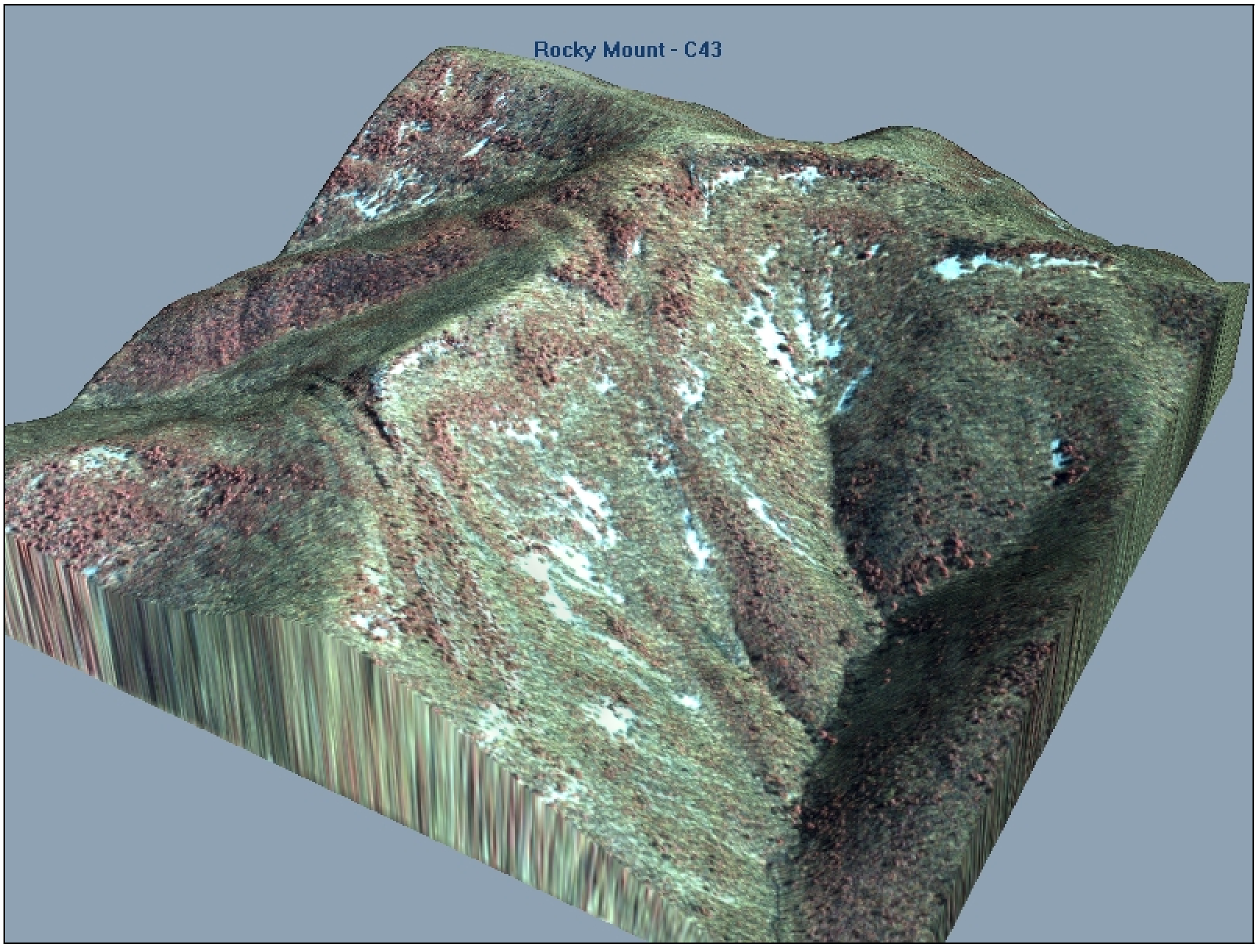
Mapping Outcrops in Shenandoah National Park
Final Report for 2006



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Key Project Data

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Abstract

Cliff and outcrop resources of Shenandoah National Park are the focus of a multiyear study, with the ultimate goal of producing an "outcrop management plan". The first step in this process was to map the location of rock outcrops in the park to assess the resource and to locate sites for field study. To accomplish this task we employed a semi-automated mapping method to delineate outcrop polygons from leaf-on and leaf-off aerial photography. We mapped 2,105 outcrop polygons throughout the park. Comparisons of mapped outcrop polygons to global positioning system (GPS) points collected in the field showed moderate to good correspondence, depending on geologic type. Correspondence of field collected points with outcrops mapped as polygons was highest on rocks of the Chilhowee Group, and less so for Catoctin metabasalt and granitic rocks. Most mapped outcrops occurred on Chilhowee group siliciclastic geology in the park's southern district in steep sloping landform types. Mapped outcrop locations were used to describe the abundance of outcrops within the park and to assist in identifying sites for further study that were not previously well known.

Executive Summary

- Rock outcrops of Shenandoah National Park (SHEN) are the focus of a multiyear study that will culminate in the development of an outcrop management plan.
- The first step in the study was to map outcrop locations in SHEN to assess the resource and to locate sites for field sampling.
- We employed a semi-automated mapping approach where an interpreter located outcrops on 51 leaf-off and 151 leaf-on digital orthophotographs (e.g. aerial photographs), but polygon boundaries were delineated automatically by remote sensing software.
- We mapped 2,105 outcrop polygons using the semi-automated approach. Mapped outcrop polygons ranged in size from < 1ha to 2.4 ha. Mean size was 0.42 ha.
- We compared outcrop polygons to maps of bedrock geology and found that 58% of mapped outcrops occur on Chilhowee Group siliciclastic rocks, 23% occur on Catoctin metabasalt, and 18% occur on granitic rock types.
- We compared mapped outcrop polygons to three sets of field collected GPS points and found overall correspondence of 58.8%, 47.8%, and 54.2%. However, correspondence of GPS points with mapped outcrop polygons varied by geologic type and varied from 88.9% to 47.2% correspondence for the major geologic types.
- Despite the potential for under-representation with this mapping method, we were successful at locating outcrops that were not well known and yet may have significant resource value. Several of these were selected for further field study.
- Additional outputs of this project were maps and an online image gallery for other study participants to use in research planning and assessment (http://www.lsc.usgs.gov/gis/shen/outcrops/).

Acknowledgements

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Introduction

Rare species and communities at cliff and outcrop areas throughout Shenandoah National Park (SHEN) have been severely degraded by essentially unmanaged and unregulated visitor use. The SHEN Mission Goals state that, "The integrity of this portion of the Blue Ridge/Central Appalachian biome is protected, maintained, and restored as appropriate", yet, "Recreation and re-creation opportunities are provided consistent with the purposes and significance of the Park". Clearly, the Park's cliff resources are to be preserved while allowing for recreational opportunities. Shenandoah National Park has initiated a multi-agency project to develop the information necessary to better manage outcrop resources. The overall project goal is to obtain information to support development and implementation of a park-wide Rock Outcrop Management Plan. Visitor access, use, and associated impacts to park outcrop areas are known to be unrestrained and significant, but the full extent of rock outcrops and the associated rare species and human impacts remains unknown.

A National Park Service – National Resources Preservation Program (NPS-NRPP) project was funded in 2004 for natural resource survey and classification work, identification of outcrop visitor use and impacts, and the development and implementation of a Rock Outcrop Management Plan (Cass et al. 2004). This information is critically needed to direct visitor recreation use to minimize impacts, mitigate resource degradation associated with visitor use, preserve valuable cliff resources, and restore damaged cliff and rock outcrop areas. This report documents results from project Task 1, "Identify and map locations of cliff resources through aerial photo interpretation and analysis of satellite imagery". Other tasks associated with this project are ongoing and are expected to be complete in 2007.

Prior to development of a cliff management plan, a census of outcrops was needed to assess the area and extent of the resource in the park. This information was also needed to develop a field sampling campaign to effectively survey and represent the characteristics and threats associated with these areas. Previous and ongoing mapping efforts in the park were not at sufficient spatial resolution to capture small outcrop features; therefore additional mapping was required. In addition, while the larger and more popular outcrop sites are well known (e. g. Hawksbill, Stony Man, Old Rag), other outcrop areas in the park are unknown or they are obscure but may contain unique habitats and therefore may be worthy of protection. The goals of Task 1 were therefore to use aerial imagery, GIS and landform data, and mapping expertise to identify and locate outcrops in SHEN.

