountain summit	Greenstone (Catoclin)
C45	South	Sawlog Ridge	Greenstone (Catoclin)
C24	North	Hogback Mtn spur	Basement rock
C31	Central	Marys Rock	Basement rock
C32	Central	Millers Head	Basement rock
C34	Central	Nakedtop Upper East Slope	Basement rock
C41	Central	Pinnacles	Basement rock
C50	Central	Upper Devils Ditch	Basement rock
C69	Central	Whiteoak Canyon	Greenstone/Basement
C38	North	Oventop	Old Rag granite
C36	Central	Old Rag southside	Old Rag granite
C37	Central	Old Rag summit east	Old Rag granite
C62	Central	Old Rag summit west	Old Rag granite
C42	South	Powell Gap cliff	Metasediments (Swift Run)
C05	South	Blackrock South District	Quartzite (Chilhowee)
C08	South	Calvary Rocks / Chimney Rock	Quartzite (Chilhowee)
C44	South	Rocky Mountain	Quartzite (Chilhowee)
C49	South	Trayfoot Saddle boulderfields E	Quartzite (Chilhowee)
C64	South	Brown Mountain	Quartzite (Chilhowee)
C65	South	Trayfoot Saddle boulderfields W	Quartzite (Chilhowee)

Table 4. Site impact assessments from cooperating researchers¹.

Site ID #	Site Name	Cliff top (VT) impact sites	Cliff base impact sites (VT)	Campsites (VT)	Social trails (VT)	Geologist's access rating	Geologist's impact rating	Biologist's impact rating
C02	Betty's Rock	1	0	0	3	Easy	Heavy	Major
C03	Big Devil's Stairs	No data	No data	No data	No data	Difficult	Mild	Minor
C04	Blackrock Central D	2	0	0	3	Easy	Heavy	Major
C05	Blackrock South D	No data	No data	No data	No data	Easy	Moderate	Minor
C07	Browntown Valley	No data	No data	No data	No data	Remote	Pristine	Pristine
C08	Calvary Rocks	2	0	1	0	Difficult	Mild	--
C10	Cres. Rock Overlook	2	0	0	1	Easy	Heavy	Major
C11	Crescent Rock South	No data	No data	No data	No data	Easy	Moderate	Minor
C12	Dean Mountain	No data	No data	No data	No data	Remote	Pristine	Pristine
C13	Dickey Hill	No data	No data	No data	No data	Remote	Pristine	--
C14	Dickey Ridge	No data	No data	No data	No data	Remote	Pristine	Pristine
C15	Franklin Cliffs North	No data	No data	No data	No data	Moderate	Mild	Minor
C16	Fr. Cliffs Overlook	2	0	0	1	Easy	Heavy	Major
C17	Franklin Cliffs South	No data	No data	No data	No data	Moderate	Mild	Major
C18	Goat Ridge	No data	No data	No data	No data	Remote	Pristine	--
C19	Gooney M. Overlook	0	0	0	1	Easy	Moderate	Minor
C20	Halfmile Cliff	No data	No data	No data	No data	Remote	Pristine	Pristine
C21	Hawksbill N. Face	No data	No data	No data	No data	Remote	Mild	Pristine
C22	Hawksbill Summit	5	0	0	4	Moderate	Heavy	Major
C23	Hightop	No data	No data	No data	No data	Moderate	Moderate	Minor
C24	Hogback Mt Spur	No data	No data	No data	No data	Remote	Pristine	--
C27	Little Devils Stairs	No data	No data	No data	No data	Difficult	Mild	--
C28	Little Stony Man	5	3	3	6	Moderate	Heavy	Major
C29	Loft Mountain	2	0	2	1	Easy	Moderate	Major
C31	Mary's Rock	2	0	1	5	Moderate	Heavy	Major
C32	Millers Head	No data	No data	No data	No data	Moderate	Mild	--
C34	Nakedtop	No data	No data	No data	No data	Remote	Pristine	--
C35	North Marshall	8	0	2	10	Easy	Moderate	Minor
C36	Old Rag Southside	0	3	0	2	Remote	Mild	--
C37	Old Rag Summit E.	No data	No data	No data	No data	Difficult	Heavy	Minor
C38	Oventop	No data	No data	No data	No data	Difficult	Mild	Pristine
C39	Overall Run S.	No data	No data	No data	No data	Remote	Pristine	--
C40	Pass Mountain	No data	No data	No data	No data	Moderate	Moderate	Minor
C41	Pinnacles	No data	No data	No data	No data	Moderate	Mild	--
C42	Powell Gap Cliffs	No data	No data	No data	No data	Moderate	Mild	Minor
C44	Rocky Mountain	No data	No data	No data	No data	Difficult	Moderate	Minor
C45	Sawlog Ridge	No data	No data	No data	No data	Remote	Pristine	Pristine
C46	South Marshall	3	0	0	2	Moderate	Moderate	Minor
C47	Stony Man Summit	3	0	0	4	Moderate	Heavy	Major
C49	Trayfoot W.	No data	No data	No data	No data	Difficult	Pristine	Pristine
C50	Upper Devil's Ditch	No data	No data	No data	No data	Remote	Pristine	Pristine
C60	Hawksbill N. Talus	No data	No data	No data	No data	Moderate	Mild	Minor
C62	Old Rag Summit W.	5	0	1	17	Difficult	Heavy	Major
C63	Overall Run Falls N	4	0	0	0	Difficult	Heavy	--
C64	Brown Mountain	No data	No data	No data	No data	Difficult	Mild	Minor
C65	Trayfoot E.	No data	No data	No data	No data	Difficult	Pristine	Pristine
C66	Field Hollow	No data	No data	No data	No data	Remote	Pristine	Pristine
C67	Bearfence	No data	No data	No data	No data	Difficult	Heavy	--
C68	Rose River	No data	No data	No data	No data	Remote	Pristine	--
C69	Whiteoak Canyon	No data	No data	No data	No data	Moderate	Mild	--

¹Studies conducted by a social science team (Virginia Tech), geology consultant (NPS), and stewardship biologist (Virginia Department of Conservation and Recreation). VT selected 17 sites for detailed study, while the other cooperators visited all 50 sites. VADCR rankings are temporarily presented here as incomplete pending final release of data.

Appendix A. Example data sheets and maps

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See Appendix B for definitions of terminology found on these sheets.

Appendix A. (continued).

Blank field data sheet

SHEENANDOAH NATIONAL PARK

ROCK OUTCROP MANAGEMENT PROJECT – GEOLOGIC DATA SHEET

SITE CODE: _____ SITE NAME: _____ PAGE ____ OF ____

GENERAL LOCATION: _____ DATA COLLECTOR: _____

DATE STUDIED: _____

GEOGRAPHIC CHARACTERISTICS

PHYSICAL CHARACTERISTICS

UTM COORDINATES: (E) _____

VEGETATION: *dense moderate open*

DATUM: _____ (N) _____

ELEVATION: _____

PHYSICAL DESCRIPTION:

DIMENSIONS:

GEOLOGIC CHARACTERISTICS

LITHOLOGY:

GEOMORPHIC CHARACTERISTICS

STRUCTURE:

EXPOSURE TYPE(S):

	<i>Cliff</i>	<i>Outcrop</i>	<i>Face</i>	<i>Ledge</i>	<i>Talus</i>
%Exposure					
Max Relief					

Aspect:

Texture:

Max slope:

STABILITY: *stable moderate loose*

GEOMORPHIC SETTING:

OTHER:

HUMAN EFFECTS

ACCESS: *remote difficult moderate easy*

IMPACTS: *pristine mild moderate heavy*

Appendix A. (continued).