Methods for mapping geologic features using aerial imagery (e. g. "photogeology") are well established, and date to the earliest uses of aerial photography (Campbell 1987, Miller 1961, Ray 1960). As with mapping other land cover from aerial photographs, image texture, tone, shape, size, and shadow are used for interpretation of lithologic units and structural features (Campbell 1987). Much of the recent research has moved beyond interpretation of aerial photography to automated digital processing using radar, multi-, and hyper-spectral imagery. However, defining consistent spectral signatures for automated classification is difficult due to spectral variability between image frames and the inherent spectral variability within rock units (Campbell 1987, Lillesand and Kiefer 2000).

Mapping of outcrops in SHEN from aerial imagery poses significant challenges. Spectral and spatial properties of outcrops (e.g. image signatures) are difficult to consistently characterize because of different rock structure types, the vertical nature of many cliff faces, and the obscuring effects of vegetation. Rock outcropping is controlled by three major bedrock geology types occurring in the park, each with its own outcrop "signature".

Granitic rocks of igneous origin occur in the central and eastern flanks of the park. These rocks form the well known outcrops of the Old Rag Mountain area. The granitic rocks of SHEN generally occur as either a light gray to white granitic gneiss, or a darker green to blue-gray charnockite (Morgan et al. 2004), and erode into large spheroidal shaped boulders and rounded blocks (Gathright 1976) that are fairly characteristic on aerial photos, but which can be obscured by vegetation (Figure 1). The Catoctin formation is a metamorphosed basalt or "greenstone" that was deposited as a series of gently sloping volcanic flows and forms the ridge crest throughout much of the park (Gathright 1976, Morgan et al. 2004). The Catoctin formation is a dark, dense, and fine grained rock and because it is more resistant to erosion than other rocks in the park, it often occurs as a "caprock" and outcrops as cliffs at contact boundaries between geologic units (Gathright 1976, Morgan et al. 2004). This predominantly flat-lying formation also occurs as a series of terraces forming a "staircase" pattern of cliff-bench-cliff on the landscape (Morgan et al. 2004). The Catoctin erodes into mineral rich soil supporting rich vegetation communities. Because of the vertical nature of many of the cliffs formed by the Catoctin formation and the lush vegetation it supports, these outcrops can be difficult to detect from vertical aerial photography typically used in mapping applications (Figure 2). Overlying the Catoctin are rocks of the Chilhowee Group consisting of quartzite, conglomerate, and other siliciclastic rocks. The rocks in these units include light gray to tan sandstone (Weverton formation), greenish-gray to brown meta-sandstone, meta-siltstone, and phyllite (Hampton and Erwin formations), and light gray to white quartzite (Antietam formation) (Gathright 1976). These formations form flatiron and hogback ridges, and some (Hampton and Erwin) erode into block and talus fields (Morgan et al. 2004). Most rocks of the Chilhowee group form thin acidic soils supporting sparse vegetation (Morgan et al. 2004). Because the rocks of the Hampton and Erwin formations are generally light gray to white in color and form large block and talus fields, they are easily detectable from the air (Figure 3). Since soils produced by these formations are generally thin and acidic, they tend to support a sparse vegetation community with a larger evergreen component. While combinations of leaf-on and leaf-off photographs are useful for detecting outcrops obscured by deciduous vegetation, it can be very difficult to detect outcrops obscured by evergreen vegetation.

Study Area

Shenandoah National Park (SHEN) encompasses 70 miles of ridge crest along the Blue Ridge mountains of Virginia, straddling habitats of both the northern and southern Appalachians and supporting a rich assemblage of flora and fauna. Rock outcrops and cliffs punctuate the otherwise forested landscape composing approximately 2% (3920 acres) of the Park's 196,000+ acre area. The cliffs of SHEN are some of the largest in the region and serve as islands of unusual habitat and species assemblages. The relatively high elevation of many rock outcrop areas in the park means that these areas provide habitat for unique communities of boreal disjunct species.

Methods

Rock outcrops were mapped by the USGS, Leetown Science Center (USGS-LSC) using remote sensing, aerial image interpretation, and GIS modeling. This mapping effort built on vegetation mapping projects currently being finalized at USGS-LSC and exploited data sources previously compiled for Shenandoah National Park. The mapping effort primarily involved interpretation of existing aerial imagery augmented by GIS analysis of slope conditions using a digital elevation model. The target of interest was the presence of exposed rock (e.g. outcrops) both in the open and under forest canopy.

The primary data source for outcrop interpretations was leaf-off color infrared orthophotography (c. 1997 and 1994) at 1:12,000 scale (USGS). This imagery was previously corrected (e.g. orthorectified) for systematic and terrain induced errors by the USGS, and was delivered as quadrangles covering one-quarter of a standard USGS 7.5' quadrangle (e.g. 3.75' coverage). Approximately 51 quadrangles were analyzed, covering the entire park. Minimum pixel resolution for this data was 1 meter (Figure 1a, 2a, 3a).

We also analyzed leaf-on color-infrared aerial photography (c. 2001) at 1:24,000 scale that we had previously orthorectified. This imagery was used to verify and cross reference outcrop interpretations. A total of 151 leaf-on air photo images were analyzed. Minimum pixel resolution of these images was also 1 meter. Since bare soil areas on leaf-off photos can easily be confused with rock outcrops, it was necessary to compare interpretations to air photographs from the growing season to determine whether those areas were indeed exposed rock. In addition, shadows cast by trees growing on the top of cliffs were also helpful in determining if cliff areas were missed in the mapping process (Figure 1b, 2b, 3b).

Digital elevation models at a scale of 1:24,000 were used to map landforms to assist in image interpretation. A seamless mosaic of digital elevation models (DEM) covering the park was available from previous projects. The minimum pixel resolution of this data is 10 meters. We derived landform classes by re-classifying the DEM, closely following the techniques of Anderson and Merrill (1998) as defined by Biasi (2001). Very steep sloped areas (greater than 35° slope) are classified as cliffs. Areas of intermediate slope (24° to 35° slope) are classified as steep slopes. Areas of moderate slope (6° to 24°) are classified as side slopes. Low sloping areas (< 6°) are classified as flats. Terrain shape is used to determine if slopes are concave or convex. Concave slopes are classified as coves or slope bottoms, while convex slopes are classified as upper slopes or side slopes. Flat slopes are classified as either ridge top or bottom, and coded as either moist or dry by overlay with locations of wetlands. Aspect or slope orientation maps are incorporated into the landform map to determine slopes facing N-NE or S-SW. While not used to delineate outcrop polygon boundaries, the landform map was useful for assessing locations of known cliff and steeply sloped areas, and to assess additional characteristics of mapped outcrop areas (Figure 4).

Rock outcrop and talus fields were identified from leaf-off digital orthophotography using semi-automated techniques. We identified representative outcrop areas on imagery using visual inspection guided by previous field surveys and GPS locations. Boundaries of rock outcrops were generated using automated "region-growing" algorithms that delineate boundaries on the basis of spectral similarity to a "seed pixel" manually identified by the image interpreter. Boundaries were extracted using a parallelepiped or "region-growing" classification technique that finds pixels in each of the 3 bands of aerial photography that match areas identified by the image interpreter (Erdas Image Analyst, Leica Geosystems, Inc.). This hybrid process mimics the boundaries that would be produced by a human interpreter, with the advantage of greater detail, consistency, and speed than a fully manual process, but with greater control and specificity than a fully automated process. A potential disadvantage of this process is the possibility that the human interpreter can miss targets that would be detected by an automated process. Boundary polygons identified in this manner were stored to an ArcGIS (ESRI, Inc.) shapefile. Mapped rock outcrop polygons were tagged with attributes of area (in sq. meters and hectares), and boundary perimeter (in meters) using GIS. All mapping was completed in UTM, zone 17 projection using the NAD83 horizontal datum.

We also cross correlated our outcrop interpretations to maps of bedrock geology (Morgan et al. 2004) to determine probable bedrock type. Note that locations of mapped outcrops are compared to predicted bedrock geology as a general guide only. Outcrops visible from the air could be of a different geologic source than that depicted on the bedrock geology map due to mapping errors (e.g. contact boundaries in improper locations or positional errors in outcrop boundaries) or due to movement of material by gravity, slides, mass wasting processes, etc.

Draft outcrop maps were presented and reviewed by cooperators in the Rock Outcrop Management Project on April 5, 2005. In order to facilitate site selection and field survey, boundaries of 49 sites of interest were generated by defining a center line connecting mapped outcrop polygons and then buffering the centerline to 100 meters. The resulting site polygons were edited by Virginia Department of Natural Heritage to further define the set of potential outcrop study sites as including a localized “complex” of exposed rock, cliffs, and surrounding vegetation (Figures 1, 2, 3, 4).

To assess accuracy of mapped outcrops, we compared outcrop polygons to 85 GPS waypoint locations from outcrop field surveys by Young (2005, unpublished data). Additionally, we compared outcrop polygons to 159 GPS locations from field surveys by Butler (2005, unpublished data), and 48 outcrop vegetation survey plots conducted by Fleming et al. prior to 2001 and from 2001-2004 (unpublished data). While these additional surveys collected data for purposes other than outcrop field validation (e.g. some points were collected for navigation or vegetation plot location), they presented an opportunity to expand the validation set with data collected external to the mapping effort. All of the field surveys generally collected GPS data with consumer-grade navigation receivers with stated waypoint mapping accuracies of ~ 15 meters and at best ~ 3 meters with Wide Area Augmentation System (WAAS) active (Garmin International, http://www.garmin.com). Some GPS waypoints were collected using mapping grade receivers (Trimble Navigation Inc.) and were differentially corrected to 1-2 meters accuracy.

In order to account for potential error in GPS coordinate locations, we assessed whether mapped outcrop boundaries were within 15 meters of mapped outcrop waypoints or vegetation plot centers. Since field surveys by Young (2005) and Butler (2005) were conducted within outcrop “complex” boundaries as defined by the Virginia Department of Natural Heritage, evaluation of GPS waypoints was limited to mapped outcrops within outcrop “complex” generalized site boundaries (Figure 4). This resulted in 85 points in 9 sites for the Young dataset and 159 points in 29 sites for the Butler dataset. Evaluations of mapped outcrops to points collected by Fleming, et al. considered whether a mapped polygon corresponded with the vegetation plot center as mapped with GPS. Fifteen-meter circular buffer polygons for all datasets were constructed by GIS operations and correspondence between individual GPS points and mapped outcrops was recorded if the mapped outcrop polygon intersected the circular point buffer. Note that this comparison only considered whether an error of omission occurred, that is whether we failed to map the presence of an outcrop when it in fact existed on the ground. We did not assess errors of commission, e.g. whether we mapped a polygon as an outcrop when in fact it was something else on the ground.

We also compared mapped outcrops to maps of bedrock geology as mapped by Morgan et al. (2004), and maps of vegetation communities and landforms mapped by Young et al. (2005). We used GIS overlay methods to determine association of each mapped polygon with geology, landform, and vegetation community polygons. Finally, we converted mapped outcrop polygons to a point representation (polygon centroid) to facilitate map display and to simplify location of outcrops.

Results

Mapping outcrops using the semi-automated approach resulted in the delineation of **2,105** outcrop polygons. Area of mapped outcrop polygons ranged from < 1 hectare (smallest polygon mapped was 1m^2) to 2.4 hectares (mean = 0.42 hectares). Summary statistics of mapped outcrop polygons are given in Table 1. An example of polygon boundaries mapped for granitic geology is given in Figure 5. Display of outcrop polygons as points allows for a park-wide assessment of outcrop density (Figure 6). While outcrops are distributed across the park, more outcrops occur on the western flank of the Blue Ridge, and especially in the southwest corner of the park. This is due to the nature of the underlying bedrock structure such as the orientation of the Catoctin lava flow contact escarpments, and the formation of talus slopes on the steep western slopes underlain by rocks of the Chilhowee Group.

Comparisons to maps of bedrock geology from Morgan et al. (2004) shows that 58% of map outcrops polygons occur on the Chilhowee Group siliciclastic geology, 23% on Catoctin metabasalt, and 18% on granitic rock types (Figure 6). Only four outcrop polygons were mapped as occurring on carbonate bedrock. By area, the outcrops on the Chilhowee Group bedrock comprise 67% of all mapped outcrops, those on Catoctin metabasalt comprise 20%, and granitic types representing 13% of the total area mapped (those on carbonate rock comprise less than 0.1% of the total area mapped). A majority of mapped outcrops occur on steep slope landforms (58.5%), followed by cliff (10.9%), and upper slope (9.4%) types. Additionally, sideslope landform types represent an additional 8.6% of mapped outcrops. Altogether, 87.4% of outcrops were mapped on cliff or slope landforms.

Comparison of GPS points collected by Young in 2005 resulted in 50 of 85 (58.8%) points identified in the field as outcrops corresponding with mapped outcrops. Outcrops mapped on charnockite rocks had the highest correspondence (88.9%) followed by granitic rocks (76.9%), rocks of the Chilhowee Group (66.7%), and metabasalt (51.8%) (Figure 7).

Comparison of outcrop maps to field collected GPS points of Butler in 2005 resulted in 77 of 159 (47.8%) points coinciding with polygons mapped as outcrops. Mapping correspondence varied by bedrock geology type, with higher correspondence on the Chilhowee Group geology (71.4%), moderate correspondence in granite (46.8%) and metabasalt (47.2%), and low correspondence in the Swift Run formation (16.7%) (Figure 8). The Swift Run formation GPS point set consisted of only 6 points, of which only 1 coincided with a mapped outcrop polygon. However, 2 of these points were actually collected for navigation purposes (Butler, personal communication) and do not represent an outcrop occurrence, so correspondence of this set is actually 25% rather than 16.7%.

Comparison of outcrop maps to outcrop vegetation plots collected by Fleming et al. resulted in 26 of 48 (54.2%) of points coinciding with polygons mapped as outcrops. Of the correctly delineated polygons, 76.7% occurred on metabasalt geology while 23.3% occurred on granitic geology.

Discussion

Mapping outcrops from digital aerial photography can be challenging due to several factors. These factors include differing illumination properties between images, difficulty of seeing cliffs from a vertical vantage point, and having features obscured by vegetation or shadow. Differences in geology can also limit the ability to extract consistent spectral signatures from digital aerial photography. While satellite images provide consistent spectral properties because of large area and synoptic coverage, they are limited in spatial resolution, making it difficult to detect small features. Therefore, interpretation from high spatial resolution imagery of 1-2 meter pixel size (such as aerial photographs, Ikonos or Orbview satellite imagery) is generally the best option for mapping or detecting small rock outcrops, even though spectral resolution is sacrificed.

Since high spatial resolution imagery is generally limited to three bands of spectral information (one channel each of infrared, red, and green wavelengths), automated classification approaches are more limited than those applied to multi- or hyper-spectral information where many, sometimes hundreds, of wavelength bands are available for analysis. Manual approaches such as on-screen digitizing are widely employed but suffer from subjectivity and high cost in time and personnel. New software approaches (e.g. eCognition, Definiens Imaging; Feature Analyst, Visual Learning Systems, Inc.) have recently become available where image spatial texture is used along with reflectance to automatically define polygon boundaries. These new approaches offer great promise, but initial testing for this project showed that they still require substantial user interaction, carry a heavy user training burden and are still subject to vagaries of between image illumination differences and inconsistent training targets. Since time to complete this mapping project was limited and few technical staff members were well versed in image interpretation, we had to fall back on more expedient methods.

We had good success detecting the presence of outcrops from aerial photography using a semi-automated, region growing approach. Though this approach required an interpreter to look through a library of images and to manually select outcrops, the extraction of outcrop boundaries was automatic and did not require a high level of training. However, we apparently undercounted actual outcrops as compared to field collected GPS data. While most of the point data was not specifically collected for assessment of outcrop mapping (the Butler and Fleming et al. datasets), ideally we should have achieved greater correspondence between mapped outcrop polygons and field collected GPS points.