Blank field GPS/photo log

SHENANDOAH NATIONAL PARK

ROCK OUTCROP MANAGEMENT PROJECT – GEOLOGIC PHOTO & GPS INDEX

SITE CODE: _____ SITE NAME: _____ PAGE _____ OF _____

PHOTOS

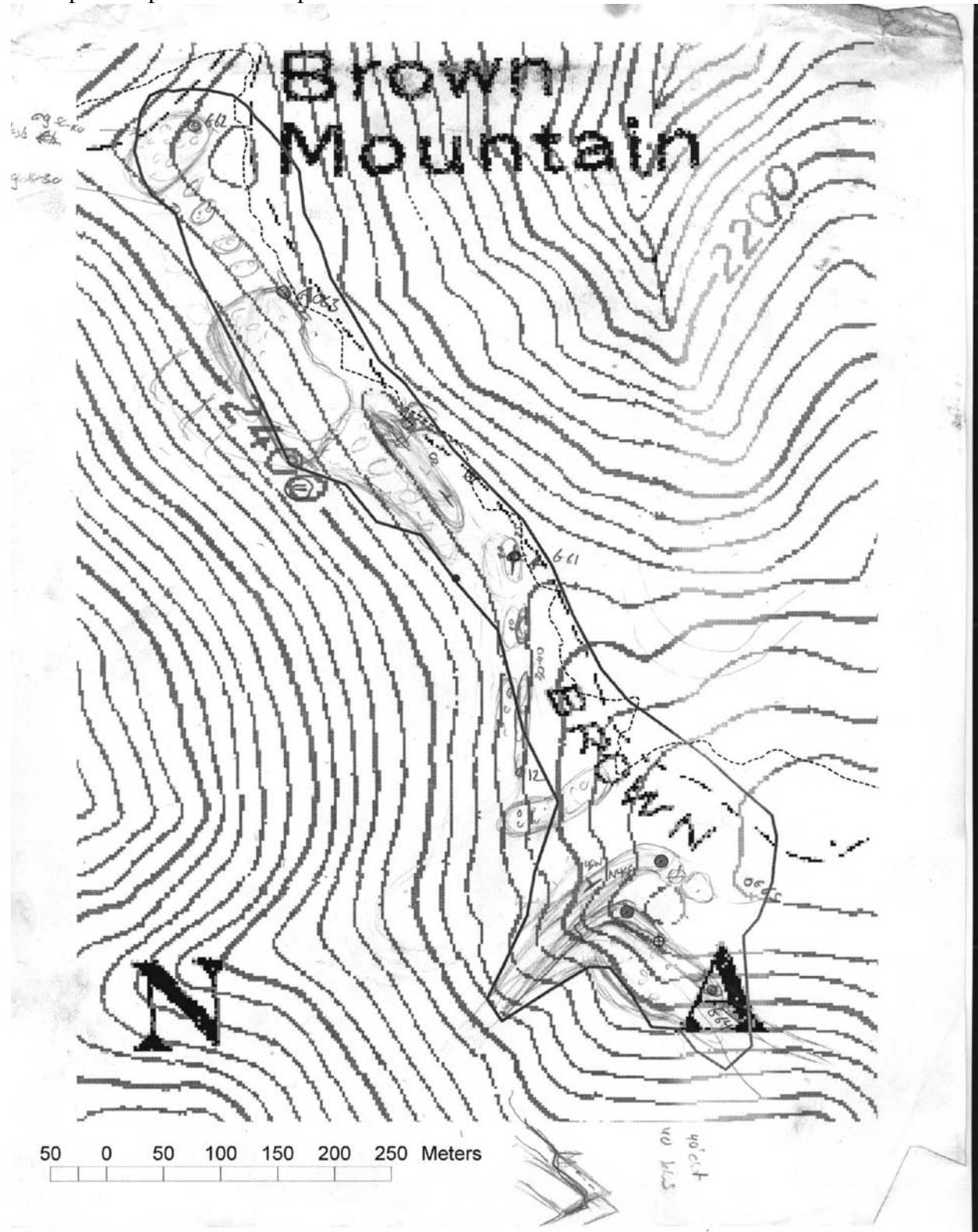
Date	GPS Point	#	Orientation	Comments

GPS POINTS (NAD 83)

Date	#	Easting	Northing	Elevation	Comments

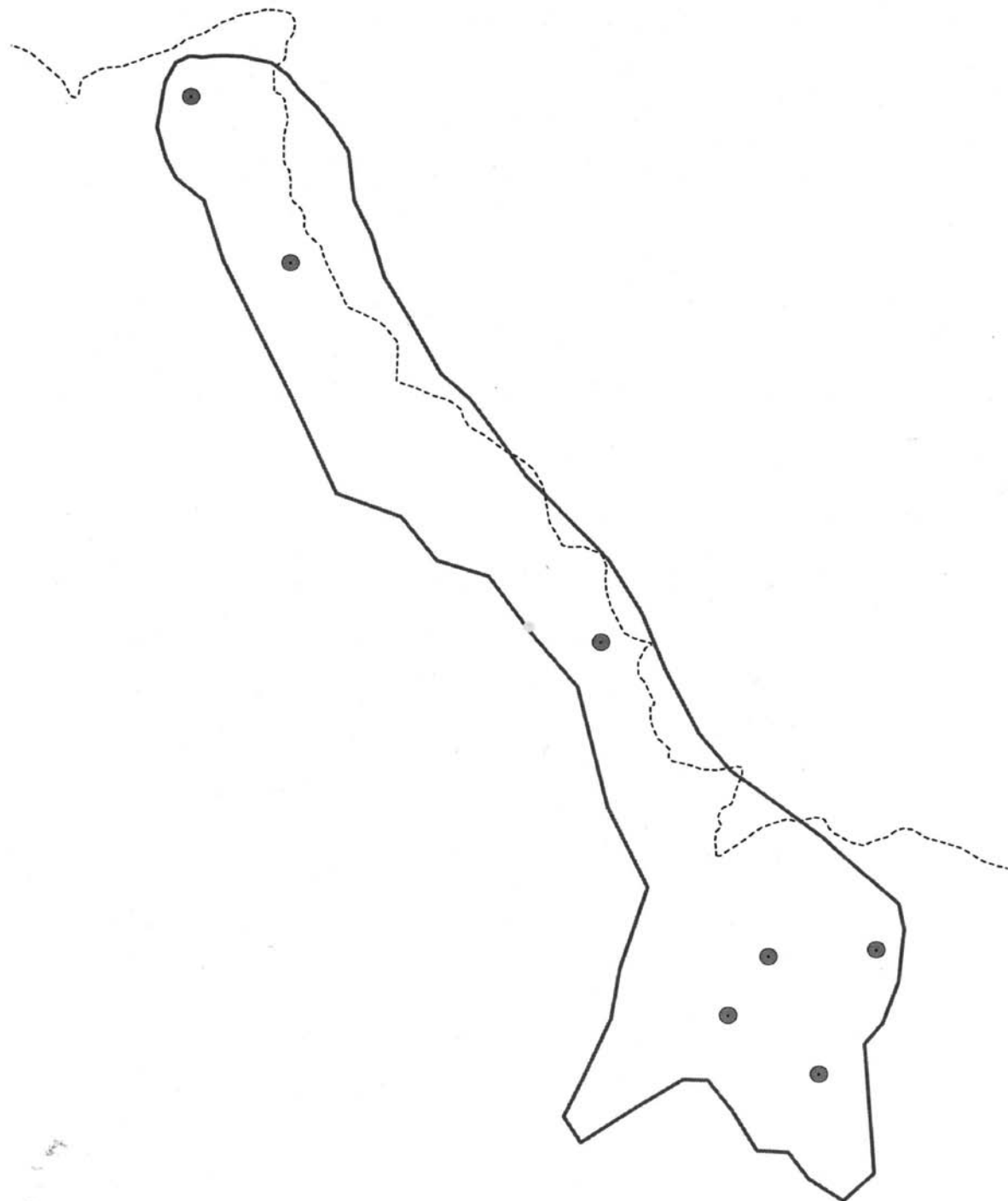
Appendix A. (continued).

Example completed field map



Appendix A. (continued).

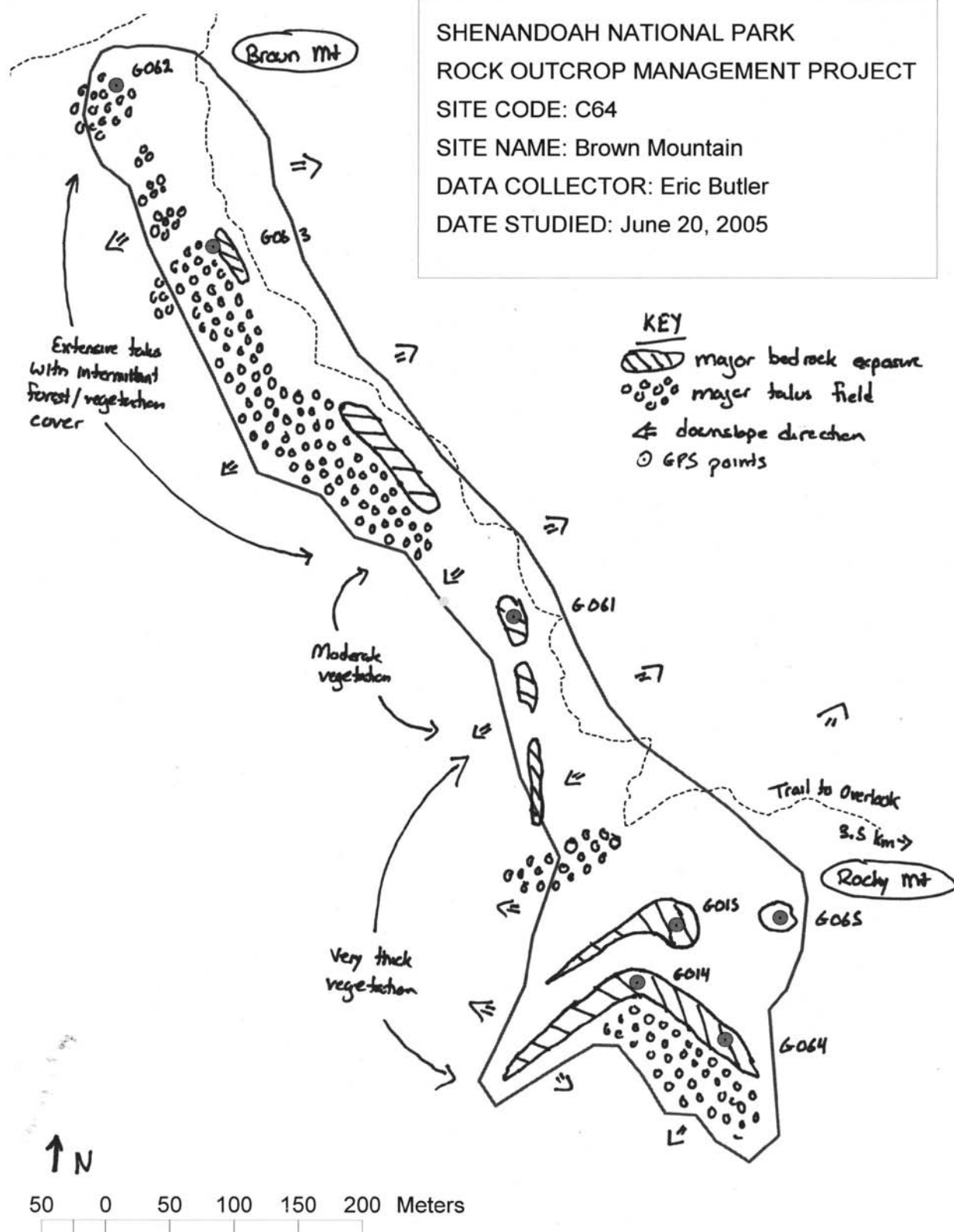
Example blank final map



50 0 50 100 150 200 250 Meters

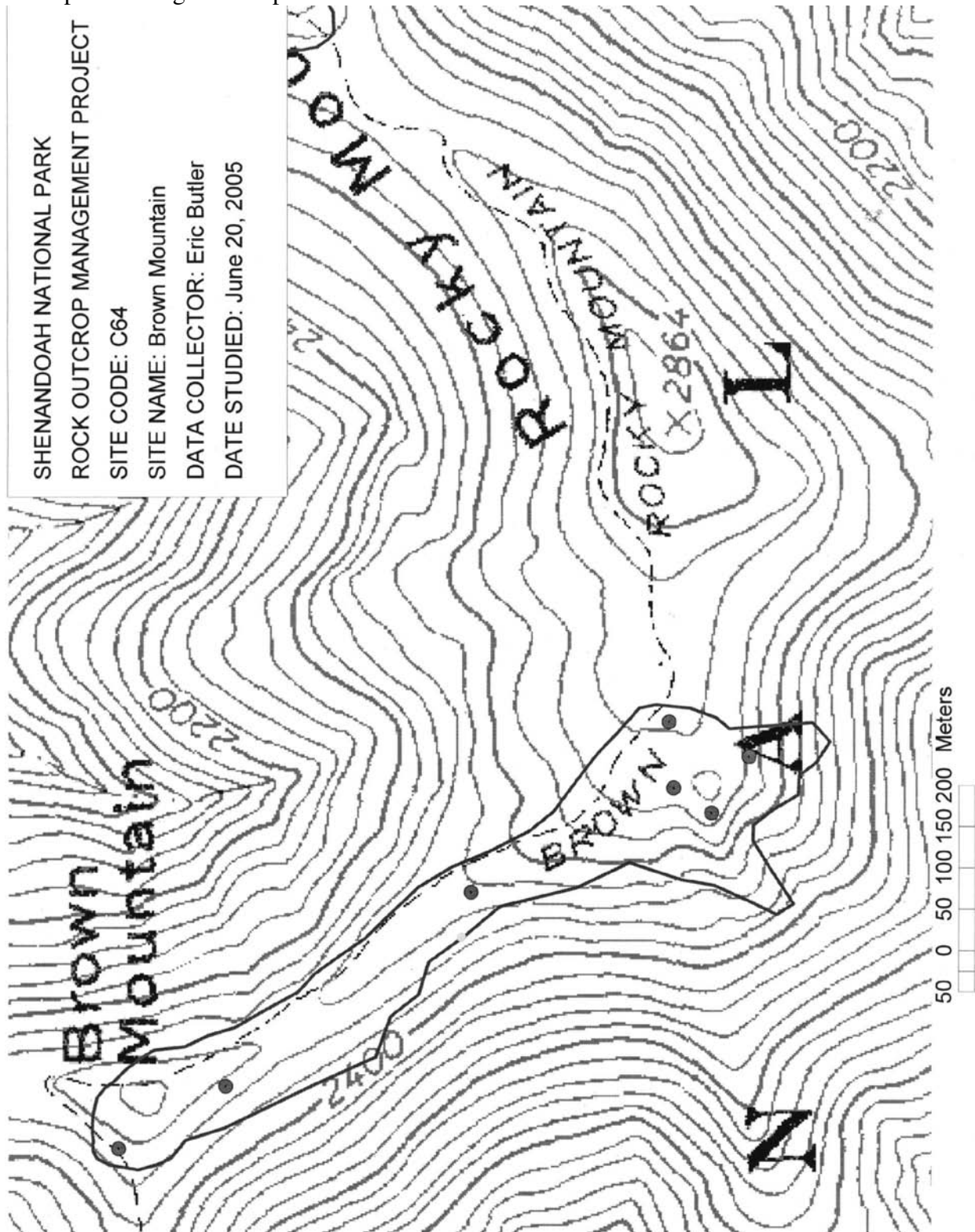
Appendix A. (continued).

Example redrawn final map



Appendix A. (continued).

Example final regional map



Appendix B. Definitions of terms used in data collection and analysis

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Appendix B. (continued).

Geographic Characteristics

UTM Coordinates – Coordinates of site centerpoint as calculated by GIS.

Elevation – range of elevation between bottom and top of site (i.e. 2600'-2750').

Dimensions – X and Y dimensions of site, measured on GIS.

Physical Characteristics

Vegetation – Overall thickness and condition of vegetation in site, re. ease of mobility.

dense: dominant thickets of vegetation significantly impede navigation.

moderate: mix of thickets and open forest, ease of navigation varies.

open: vegetation is not a significant barrier to navigation.

Physical description – Summary of general nature and appearance of site (not scientific).

Geologic Characteristics

Lithology – description & identification of major rock units found at site, including mineralogy, provenance, and history as necessary.

Structure – description of any important structures in rock, such as faults, folds, or joints, including measurements & interpretation if possible.

Other – any other necessary observations, potentially soils, springs, views, fossils, etc.

Geomorphic Characteristics (see Fig. 2 for examples)

Cliff – Near-vertical exposure that dominates or creates surrounding topography. Usually continuous across slope, though may be interrupted by talus slopes or other erosional features. Generally sheer, with minor ledges along the vertical drop.

Face – Continuous, rounded, gently sloping exposure (<45°) of smoothly weathered rock. Not steep enough to be a cliff, too continuous and smooth to be an outcrop, and too large and rounded to be a ledge.

Outcrop – Intermittent exposures that stand out from surrounding topography but do not influence it. Most commonly sloping, rugged exposures with many associated ledges. May also consist of intermittent protruding rock ribs that are not continuous or wide enough to be a cliff.

Ledge – Near-horizontal exposure along top or sides of cliffs and outcrops, where a local break in slope occurs, but trees and thick soil have not yet accumulated. Often hosts vegetation.

Talus – Continuous to scattered rock debris, clast-dominated with little to no soil development, covering general topography. May or may not be associated with in-place bedrock exposures.

% Exposure – Percentage of total exposed rock (not of whole site) consisting of a certain geomorphic type. Estimated from field observations, should not be considered a quantitative measurement.

Max Relief – Greatest vertical distance between top and bottom of a single unit of a certain geomorphic type. Estimated from field observations, should not be considered a quantitative measurement.

Appendix B. (continued).

Geomorphic Characteristics (continued)

Max Slope – Steepest slope encountered in the site's surrounding topography, not including the rock exposures.

Aspect – Orientation(s) of rock exposures, recorded by alphabetic bearing (i.e., NW, SSE).

Texture – Overall surface morphology of the bedrock.

fractured: Widespread cracks, joints, or other breaks which dominate the surface. Generally no common surface identifiable.

rough: uneven and moderately fractured, but an identifiable, common surface is present.

smooth: continuous surface with no major disruptions; may have minor topography.

Stability – Physical condition and safety of exposures.

loose: bedrock is heavily fractured and appears to be actively eroding; not safe to approach edges of cliffs, for example. ALSO talus fields that are especially unstable.

moderate: site is a mix of loose and stable bedrock areas. ALSO talus fields that have low slopes and/or do not shift underfoot.

stable: bedrock is solid and provides no apparent danger of movement, little to no loose material on surrounding slopes.

Geomorphic Setting – Description & discussion of how exposures fit into surrounding area. Is there a geologic control on the physical shape and location of the site? How does it relate to the surrounding landscape? What geologic/geomorphic factors are affecting the site?

Human Effects

Impacts – Evidence of human activity on the outcrop.

pristine: no impacts; trails/compaction nonexistent, absolutely no signs of human use or visitation.

mild: minor impacts; minor trails, slight compaction, , vegetation sporadically affected, most of site is untouched.

moderate: significant impacts; trails and compaction are common, areas of use are clearly visible, vegetation clearly affected and diminished..

heavy: ubiquitous impacts; trails and compaction are prevalent, rocks are carved, polished, or otherwise obviously impacted, trash or other debris may be common, vegetation severely diminished..

Access – ability of visitors to reach the outcrop from starting point on an access road).

remote: not accessed by any trail or road. Generally not visible from trails or roads; if visible, requires negotiation of significant backcountry and/or topography to reach.

difficult: generally greater than 2 trail km from road OR nearer road but requires negotiation of strenuous topography or trail conditions to reach.

moderate: generally located within 2 trail km from road, visible from trails; may have some obstacles to access (slope, vegetation, etc...).

easy: generally located within 500m of road along clearly marked trails with signs leading to site OR located within 20m of road and clearly visible with obvious trails, no topography or other difficulties preventing access.

Appendix C. Geologic history and formations of SHEN.

Summary

The geologic history of Shenandoah National Park (SHEN) spans the rise and fall of two distinct mountain ranges. While the current Appalachian Mountains may be considered the oldest in North America, much of the region's bedrock is related to an earlier, larger mountain range that eroded away long before the current topography began to develop.