One potential conceptual problem in the comparison was that our goal was to map only the presence of exposed rock as seen by aerial imagery, while ground surveys incorporated a more expansive view of an outcrop site that may have included exposed rock as well as rock wholly or partially covered by vegetation, soil, or leaf litter. Aside from these conceptual problems, some of the outcrops mapped in the field as exposed rock may have been beyond the detection capabilities of even 1-meter orthophotography, and some outcrops were most likely obscured by evergreen vegetation and/or shadows on imagery. Certainly, cliffs that have large vertical faces as viewed from the ground may appear as indistinct features on vertical aerial imagery as only the narrow, exposed top of the cliff is imaged. In addition, dark rock targets are difficult to separate from background soil reflectance, even on the highest resolution three-band imagery. Indeed, we had more limited success mapping outcrops of Catoctin metabasalt geology that produces dark rocks and vertical cliff faces than we did mapping the lighter colored quartzites and talus fields of Chilhowee Group geology. Perspective views of topography and aerial imagery can help to detect such features if they are not obscured by other topographic features, shadows, or vegetation and we employed this technique on a limited basis.

While we were not able to fully map all individual rock outcrops using the semi-automated approach, we were successful at detecting the presence of outcrop locations that were not well known. In fact, several sites were identified for additional field study from our analysis that were obscure but have the potential to contain significant resources. In addition, the mapping effort and imagery resources applied to this project benefited the overall Rock Outcrop Management Project study group by providing a mapping base from which to assess the sites selected for more detailed field study. Outcrop locations were used as a guide to defining study site boundaries (e.g. outcrop "complex" boundary), and a gallery of image subsets depicting the 49 study sites was created and placed on the Internet for use by the research group (http://www.lsc.usgs.gov/gis/shen/outcrops/).

Maps of landform were helpful for assessing characteristics of outcrops, but cannot be relied upon as a primary source for mapping. While the majority of mapped outcrops occurred in steep slope and cliff landforms, outcropping in many areas could not be predicted by slope alone, but instead may be influenced by rock characteristics (e.g. resistance to erosion), soil formation, vegetation distribution, etc. However, landform maps were very useful in guiding field surveys to help determine where additional exposures may be found, or not found (E. Butler, personal communication). Field work confirmed the usefulness of these maps as they directed field crews in several instances to areas that were not previously known to support cliffs.

Conclusion

We had good success locating outcrops and moderate success mapping boundaries of individual rock outcrops using aerial photo imagery and a semi-automated mapping approach. However, it was difficult to accurately map all exposed rock in the park due to various factors, including limited spectral information of aerial photographs, difficulty detecting vertical cliff faces from vertical aerial photography, illumination variations in imagery, features obscured by vegetation, and etc. More experimentation with feature extraction and segmentation mapping methods should be explored for future mapping to maximize the benefits of automated approaches such as timeliness and consistency while incorporating the judgment and flexibility of human interpreters. Additionally, light detection and ranging (LiDAR) and stereoscopic viewing technologies should be explored in future projects to determine if they are better able to detect and map outcrops that are difficult to map using vertical aerial imagery. As new methods reveal additional outcrop areas, or as new landform processes create new outcrops (e.g. floods and debris slides) these should be added to the inventory of outcrops begun by this project so that the most complete and up-to-date inventory is available for management of these unique and important environments.

Tables and Figures

Table 1. Summary statistics of mapped outcrop polygons (n=2105).

Area (m^2)		***Perimeter (m)***		***Hectares***	
Mean	422.85	Mean	147.41	Mean	0.0423
Standard Error	25.42	Standard Error	5.55	Standard Error	0.0025
Median	117.91	Median	70.99	Median	0.0120
Mode	2.78	Mode	19.19	Mode	0.0010
Standard Deviation	1166.50	Standard Deviation	254.72	Standard Deviation	0.1167
Range	24220.50	Range	3563.05	Range	2.4220
Minimum	1.03	Minimum	4.12	Minimum	0.0000
Maximum	24221.53	Maximum	3567.17	Maximum	2.4220
Sum	890089.11	Sum	310288.99	Sum	88.9890
Count	2105	Count	2105	Count	2105

Table 2. Correspondence of GPS field collected data (Butler, Young) with mapped outcrop polygons within generalized outcrop "complex" study sites. Table notes number of field collected GPS points that correspond to mapped outcrop polygons, the percent of points that were correctly mapped as outcrops form aerial photography, and the bedrock geology of mapped points.

Site ID	Site Name	Butler Points	Mapped as outcrop	Percent Correct	Young Points	Mapped as outcrop	Percent Correct	Bedrock
C02	Bettys Rock	2	1	50.0%	0	0		metabasalt
C03	Big Devils Stairs	2	0		0	0		metabasalt
C04	Blackrock - Central District	3	2	66.7%	0	0		metabasalt
C05	Blackrock - South District	4	4	100.0%	0	0		Chilhowee Group
C07	Browntown Valley Overlook Cluster	8	4	50.0%	16	9	56.3%	metabasalt
C08	Calvary Rocks - Chimney Rock	0	0		6	4	66.7%	Chilhowee Group
C10	Crescent Rock Overlook	6	2	33.3%	0	0		metabasalt
C11	Crescent Rock South	4	4	100.0%	0	0		metabasalt
C12	Dean Mountain Ridge	4	0		10	1	10.0%	metabasalt
C13	Dickey Hill	5	3	60.0%	7	3	42.9%	metabasalt
C14	Dickey Ridge - W of Visitor Center	6	4	66.7%	0	0		metabasalt
C16	Franklin Cliffs Overlook	4	3	75.0%	0	0		metabasalt
C17	Franklin Cliffs South	6	6	100.0%	0	0		metabasalt
C18	Goat Ridge	5	1	20.0%	0	0		metabasalt
C19	Gooney Manor Overlook	10	7	70.0%	0	0		metabasalt
C20	Halfmile Cliff	2	0		0	0		metabasalt
C23	Hightop	3	1	33.3%	0	0		metabasalt
C24	Hogback Mtn spur	6	2	33.3%	13	10	76.9%	granite
C28	Stony Man: Little Stony Man	5	2	40.0%	0	0		metabasalt
C29	Loft Mountain summit	7	3	42.9%	0	0		metabasalt
C31	Marys Rock	0	0		9	7	77.8%	charnockite
C32	Millers Head	0	0		6	6	100.0%	charnockite
C35	North Marshall summit	8	6	75.0%	2	2	100.0%	metabasalt
C37	Old Rag summit outcrop complex - east	2	1	50.0%	0	0		granite
C40	Pass Mountain	5	4	80.0%	0	0		metabasalt
C42	Powell Gap cliff	6	1	16.7%	0	0		Swift Run formation
C45	Sawlog Ridge	3	1	33.3%	0	0		metabasalt
C46	South Marshall cliff	8	2	25.0%	0	0		metabasalt
C47	Stony Man: summit/N slope	7	3	42.9%	0	0		metabasalt
C62	Old Rag summit outcrop complex - west	7	4	57.1%	0	0		granite
C64	Brown Mountain	7	3	42.9%	0	0		Chilhowee Group
C66	Field Hollow Cliffs	14	3	21.4%	16	8	50.0%	metabasalt
	Totals:	159	77		85	50		

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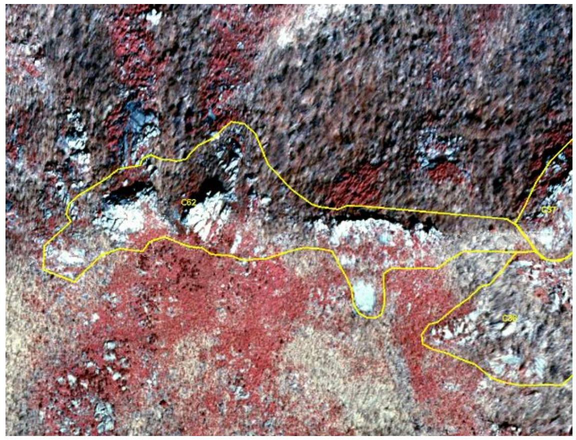

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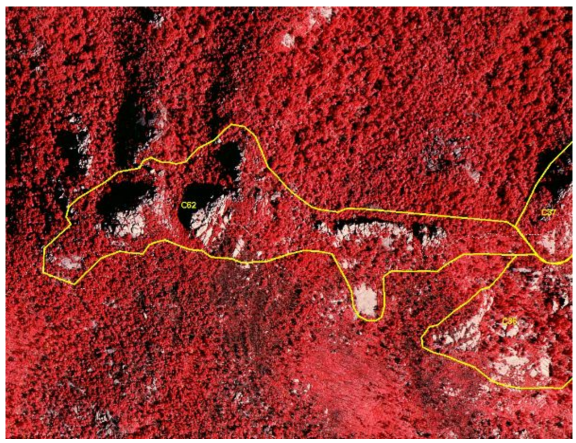


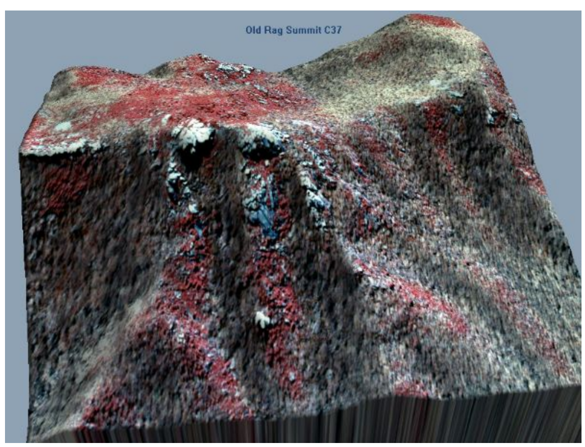
C.