During a period of time 1.2-1.0 billion years ago, a major collision between tectonic plates created a long chain of mountains along what is now the eastern margin of North America (Burton and Southworth, 2004). This period of mountain-building, known as the Grenville Orogeny, produced a thick suite of metamorphic rocks deep beneath the earth's surface, as intense heat and pressure deformed pre-existing sedimentary and igneous rock into new compositions and structures. Some areas melted entirely, creating pockets of new igneous rocks that intruded into the surrounding metamorphic rock (Tollo et al., 2004).

These deep-rooted igneous and metamorphic rocks formed the core of the Grenville Mountains, which extended from present-day Texas to Newfoundland, although the North American continent had not yet formed as such (Badger, 1999). The peaks were likely as tall as any on Earth today, but as tectonic pressures faded, they slowly eroded away. By around 600 million years ago, the landscape was apparently reduced to low, rolling hills with a few higher points (perhaps several thousand feet tall), a scene not unlike today's Virginia Piedmont. With no terrestrial plants or animals having evolved yet, however, it would have been a landscape of barren, rock-strewn slopes, gravelly river valleys, and occasional lakes (Gathright, 1976).

Around 570 million years ago, the tectonic pressures reversed themselves and the plates began pulling apart, forming a rift zone thousands of miles long. This rifting allowed molten rock from deep within the earth to rise to the surface, resulting in widespread volcanism that erupted lava flows from Newfoundland to North Carolina, covering at least 11,000 km² (Badger and Sinha, 2004). Within SHEN, at least 16 lava flows form a sequence up to 2,000' thick, blanketing the old topography of the eroded Grenville landscape (Gathright, 1976).

While the duration of individual flows (and the time lapse between them) is unknown, the entire sequence likely erupted within a span of several million years (Badger, 1999). Following the cessation of active volcanism, the rift continued to spread, creating a growing ocean basin in a process similar to the formation of today's Atlantic Ocean. This ocean, however, predated the Atlantic by several hundred million years; it was named Iapetus, after the father of Atlantis in Greek mythology (Connors, 1988).

The Iapetus Ocean continued to grow as the rift widened, and rising marine waters began to deposit a thick sequence of sediments over the now-cooled lavas. The earliest deposits consist of gravelly sandstones, representing the river systems draining into the growing ocean. Following these came a mixture of siltstones (reflecting a shallow-marine beach/lagoon environment), shales (deeper water), and pure quartz sandstones (beach/dune environments); this complicated sequence reflects the minor fluctuations in sea level occurring during the overall advance of the

Appendix C. (continued).

ocean. Many more layers of rock were deposited in the long history of the Iapetus Ocean, including thick units of limestone, but these exist mainly outside of SHEN.

By around 450 million years ago, plate movements had reversed themselves once again, and the Iapetus Ocean began to close as tectonic processes came full circle. A series of three major continental collisions took place between 450 and 300 million years ago, raising new mountains where the old Grenville range once stood (Badger, 1999). The Appalachian Mountains, like their predecessors, stretched thousands of miles and rose just as high in their prime. Deformation and faulting once again altered the bedrock, recent and ancient, in the formation of these mountains. Several major thrust faults stacked thick sequences of bedrock on top of one another, significantly increasing the thickness of the crust and the height of the mountains in these areas. Intense folding was especially prevalent in the sedimentary rocks above the lava flows and basement rocks; some of these folds can still be seen today. Both the folding and the faulting are a major control on the shape and nature of the topography in SHEN even today (Burton and Southworth, 2004).

Eventually the tectonic processes reversed themselves yet again, and the mountain building came to an end. Around 200 million years ago, the modern continents of Africa and North America began to split apart, in the same way as the old Grenville plates had. This final rifting event created the Atlantic Ocean, which continues to spread today. As tectonic pressures faded, the Appalachians stopped rising, but erosion continued to wear down the landscape. Today, the former high, rugged peaks are worn down almost to their roots, once again exposing bedrock that was miles below Earth's surface during the peak of Appalachian mountain-building.

The bedrock found within SHEN preserves only the early portion of this long and complex history; the youngest rock found here is over 400 million years old. Tectonic processes and erosion have combined to remove everything younger. The remaining stratigraphy consists of "basement" gneisses and granites from Grenville times, overlain by basaltic/greenstone lava flows erupted during the Iapetus Ocean rifting, in turn overlain by a sequence of quartzites, siltstones, and limestone deposited by the early Iapetus (Gathright, 1976). The following sections will discuss these individual formations in more detail.

Basement rocks

The oldest rocks found within SHEN are a diverse set of igneous and metamorphic rocks which form the base of the Blue Ridge. Traditionally, these rocks were collectively treated as a single unit known as the Pedlar Formation, and were not further subdivided or studied in great detail (with a few exceptions). Recent research (e.g. Tollo et al., 2004) has investigated these rocks further, developing a more thorough understanding of their complex composition, structure, and history. Although the term "Pedlar Formation" is widely known and understood, it implies a homogeneity that is not representative of this diverse suite of rocks, and some recent researchers have ceased using that name. In this report, the term "basement rock" is used instead in reference to any and all Precambrian igneous or metamorphic rocks that form the base of the stratigraphic sequence within the Blue Ridge.

Appendix C. (continued).

At a broad scale, the basement rock within SHEN consists of various high-grade gneisses (Tollo et al., 2004), rock which has been deformed at temperatures at or exceeding 700°-800°C, and up to 12 kilobars of pressure (Blatt and Tracy, 1999). This grade of metamorphism is nearly as high as a rock can achieve without simply melting to form an igneous rock. These gneisses display varying degrees of foliation, a planar, banded appearance created by the alignment and segregation of similar mineral types during intense deformation. The composition of these rocks is generally granitoid, meaning they are dominated by the light-colored minerals quartz and feldspar, with variable but smaller amounts of darker accessory minerals such as pyroxene, amphibole, garnet, or biotite mica (Tollo et al., 2004). Rocks of this type often contain biotite, but in this region pyroxene is also common. Pyroxene-rich granitoids are referred to as “charnockite”, and make up a significant portion of the basement rock in SHEN (Tollo et al., 2004).

Various bodies of igneous rocks, or plutons, are also present within the basement rock. The most distinct unit is the Old Rag Granite, an unusual rock composed almost exclusively of coarse crystals of blue-grey quartz and white-pink feldspar, giving it a very light-colored and distinctive appearance. It occurs mainly in a single body centered on Old Rag Mountain, with a long, narrow finger extending many kilometers to the north (Gathright, 1976). This rock is remarkably uniform in texture, composition, and appearance, generally having very little evidence of deformation (with the exception of a fault zone running west of Old Rag Mountain, through Weakley and Berry Hollows). Most other common igneous rocks within SHEN are similar in composition to the granitic gneisses described above, containing variable amounts of quartz and feldspar along with several darker accessory minerals, and most show some level of deformation.

In reality, the boundaries between these two major basement rock types within SHEN can be quite subtle and gradational. As discussed above, most of the gneisses are interpreted to be igneous in origin, while some of the igneous rocks are deformed enough to approach metamorphic status. All of these rocks developed into more or less their present form during the intense temperatures and pressures created by the mountain-building events associated with the Grenville Orogeny, 1.2-1.0 billion years ago (with later effects from Appalachian mountain-building). These extreme conditions deformed pre-existing igneous rocks to create the various gneisses, which were intruded by various bodies of magma while this deformation was ongoing, thus creating igneous bodies that themselves show signs of deformation. Tollo et al. (2004) defined three distinct periods of magmatic activity within the Grenville Orogeny; from 1160-1140 million years ago (Ma), 1112 Ma, and from 1080-1050 Ma.

The result of all this is a complex suite of rocks that grade between igneous and metamorphic textures and variable mineralogic compositions, blending and interfingering at scales ranging from tens of centimeters to tens of kilometers. While broad trends in these different rock units can be mapped at a large scale (see Tollo et al., 1999, fig. 3), it is difficult at the outcrop scale to distinguish between and map these units in a meaningful and consistent way, especially with plant and lichen cover. Therefore, this report considers the basement rocks as a single unit distinct from the volcanic and sedimentary rocks found in SHEN, though individual site reports

Appendix C. (continued).

describe mineralogic and structural details of the local bedrock. The only exception to this practice is the Old Rag Granite, which is mineralogically and visually distinct enough to be identified separately, does not interfinger with other basement rocks at a significant scale, and occurs only within a specific, mappable area.

One other rock type is found within the basement rocks; greenstone dikes are common throughout these areas. These are narrow, planar units of igneous rock that intruded into the basement rocks along joint or fracture planes. These dikes were originally composed of diabase (the same mineral composition as basalt, only cooled underground), and like the Catoctin Formation metabasalts, were metamorphosed into greenstone later in their history. The age and relationship of these dikes to the very similar Catoctin Formation rocks is somewhat uncertain. The dikes are commonly assumed to be part of the “feeder system” that allowed the molten rock to intrude through the basement rocks before erupting onto the surface as lava flows, but it is unclear whether these specific dikes actually reached the surface, or are simply small outliers of a larger network of fractures located elsewhere.

The greenstone dikes are rarely found in-place, but more often as linear deposits of loose greenstone rocks on the forest floor, looking notably out-of-place when surrounded by granitic detritus. Where the dikes are found in-place, it is almost always on high, rugged peaks, where a lack of soil cover has exposed them. Old Rag Mountain is the primary example of this, where many dikes up to 3m wide can be found along the summit and exposed ridgelines.

Swift Run Formation metasediments

Overlying the basement rocks is a generally thin, discontinuous unit of metasediments. The Swift Run Formation preserves a diverse set of material that was deposited on the pre-Catoctin paleotopography by streams, rivers, lakes, and hillslope processes. The formation also includes some volcanic debris and ash, most likely from the earliest eruptions related to the Catoctin-era rifting events. The Swift Run is extremely variable in composition, grading quickly from shale/slate/phyllite units that likely reflect old ponds and lakes, to sandy/quartzitic/cobbly units that likely reflect rivers or bank environments, to coarse-clastic breccias that likely reflect debris flows or other hillslope erosion processes. The formation is often not present at all, which most likely indicates areas of higher relief (where sediments would not be deposited) or areas scraped clean of sediments by advancing Catoctin lava flows. In addition, layers of sediment similar to the Swift Run are often found between lava flows within the Catoctin, suggesting the repeated redevelopment of rivers and erosional processes between eruptive periods.

The Swift Run can be difficult to distinguish from other metasedimentary rocks of the much younger Chilhowee Group, and attention to a geologic map and surrounding rock units can be as useful in specimen identification as any other method.

Appendix C. (continued).

Catoctin Formation greenstone

Overlying the basement rocks and the Swift Run Formation is a sequence of lava flows up to 2,000' thick (Gathright, 1976). These flows constitute the Catoctin Formation, a near-continuous unit of volcanic rock that can be traced from southern Virginia into southern Pennsylvania, covering over 11,000 square kilometers (Badger and Sinha, 2004). The lavas were originally formed from basalt, a dark-colored volcanic rock composed primarily of plagioclase feldspar and pyroxene (Blatt and Tracy, 1999). Basalt is very low in silica, and thus has a relatively low viscosity. Basaltic magmas tend to behave very fluidly, erupting onto the surface in liquid flows that follow topography and fill in low areas. In contrast, high-silica magmas are very viscous and tend to erupt as violent explosions (e.g. Mt. St. Helens) compared to flowing, low-silica magmas (e.g. Hawaii).

As the paleocontinent first began to rift apart around 570 million years ago, a process which would eventually form the Iapetus Ocean, large volumes of basalt from deep within the Earth followed the rifts in the crust upward and erupted onto the surface. This is a common process that still occurs at active rift zones today, such as those in Iceland and portions of eastern Africa. Similar eruptions occurred all along the rift zone, so that even today related deposits can be identified from Newfoundland to North Carolina (Badger and Sinha, 2004).

In the SHEN area, the basaltic lava flows spread across the rolling, rocky terrain underlain by Grenville basement rocks exposed by hundreds of millions of years of erosion, gradually filling in river valleys and lapping against the hillsides. This did not occur all at once, but rather in a series of separate events, allowing each flow to cool and solidify before the next flow erupted above it. The result was a thick (up to 2,000') sequence of distinct lava flows that can still be identified today (Gathright, 1976). While the time interval between each flow is unknown, it appears that the entire sequence was erupted over a span of only several millions years (Badger and Sinha, 2004).

Individual flows range in thickness from several meters to over 30m. Often, the upper few meters of a flow contains numerous preserved gas bubbles (vesicles) which are now filled by quartz and/or epidote (amygdules). This texture represents the "frothy" nature of a flow surface, in which pressurized gas is escaping in the same manner as a shaken bottle of soda. Flows may be separated by thin deposits of sediments, representing the re-establishment of drainage systems across the older flow surface prior to the next eruption. The thickness of these deposits may be a proxy for elapsed time between eruptions, but this has not been proven. Commonly, flows are separated by zones of breccia up to several meters thick, containing fragments of vesicular or amygdaloidal basalt, ripped-up clasts of sediments, and/or quartz pebbles, generally surrounded by a greenish, highly epidotized matrix. These breccias formed as an advancing flow ripped up fragments from the underlying flow's surface and mixed them with whatever sediments had been deposited on the short-lived depositional surface (Gathright, 1976).

Although these flows were erupted as basalt, they have since been affected by low-level metamorphism. Heat and pressure related to the formation of the Appalachian Mountains has

Appendix C. (continued).

altered the composition and textures of the rock to form greenstone, which is the common name for metamorphosed basalt. While basalt consists primarily of plagioclase feldspar and pyroxene, this metamorphism encouraged the growth of minerals such as chlorite and epidote. Epidote replacement can be widespread, and results in a grainy, lime-green appearance, while chlorite growth produces a darker green color and a platier texture.

A common structure within the greenstone is cleavage, which is a series of planar, parallel fractures that can look very similar to sedimentary bedding. This structure develops during metamorphism, as pressures on the rock start to create small fractures, while the mica-like mineral chlorite grows and aligns itself with these fractures, creating a platy texture similar to that of slate. In general, the cleavage planes found within the Catoctin Formation dip eastward at around 45-60 degrees, and as such are very distinct from the near-horizontal orientation of the lava flows themselves.

Another common structure within the greenstone is columnar jointing, which is a fracture pattern formed as the molten lava cooled on the surface. Lava, like most substances, contracts as it cools and hardens. As it does so, a series of angular fractures can develop, usually at 120 degree angles to one another, creating a hexagonal pattern within the rock. These fractures can extend many meters vertically, producing what appear to be a series of tall, polygonal columns within the rock that can be over a meter wide. Much of the columnar jointing in the park is poorly developed or preserved, but a few locations contain spectacular examples of this distinctive feature.

Metamorphism and hydrothermal activity within the Catoctin have resulted in locally common metal deposits, including iron and copper. These can be seen as mineral growths within fractures, or within the greenstones themselves. During historic times, these deposits were targeted for small-scale prospecting and mining operations, including the small mine and furnace located high on Stony Man Mountain in the early 20th century.

Chilhowee Group Metasediments

The Chilhowee consists of three formations, closely related to one another but generally distinct in appearance and depositional environment. Deposition of these rocks apparently began shortly after the cessation of Catoctin volcanism, and continued as the advancing Iapetus Ocean covered the area (Badger, 1999). The Chilhowee grades from sandstone/conglomerate (Weverton Fm) into sandstone/siltstone/shale (Hampton Fm) into quartzite (Erwin Fm), and ends where a thick sequence of dolomite and limestone (Tomstown Fm) overlies it (Morgan et al., 2004).

Weverton Formation

After Catoctin volcanism had ended, and the lava flows had cooled, rivers and streams re-established drainage patterns over the new landscape. The first evidence of this transition comes in the Weverton Formation, which consists of coarse clastic sedimentary deposits, including some conglomerates, representing the initial movement and deposition of debris by rivers

Appendix C. (continued).

(Gathright, 1976). The Weverton can generally be recognized by the presence of large quartz pebbles within sandstone, and is only 31-152m thick (Morgan et al., 2004).

Hampton Formation

Overlying the Weverton sandstones is a thick (600m) unit of sandy shale and siltstone, comprising the Hampton Formation (Morgan et al., 2004). These rocks have been largely metamorphosed into phyllite, a platy low-grade metamorphic rock. The original lithology records the presence of lagoons, marshes, or other mixed-energy shallow-water environments at the time of deposition. It is likely that, as the Iapetus Ocean advanced, the landscape began to flood behind a series of barrier islands, similar to the modern environment found today along the southeast Atlantic and Gulf Coasts. Within the thick sequence of shales and siltstones, several beds of quartzite occur, which likely represent barrier island/beach environments formed during minor changes in sea level (as sea level fluctuates, the coastline moves inland and seaward, leaving shoreline deposits at various places within the stratigraphic record) (Gathright, 1976).

Erwin Formation

As the Iapetus Ocean continued to advance, the inland lagoons and bays gradually transitioned to beachfront property, and silts and shales gave way to quartz sand dunes, beaches, and barrier islands. The Erwin Formation is dominated by beds of clean, pure white quartz sand, now hardened into a very resistant quartzite by later metamorphism. These quartzites often preserve original sedimentary structures, such as layering and cross-bedding, that record their beach/dune environment. The Erwin quartzites also commonly contain remnant trace fossils called “skolithos”, which are preserved burrows from an early form of worm. These fossils appear as thin, straight, tube-like structures within the rock, and are often extremely prevalent throughout the rock. The Erwin is not entirely quartzite, but rather a series of quartzite beds separated by less resistant layers of siltstone and shale which are rarely found as exposed bedrock. As in the Hampton Formation, this sequence represents the continued minor fluctuations in sea level during the overall advance of the Iapetus (Gathright, 1976).

Appendix D. Bedrock-influenced geomorphic patterns in SHEN.

The following descriptions and interpretations draw on the author's personal observations and experiences, as well as previous work by Gathright (1976), Connors (1988), and Badger (1999).

General bedrock patterns

The bedrock geology of SHEN is a controlling factor in the location and physical character of open rock exposures, as well as in the general morphology of the landscape. In the North and Central Districts of the park, the ridgeline is generally capped by greenstone lava flows that dip eastward. Thus, many open rock exposures in this lithology are found at high elevation, facing generally westward (e.g. Stony Man and Hawksbill Mountains). Where significant exposures occur on the east side of the ridge, they are generally associated with deep slot canyons incised into the greenstone layers by streams (e.g. Little and Big Devil's Stairs, Whiteoak Canyon). In the southern portion of the North District, the greenstone layers dip west as well, producing a similar texture on the western side of the park (Jeremy's Run, Overall Run).