Figure 1. Three views of the Old Rag summit outcrop complex demonstrating outcrops of granitic geology in Shenandoah National Park. Image A. shows appearance of outcrops on leaf-off orthophotography (1:3,780), image B. shows appearance on leaf-on orthophotography (1:3,780), and image C. shows a perspective view from the east. The yellow line denotes the outcrop “complex” study site boundary.

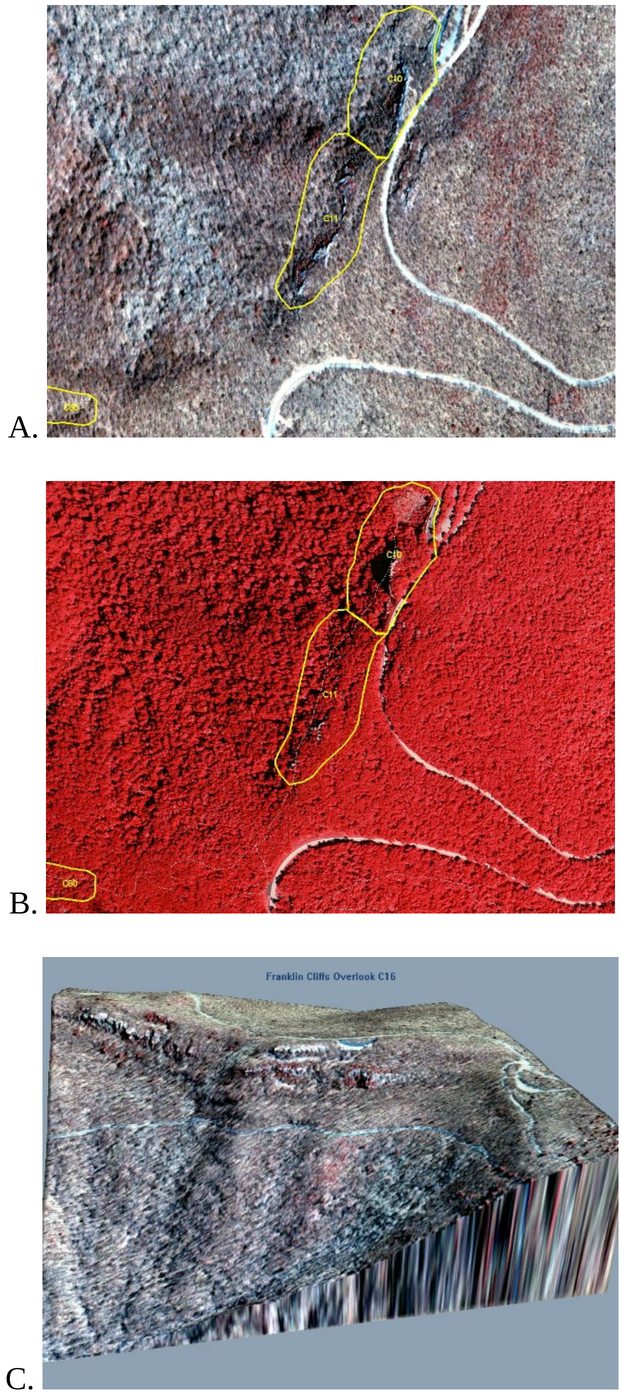
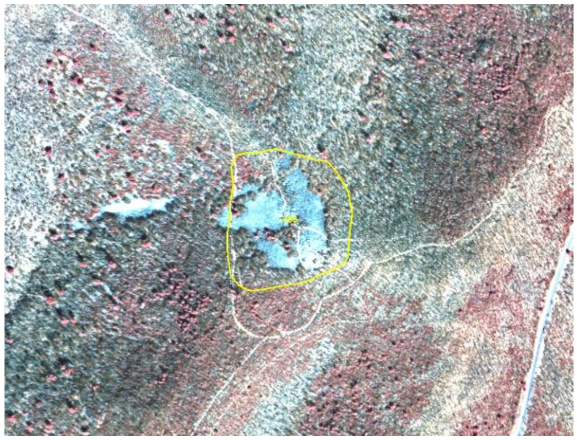


Figure 2. Three views of the Crescent Rock outcrop complex (south) demonstrating outcrops of metabasalt geology in Shenandoah National Park. Image A. shows appearance of outcrops on leaf-off orthophotography (1:3,780), image B. shows appearance of outcrop on leaf-on orthophotography (1:3,780), and image C. shows a perspective view from the west. The yellow line denotes the outcrop "complex" study site boundary.

A. 

B. 

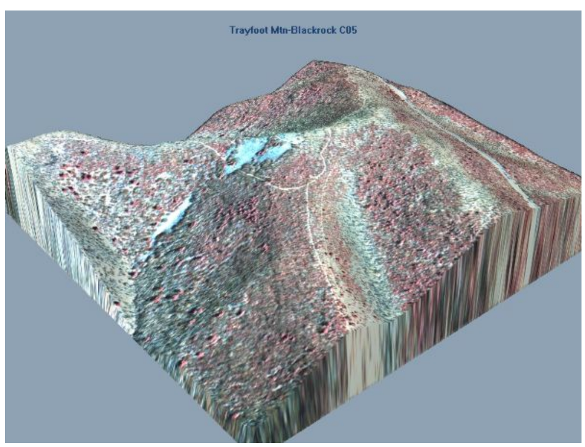
C. 

Figure 3. Three views of the Blackrock outcrop compex demonstrating outcrops of Chilhowee Group siliciclastic geology in Shenandoah National Park. Image A. shows appearance of outcrops on leaf-off orthophotography (1:3,780), image B. shows leaf-on orthophotography (1:3,780), and image C. shows a perspective view from the southwest. The yellow line denotes the outcrop “complex” study site boundary.