In the North and Central Districts, basement rocks are generally found at lower elevations, underlying the greenstones, and so are less likely to produce significant open rock exposures. Significant exceptions to this rule are found where faulting has thrust the basement rocks over the greenstones (e.g. Pinnacle Ridge/Mary's Rock), where similar faults separate basement rock areas into solitary summits (e.g. Old Rag and Oventop Mountains), or where the original paleotopography of the pre-Catoctin land surface has preserved an especially high point (e.g. Hogback Mountain).

While the North and Central Districts are relatively similar in their bedrock geology and structures, the South District is distinctly different. Here, the Chilhowee Group has not yet been eroded away, and the orientation of the rock sequence dips strongly to the west, so that the younger rocks are exposed to the west. Thus, the dominant bedrock of this district is the Chilhowee, and most of the ridgelines and valleys are formed in this lithology. The Catoctin is still present along the eastern slope of the main ridge, and the basement rocks are mostly deep in valleys or outside the park boundary.

General structural patterns

Large-scale geologic structures significantly influence the location and shape of the Blue Ridge in Shenandoah. As discussed above, several large faults run through the park, along which thick sequences of bedrock were thrust and stacked atop one another, creating ridges and peaks that would not otherwise exist (e.g. Mary's Rock and Pinnacles). In addition, the actual traces of these faults are often areas of accelerated weathering, since fault activity tends to grind up and weaken bedrock in the area. Thus, these faults create gaps and valleys (e.g. Thornton Gap, Berry & Weakley Hollows) that may isolate certain peaks (e.g. Old Rag and Oventop). Several smaller faults cut across the main ridge, perhaps influencing the development of gaps at these locations (e.g. Fishers Gap and Hawksbill Gap).

Appendix D. (continued).

At a smaller scale, physical structures such as joints, foliation, and cleavage provide planes of weakness along which weathering processes act to shape rock exposures. Where such structures are oriented parallel to the surrounding slope, longer, linear, more sheer rock exposures may be expected. Where such structures are oriented against the surrounding slope, isolated, protruding outcrops of rock may be more likely. In addition, the presence and quantity of ledges (prime vegetation habitat) is directly related to the presence and nature of such geologic structures; cleavage and layering in particular are conducive to ledge formation.

Basement rocks

In general, most granitic-type rocks will erode into smooth, rounded landforms due to the relative uniformity of their mineral textures and the processes of spheroidal weathering and exfoliation. The former acts to chemically break down minerals (especially those found in granitic rocks) in exposed areas, thus rounding off any sharp corners and producing the smooth, rounded knobs and boulders found at places like Old Rag Mountain. Exfoliation occurs when a bedrock area slowly expands and contracts due to temperature changes; the subtle flexing that occurs under these conditions creates curved fractures by which rounded slabs of rock break off. This process is especially common in fine-grained, structureless crystalline rocks, where it produces an onion-like surface texture of smooth, rounded rock faces with multiple layers of curved fractures parallel to the surface.

Where jointing is present, the joints create natural planes of weakness for such weathering processes to focus on, resulting in a series of rounded blocks, boulders, and distinct knobs, all bounded by joints. Where strong foliation is present, these rounded surfaces may take on some of the orientation of that foliation, and make the exposure appear platy or oblong. Where these structures are both present, they interact to form complicated rounded, polygonal rock exposures. Where they are absent or minor, the rocks tend to form smooth, expansive rock faces unbroken by any other feature (and exfoliation is likely dominant).

In SHEN, the basement rocks tend to erode faster than the overlying Catoctin greenstones. This factor, in combination with the relative lack of structures (compared to the dominant planar flows in the Catoctin), results in basement rock areas generally being steeper, more rugged, and containing deeply incised ravines and valleys. It is often easy to see the contact between the Catoctin and the underlying basement rocks from afar simply by looking for the point along a slope where deep ravines and narrow ridges suddenly develop below an upper areas that is smoother and more gently sloping.

Catoctin Formation

The Catoctin Formation creates a unique landscape where it is present. Individual lava flows tend to be more resistant to erosion than the fractured, brecciated contact zones between flows. This results in a staircase-like topography, where cliffs and/or steeper terrain form within individual flows, while flatter topographic benches develop along the contacts between flows. Structurally, the flows are most commonly near-horizontal, dipping up to 20 degrees (though

Appendix D. (continued).

many other orientations do occur). These factors combine to produce a landscape in which the gentler slopes of Catoctin areas form smooth, gently dipping planes cut by occasional stream canyons, while opposite slopes are dominated by sheer cliffs and steep slopes formed by the upthrust faces of individual flows. This pattern is most commonly found in the Central and North Districts, where east-dipping flows produce west-facing cliffs.

It is not a coincidence that most of the major waterfalls within the park are located to the east, where streams draining the broad, smooth surfaces cut down into the stacked flows to create sequential waterfalls at each boundary. Often within this landscape, the individual lava flows are exposed as parallel cliff/outcrop lines that angle sharply up the slope, due to the geometry of the steep canyon walls interacting with the gentle eastward dip of the flows. The result can be a “tilted staircase”, where the topographic benches between flows become ramps ascending the slope, delineated by continuous lines of rock exposure that often stretch from top to bottom of the valley’s sides (e.g. Rose River). In other canyons, the dip of the flows is gentle enough that a single flow can form a recognizable cliff line throughout the canyon (e.g. Big Devil’s Stairs).

The Catoctin can form very diverse rock exposures. The most common formation is the “staircase” pattern of cliffs and ledges discussed above, but boulder fields, isolated outcrops, and angled slopes of bedrock are all present within SHEN. The individual texture of each flow (amount of cleavage and fractures, columnar jointing, mineral composition, geographic location) varies widely, and so the landscape can change dramatically from one slope to another. A common way to distinguish one lava flow from the next is to note the change in character of the landscape and bedrock exposures across a certain vertical distance.

The Chilhowee Group

The metasediments of the Chilhowee Group form a distinct terrain, despite the diverse nature of the rocks within this group. Quartzite in particular is very hard, strong rock, and difficult to erode. However, most areas underlain by the Chilhowee have also been significantly deformed by tectonic activity, and the quartzites generally reacted to these pressures by breaking rather than deforming. Thus, most quartzite areas are laced with fractures along which weathering processes operate, resulting in large, unstable cliff areas and widespread boulder fields formed from the crumbling bedrock. Large-scale folds in the bedrock are also common, visible as arch-shaped white quartzite cliffs shaping the mountains (e.g. Rocky Mountain).

The siltstones, shales, and other more fine-grained rocks of the Chilhowee are more easily eroded, and are less likely to form bedrock outcrops. The combination of hard, resistant quartzite layers and easily eroded silty layers results in a very rugged landscape in which ridges are held up by quartzite while steep slopes and deep ravines are eroded into the other rocks. Thus, the South District has a much more rugged, undulating appearance than elsewhere in the park, created by the numerous sharp ridges and narrow valleys created by these processes. At the very western edge of the Blue Ridge, the Erwin Formation takes one last plunge into the earth, creating a steep rampart of topography that ends abruptly in the much softer limestones and dolomites of the Shenandoah Valley.

Appendix E. Glossary of geologic terms and mineral compositions

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The following definitions are adapted from Blatt & Tracy (1999), Deer et al., (1966), Gathright (1976), and Parker (1994), as well as personal knowledge and experience from the author.

Terms Specific to This Report

Basement Rock – A general descriptive term for the complex set of igneous and metamorphic rocks, 1-1.2 billion years in age, that underlie the Blue Ridge in Shenandoah and the surrounding region. Used in this report in favor of the old “Pedlar Formation” designation; see that entry for details.

Catoctin Formation – A unit of greenstone lava flows that extends from southern Pennsylvania through Maryland and portions of Virginia, erupted onto the surface around 570 million years ago.

Chilhowee Group – A group of three related metasedimentary formations deposited over the Catoctin Formation. Chilhowee rocks are predominately found in the South District, with minor occurrences in the Central and North Districts.

Cliff – In this report, a specific type of exposure morphology. See Figure 2 or Appendix D for definition.

Erwin Formation – This uppermost unit of the Chilhowee Group is known for its thick, white quartzite beds that dominate ridgelines in the South District. These layers commonly form sheer cliffs and large, open boulder fields on the steep flanks of narrow ridges.

Exposure – See Open Rock Exposure.

Face – In this report, a specific type of exposure morphology. See Figure 2 or Appendix D for definition.

Hampton Formation – This central unit of the Chilhowee Group is composed primarily of fine-grained metasandstones and phyllites, commonly containing a strong, planar cleavage structure that appears similar to layering. The unit also contains several distinct quartzite beds that are similar in appearance to the Erwin Formation, though darker in color.

Ledge – In this report, a specific type of exposure morphology. See Figure 2 or Appendix D for definition.

Open rock exposure – Any area of bedrock or talus area that is mostly open to the sun, i.e. not shaded or obscured by tree canopy, shrubs, or soil. Lichen coverage is not considered in this definition.

Outcrop – A general term used for any exposed bedrock area. In this report, a specific type of exposure morphology. See Figure 2 or Appendix D for definition.

Pedlar Formation – An old collective designation for the complex set of igneous and metamorphic rocks, 1-1.2 billion years in age, that underlie the Blue Ridge in Shenandoah and the surrounding region. This term has fallen out of favor among some geologists in recent years as further work establishes how diverse this suite of rocks really is. In this view, “Formation” implies too much shared history and character. In this report, the term “basement rock” is used instead to avoid controversy.

Appendix E. (continued).

Terms specific to this report (continued).