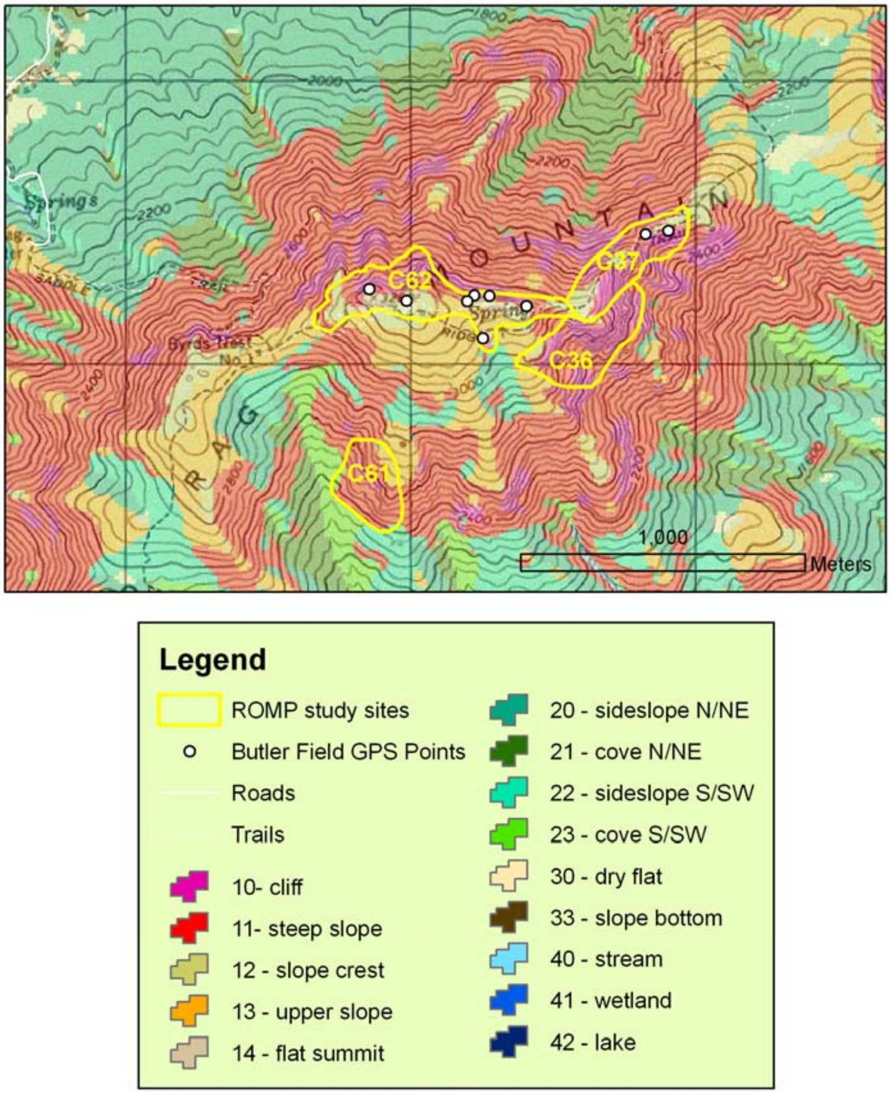


Figure 4. Example of landform interpretation, study site boundary delineation, and field collected GPS point locations. This site is the Old Rag summit outcrop complex.

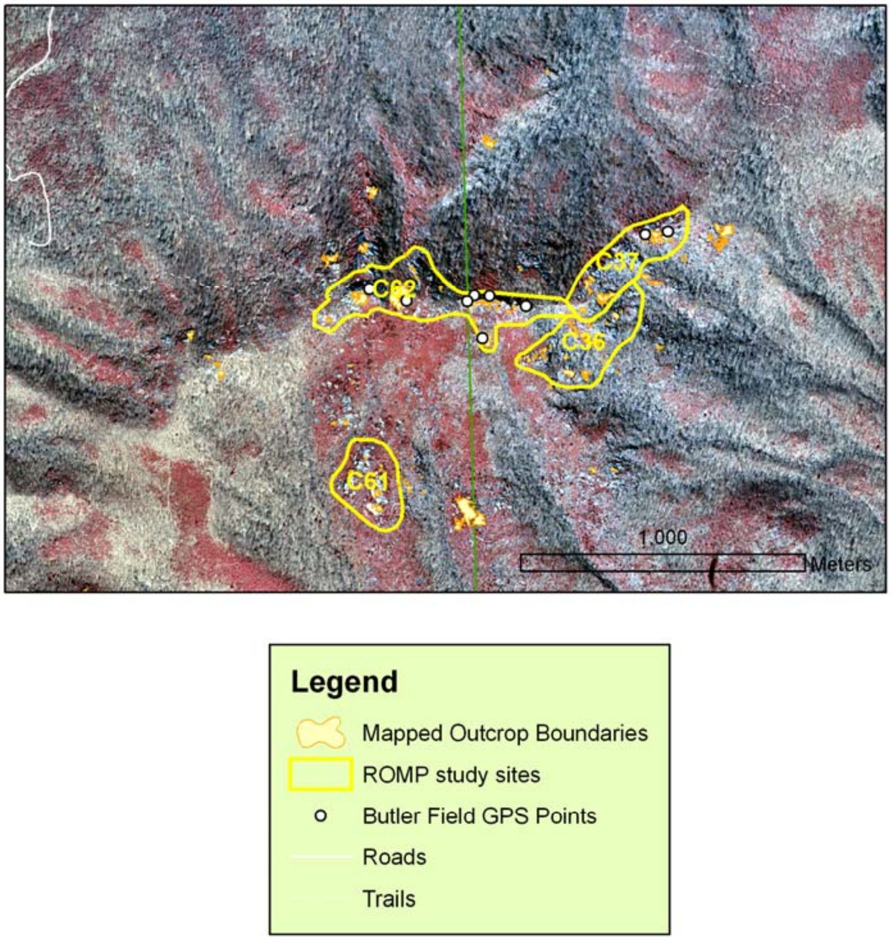


Figure 5. Example of outcrop mapping results using aerial photography and a semi-automated interpretation approach. Image shows mapping results for the Old Rag Mountain summit complex. Mapped outcrop polygon boundaries are shown in tan color with orange boundary. Generalized outcrop complex study site boundary is shown in yellow. Backdrop image is a USGS leaf-off digital ortho-photograph at 1: 12,000 scale.

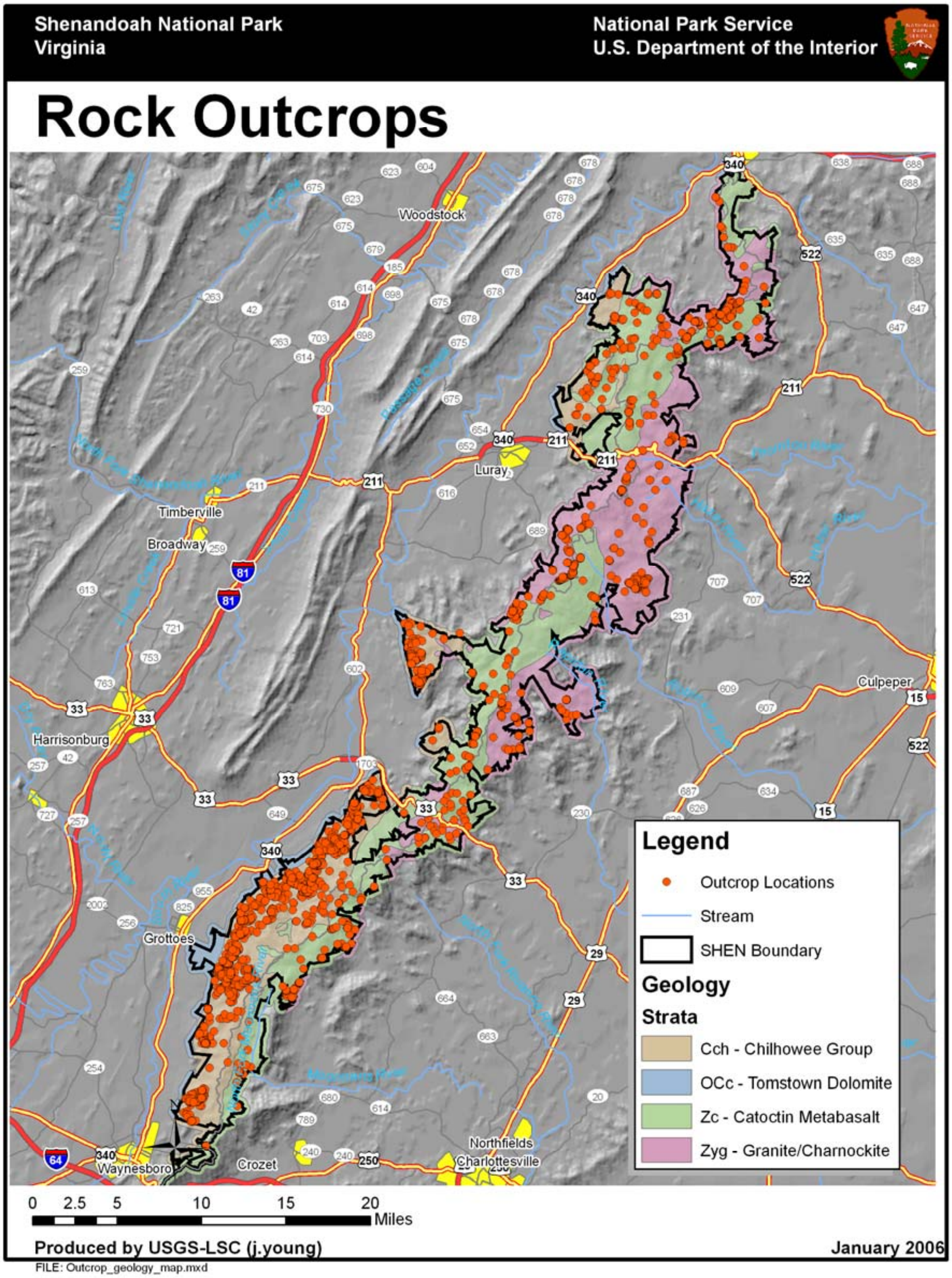


Figure 6. Map depicting rock outcrop locations (as points) in relation to SHEN geography and geologic strata.