Social trail – Any trail, path, or route created or maintained by humans, but not sanctioned, recognized, or maintained by authorities. Commonly found leading from official trails to overlooks, campsites, or other areas of interest to visitors.

Talus – A general term for loose rock on a slope (see Talus, General Geologic Terms). Also, in this report, a specific type of exposure morphology. See Figure 2 or Appendix D for definition.

Weverton Formation – This is the lowermost unit of the Chilhowee Group, deposited directly onto the final Catoctin Formation lava flow. The formation is most commonly composed of metasandstone, quartzite, and some pebble/cobble beds, and represents the onset of erosion and river system development once the Catoctin eruptions had ceased.

General Geologic Terms

Amygdule/Amygduloidal – A texture found in volcanic rocks, in which previously formed vesicles are filled in by mineral deposits after the rock has cooled. These are very common in concentrated zones 1-2 meters thick near the tops of lava flows within the Catoctin Formation. Quartz is by far the most common filler mineral, with epidote and chlorite present in some cases.

Bedrock – General term referring to any solid rock that remains fully attached to the earth (i.e. not soil, river sediments, or loose boulders). It does not refer only to the lowest in a sequence of rocks, but to any and all that fit the above definition.

Boulder field – see Talus.

Charnockite – A specific type of granitic rock where pyroxene is the dominant dark-colored mineral rather than biotite. Generally unusual, it is common in parts of Shenandoah.

Crystalline – A rock texture composed of fully intergrown mineral crystals, rather than individually cemented grains. Typical of igneous rocks, this texture can also be found in some metamorphic rocks (if the minerals have been deformed enough to grow together) and sedimentary rocks (if the minerals chemically grew together in the first place, e.g. limestone and chert). Can be identified by observing minerals closely to determine whether they are intergrown or cemented by some independent substance.

Formation – When used as a noun, any unit of bedrock or associated units that are locally classified together as part of the interpretation of their geologic history. Formations do not have to be the same rock type, but generally share similar histories. For example, the Catoctin Formation contains both volcanic and metasedimentary rocks, but these are classified together based on a shared origin and history, and to distinguish them from other, less related rocks.

Geochemistry – Relating to the chemical composition of rocks and/or minerals.

Geomorphology – In general, the study of the Earth's surface and the processes that shape the landscape (distinct from studying the bedrock underlying that landscape). As an adjective, can be used to refer to the character of a certain landscape, e.g. "the geomorphology of that river valley". This latter usage is often interchangeable with Morphology, though the latter also implies a smaller scale area.

Appendix E. (continued).

General Geologic Terms (continued).

Igneous – Any rock formed by the cooling and solidification of molten rock, whether underground or on the Earth's surface.

Lithology – The general composition and/or classification of a particular rock or rock unit.

Metamorphic – Any rock formed through the physical and/or chemical alteration of a pre-existing rock to the point that it becomes distinct from the original rock. Metamorphism refers to the process of these changes, and the prefix Meta- can be attached to most rock types to indicate that metamorphism has occurred, especially if the effects were not strong and the rock retains many of its original features (e.g. metabasalt).

Mineral – Any naturally occurring, solid substance with a known chemical composition and crystal structure. Minerals are most easily thought of as individual crystals that make up a rock (some rocks are made up entirely of crystals of a single mineral type, e.g. limestone {calcite}).

Morphology – Referring to the physical character or shape of a rock, exposure, or landscape. Similar to Geomorphology, but generally describing a smaller scale, e.g. “the morphology of this cliff”.

Paleotopography – A landscape present at some past time in Earth's history, usually different from that seen today. This may be directly observed from the shape and nature of contacts between rock layers, or inferred from sedimentary deposits collected elsewhere.

Plate tectonics – The slow movement of solid portions of the Earth's crust (plates), interacting to form mountains, oceans, volcanoes, and all other features of the Earth's surface.

Sedimentary – Any rock formed by the physical collection and cementation together of individual mineral grains (e.g. sandstone), or the chemical growth of minerals at or near the earth's surface (e.g. some limestones, cherts, and cave formations).

Structures – Any physical feature other than minerals present in a rock. Structures may be internal and integral to the rock, such as layering and foliation, or may be imposed upon the rock, such as cleavage, joints, and faults.

Talus – Loose rock fragments accumulated on a slope. Generally used to describe areas where these fragments are dominating the slope, at the expense of soil or vegetation growth. Usually, but not always, associated with a bedrock cliff or other exposure from which the fragments have eroded. Also referred to as Boulder Field. Also used in this report as a specific type of exposure morphology; see Figure 2 for definition.

Tectonic – Adjective referring to the actions or results of Plate Tectonics, e.g. “tectonic activity creating mountains” refers to the collision of crustal plates to form topography.

Vesicle/Vesicular – A texture formed in volcanic rocks, consisting of empty cavities created from gas bubbles present in the cooling rock. In Shenandoah, these are rarely found as true vesicles (empty), but generally as Amygdules, where the cavity has been filled by mineral deposits.

Appendix E. (continued).

Rock Types

Basalt – A dark-colored volcanic rock composed primarily of the minerals plagioclase, pyroxene, and olivine. Generally erupted from volcanoes or rift areas, forming fluid lava flows that cool on the surface of the earth. Individual crystals are small and rarely visible, due to the rapid cooling of the lava above ground. Can be used as an adjective describing the general mineral composition of a rock; e.g. basaltic.

Breccia – A sedimentary rock formed from angular fragments of other rocks, mixed together and cemented by other minerals. This often reflects a landslide or other active erosional process. A volcanic breccia is formed when lava flows or other volcanic processes rip up and collect rock fragments into a distinct unit. A conglomerate is similar, but contains mostly rounded fragments, generally reflecting an origin in river or stream gravels.

Conglomerate – See Breccia.

Gneiss – Any crystalline metamorphic rock containing a planar structure formed by alternating bands of similar mineral types. This banding forms during intense metamorphism, as individual minerals within the rock segregate themselves into bands containing other like minerals. This banding, or foliation, is distinct from the layering found in sedimentary rocks (in which minerals are deposited in place) or the foliation found in other metamorphic rocks such as schist or phyllite (in which the planar structure is formed by alignment of platy minerals such as micas). Can be used as an adjective describing any rock containing this banding structure (implying very intense metamorphism); e.g. gneissic.

Granite – A generally light-colored igneous rock composed primarily of quartz, orthoclase, and plagioclase, with lesser amounts of other minerals such as biotite, garnet, and pyroxene. Forms from molten rock which cools slowly underground into a solid, crystalline body; individual minerals are almost always visible. Can be used as an adjective describing the general mineral composition of a rock; e.g. granitic.

Greenstone – A rock formed by the low-grade metamorphism of basalt. Under these conditions, the original mineral composition of the basalt is altered to form the minerals chlorite, epidote, and actinolite. These new minerals give the rock a greenish tint; thus the name. This rock is also commonly referred to as metabasalt. Its physical appearance preserves many original features of the basalt, and is generally similar, except for the common green tinge, a slight trend toward being more coarse-grained, and the common presence of cleavage structures formed by alignment of chlorite crystals during the metamorphism.

Limestone – A sedimentary rock composed primarily of calcite, formed in marine environments from the detritus of living organisms. Limestone is generally white-grey and massive (little to no prominent layering or structures), and will react with hydrochloric acid to produce bubbles of carbon dioxide.

Quartzite – A metamorphic rock formed by heat and pressure acting on sandstone. The term specifically refers to rocks containing virtually all quartz (originating in a clean sandstone), where the individual sand grains have been fused together to form a very solid mass of pure crystalline quartz. A metamorphosed sandstone which contains significant amounts of mineral grains other than quartz would be a metasandstone.

Sandstone – A sedimentary rock formed primarily of sand grains cemented together. This rock most commonly reflects the presence of a beach, river, or dune at the time of its formation.

Appendix E. (continued).

Rock Types (continued).

Sandstones vary from “clean” (containing virtually all quartz sand) to “dirty” (containing sand grains of many different minerals mixed together), the composition reflecting the age and energy of the original environment. A mature beach or dune is most likely to produce clean sandstone, while an actively eroding river is more likely to produce a dirty sandstone.

Shale – A sedimentary rock formed primarily of very fine silt and clay particles, forming thin layers along which the rock easily breaks. Generally, little to no individual minerals can be seen in shale, which appears most often as a solid grey-black, platy rock. This rock reflects an original environment of deep, calm water such as lakes and oceans, in which very fine sediments are able to settle to the bottom in thin layers.

Siltstone – A sedimentary rock compositionally between sandstone and shale, containing a mixture of fine-grained silt and clay minerals combined with coarser sand grains. This rock is quite variable in appearance, generally containing noticeable layering which still appearing grainy. This rock often reflects lagoon/delta environments, where both flowing and calm water can be found.

Geologic Structures

Banding – See Foliation.

Cleavage – A roughly planar fracture system within a rock, formed during metamorphism through the growth or realignment of platy minerals such as biotite or chlorite. Generally gives the rock a fractured, jagged appearance, and often cross-cuts internal structures such as layering or foliation. Similar in appearance to foliation in some rocks, but occurs as a set of semi-planar fractures imposed on the rock, and related to mineral orientations, rather than a planar structure internal to the rock. Distinct from joints in that cleavage is generally more unruly in appearance, closer-spaced, and smaller at the scale of each individual fracture plane. **ALSO** – A planar structure within certain minerals, related to the crystal structure of that mineral type. Common in platy minerals such as micas.