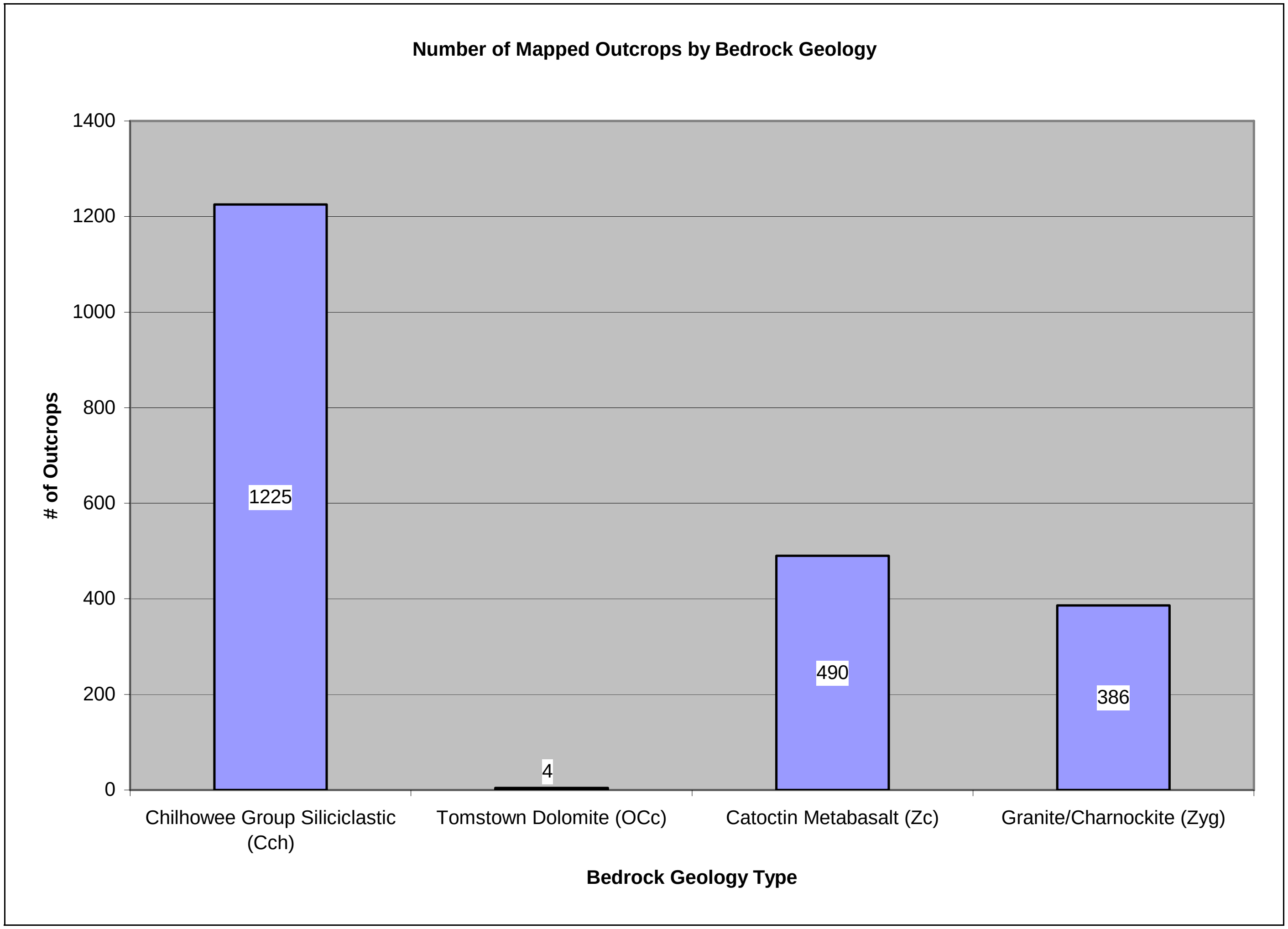


Figure 7. Mapped outcrops (n=2105) occurring in bedrock geology classes. Bedrock geology is from Morgan et al. 2004.

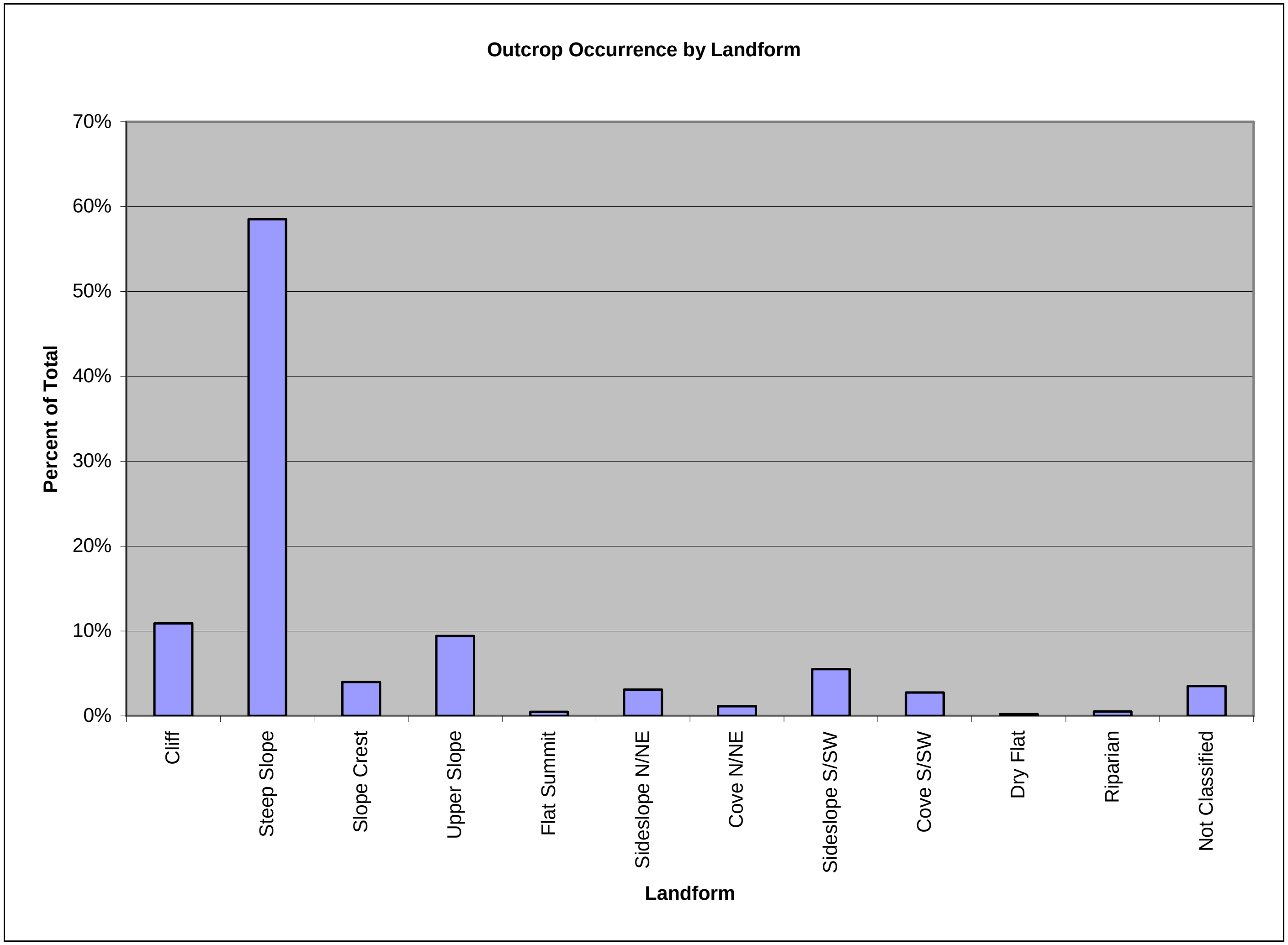


Figure 8. Percentage of mapped outcrops (n=2105) occurring on landform types. Landforms were mapped by Young et al. (2005) from digital elevation models and represent unique combinations of slope, surface shape, and aspect.

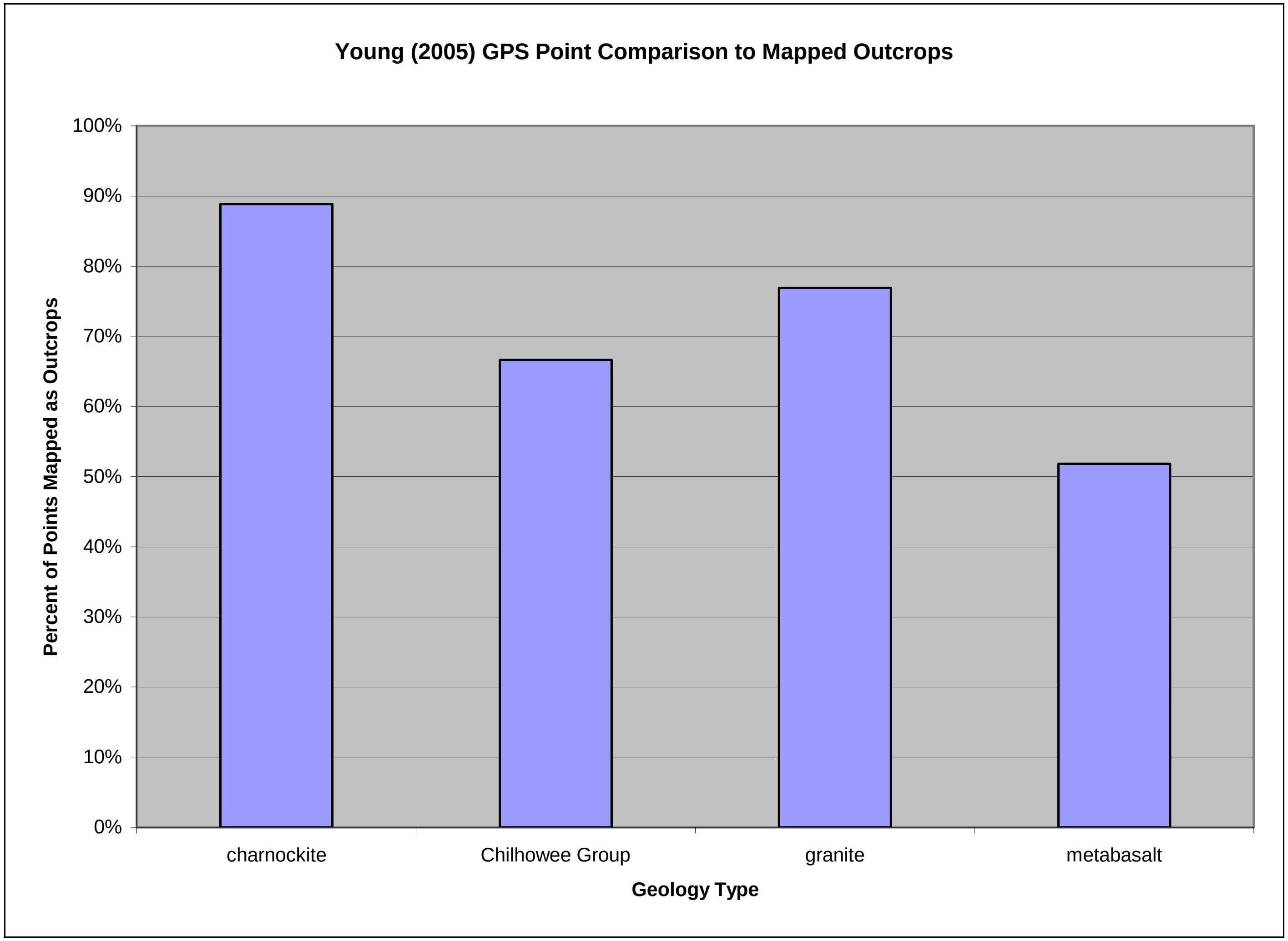


Figure 9. Percentage of GPS field points collected by Young (n=85) that correspond to mapped outcrops within each geology type.

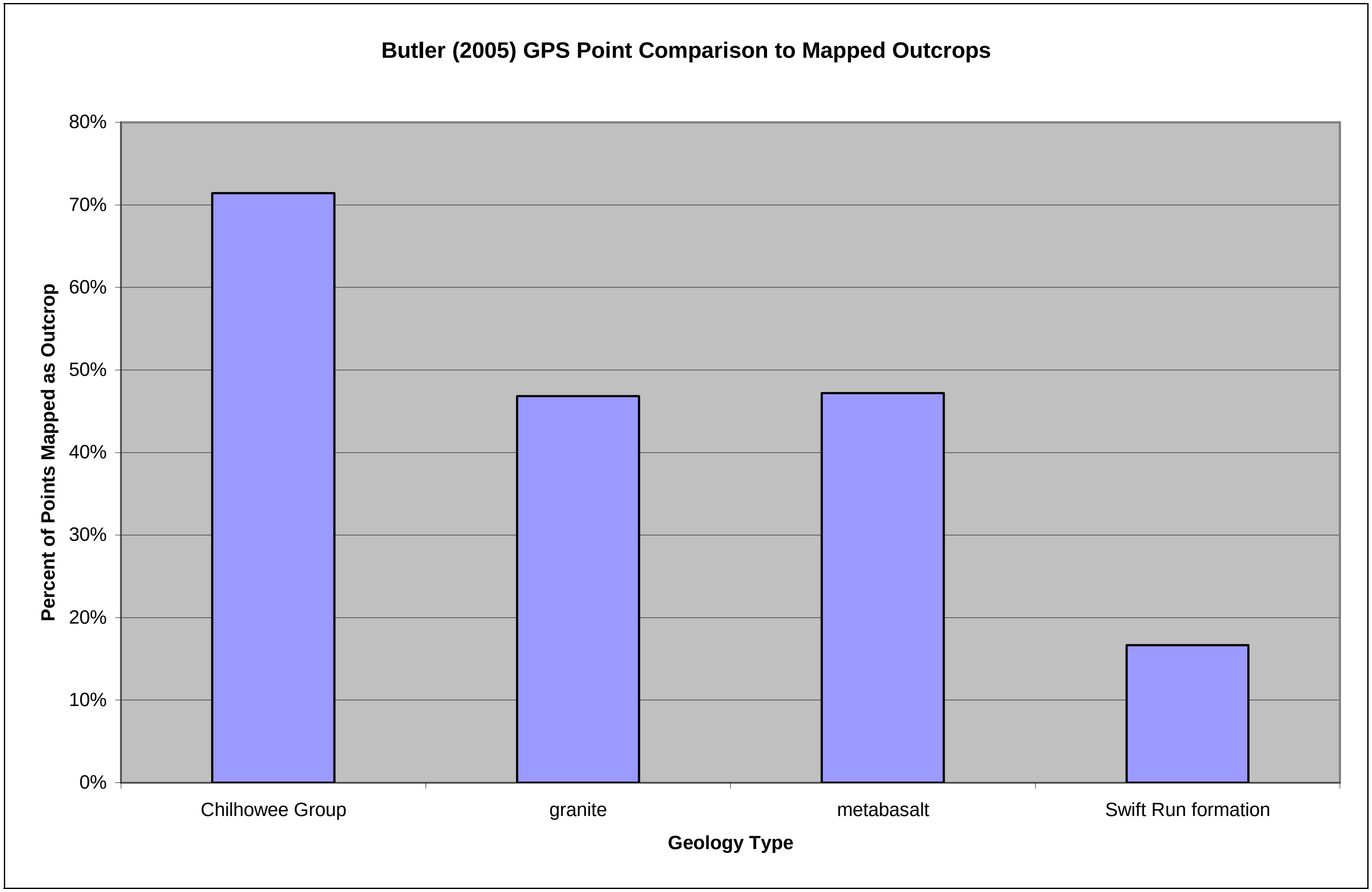


Figure 10. Percentage of GPS field points collected by Butler (n=159) that correspond to mapped outcrops within each geology type.

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