Columnar joints – These are a special subset of joints that occur in cooling igneous rock, generally lava flows or dikes. As the molten rock cools, it contracts, and under certain conditions will fracture into smooth joints at obtuse degree angles to one another, forming polygonal columns of rock from 10-100cm in diameter or larger. Although columnar joints are technically the fracture set, the term is often used to refer to the resulting polygonal column of rock. Columnar joints develop perpendicular to the surface constraining the molten rock; vertically in erupted lava flows, and in dikes perpendicular to the walls of the fracture containing the dike.

Dike – A narrow, generally planar, discrete body of igneous rock cutting through the mass of another rock. These form when underground molten rock follows joints or other fractures up into solid rock, and cools within the fracture. Dikes are distinct from veins in being generally bigger, more planar, and forming from cooled molten rock rather than minerals deposited by water.

Appendix E. (continued).

Geologic Structures (continued).

Foliation – A planar structure within a rock, formed by alignment of minerals into distinct bands. This may take the form of very thin, platy surfaces formed by micas, or a more general banded texture formed by quartz, feldspar, or other minerals. Similar to cleavage, but internal to the rock rather than an imposed fracture system (see Cleavage). Similar to layering, but found in igneous or metamorphic rocks as an alignment or segregation of like minerals, rather than a series of independently formed layers of sediments.

Joint – A very planar fracture within a rock that shows no displacement on either side. Joints generally occur in parallel sets, all following the same orientation and spaced over 50cm apart. Joints are distinct from cleavage in being larger, more planar, spaced farther apart, and not being related to any mineral orientation or structures.

Layering – A planar structure within a rock, consisting of a discrete unit of sediments or minerals that share a common history of deposition or formation distinct from the layers above and below. Appears similar to foliation or banding, but layers form individually and consecutively during the formation of the rock itself, rather than collectively due to outside pressures or forces (as in foliation). Most common in sedimentary rocks, though certain igneous and volcanic rocks may form a crude layering as they cool and solidify.

Vein – A small, narrow mineral deposit within a rock, generally formed underground by water intruding into fractures in the rock and depositing dissolved minerals into the fracture. Veins often contain deposits of unusual or valuable minerals, collected and concentrated by heated and pressurized water deep underground. Distinct from dikes in being mineral deposits rather than cooled igneous rock, and generally being much smaller and less planar.

Common or Important Minerals in SHEN

Actinolite – $\text{Ca}_2(\text{Fe}, \text{Mg})_5\text{Si}_8\text{O}_{22}(\text{OH})_2$ – A dark green mineral commonly formed during metamorphism of basaltic rocks. Actinolite can form somewhat fibrous, elongated crystals that may occur in veins within greenstone.

Biotite – $\text{K}(\text{Mg}_3, \text{Fe}_3)\text{AlSi}_3\text{O}_{10}(\text{OH})_2$ – One of many mica minerals that form thin, platy sheets with highly reflective surfaces. Biotite is usually dark brown to black, and forms thin flakes primarily within igneous rocks.

Chlorite – $(\text{Fe}, \text{Mg}, \text{Al})_6(\text{Si}, \text{Al})_4\text{O}_{10}(\text{OH})_8$ – A dark green mica mineral commonly formed during metamorphism of basaltic rocks. Chlorite, like other micas, forms a thin, platy crystal structure, and will often align itself into planes under pressure, creating a strong cleavage structure within the rock. This is common in greenstone areas of Shenandoah.

Epidote – $\text{Ca}_2\text{Al}_2\text{FeSi}_3\text{O}_{12}(\text{OH})$ – A lime/pistachio green mineral commonly formed during metamorphism of basaltic rocks. Epidote replacement is very common in the Catoctin Formation greenstones, and ranges from producing a light green tinge to solid masses of pistachio green rock meters in diameter. Areas with a great deal of epidotization often appear grainy or even sandy compared to the finer grained greenstone nearby. Epidote can also be found in a more crystalline form in amygdulites or other small pockets of mineral growth. In

Appendix E. (continued).

Common or Important Minerals in SHEN (continued).

addition, it may form in granitic rocks during local metamorphism (such as the intense heat generated by a lava flow covering the rock), producing the pink-and-green rock unakite.

Feldspar – A general term for a large family of common aluminosilicate minerals (their structure is based on a framework of silicon, aluminum, and oxygen). There are two main classes of feldspar; plagioclase and orthoclase, both of which are found in Shenandoah. These two are often difficult to tell apart in the field; in Shenandoah, orthoclase is often white-pink, while plagioclase is often white-grey. Both may fracture into planar, reflective surfaces and form blocky crystals. In igneous rocks, where they are most commonly seen, individual crystals may grow many centimeters in diameter. Orthoclase is found chiefly in granitic rocks, particularly the Old Rag Granite, while plagioclase is common throughout the granitic gneisses of the Basement Rocks and as a main constituent of basalt/greenstone. Either may be found in small quantities as mineral fragments in sedimentary rocks.

Garnet – $(\text{Fe}, \text{Mg}, \text{Ca}, \text{Mn})_3\text{Al}_2\text{Si}_3\text{O}_{12}$ – A common accessory mineral in granitic rocks, rarely found in abundance but often present in minor amounts. Garnet can take on a wide range of colors, but is mostly commonly dark red to maroon, and appears as small red spots within granite.

Olivine – $(\text{Mg}, \text{Fe})_2\text{SiO}_4$ – A common ferromagnesian (see Pyroxene) mineral in dark-colored low-silica rocks such as basalt. Olivine is never found together with quartz, which is common in lighter-colored, high-silica rocks such as granite. Olivine is generally dark green, though it is rarely seen as a visible crystal in Shenandoah.

Orthoclase – KAlSi_3O_8 – One of two common feldspar types (with plagioclase), containing potassium (K). Orthoclase is found mainly in granitic rocks, particularly the Old Rag Granite. For more on distinguishing orthoclase from plagioclase, see Feldspar.

Plagioclase – $\text{NaAlSi}_3\text{O}_8$ – $\text{CaAl}_2\text{Si}_2\text{O}_8$ – One of two common feldspar types (with orthoclase), containing variable amounts of sodium (Na) and calcium (Ca). Plagioclase is common in granitic rocks, as well as basalt/greenstone. For more on distinguishing plagioclase from orthoclase, see Feldspar.

Pyroxene – MgSiO_3 – FeSiO_3 (with associated Na, Ca, and others possible). A general term for a broad and diverse group of dark-colored ferromagnesian minerals (their structure is based on iron and magnesium in a framework of silicon and oxygen). Pyroxenes are generally black, and form small, blocky crystals within igneous rocks. They are an important part of basalt/greenstone, but are less common in granitic rocks, where Biotite is a more common dark mineral.

Quartz – SiO_2 – Very common, clear-white mineral. Usually forms no specific crystal shape, and breaks in random, curved fashion without flat, reflective surfaces. Has a glassy or waxy shine and is often partially translucent. Can be stained a number of different colors by minor impurities, but generally solid white to milky/clear. Most prominent in sandstone, quartzite, and granite; also found in veins and amygdules within greenstone.

Appendix F. ROMP geologic site reports

C02	Bettys Rock.....	5 pages
C03	Big Devils Stairs.....	8 pages
C04	Blackrock Central District.....	6 pages
C05	Blackrock South District.....	7 pages
C07	Browntown Valley Overlook	7 pages
C08	Calvary Rocks / Chimney Rock.....	8 pages
C10	Crescent Rock Overlook.....	7 pages
C11	Crescent Rock South.....	6 pages
C12	Dean Mountain Ridge.....	5 pages
C13	Dickey Hill.....	5 pages
C14	Dickey Ridge	5 pages
C15	Franklin Cliffs North.....	8 pages
C16	Franklin Cliffs Overlook.....	7 pages
C17	Franklin Cliffs South.....	7 pages
C18	Goat Ridge.....	6 pages
C19	Gooney Manor Overlook.....	7 pages
C20	Halfmile Cliff.....	7 pages
C21	Hawksbill N slope outcrops.....	13 pages
C22	Hawksbill summit.....	8 pages
C23	Hightop.....	6 pages
C24	Hogback Mtn spur.....	8 pages
C27	Little Devils Stairs.....	8 pages
C28	Little Stony Man.....	9 pages
C29	Loft Mountain summit.....	7 pages
C31	Marys Rock.....	7 pages
C32	Millers Head.....	8 pages
C34	Nakedtop Upper East Slope.....	7 pages
C35	North Marshall summit.....	7 pages
C36	Old Rag southside.....	8 pages
C37	Old Rag summit east.....	11 pages
C38	Oventop.....	8 pages
C39	Overall Run Falls south.....	6 pages
C40	Pass Mountain.....	7 pages
C41	Pinnacles.....	9 pages
C42	Powell Gap cliff	6 pages
C44	Rocky Mountain.....	8 pages
C45	Sawlog Ridge.....	7 pages
C46	South Marshall cliff.....	7 pages
C47	Stony Man summit.....	10 pages
C49	Trayfoot Saddle boulderfields E.....	6 pages
C50	Upper Devils Ditch.....	8 pages
C60	Hawksbill N slope talus.....	8 pages
C62	Old Rag summit west.....	7 pages
C63	Overall Run Falls north.....	8 pages
C64	Brown Mountain.....	8 pages
C65	Trayfoot Saddle boulderfields W.....	7 pages
C66	Field Hollow Cliff.....	9 pages
C67	Bearfence.....	9 pages
C68	Rose River.....	8 pages
C69	Whiteoak Canyon.....	7 pages