BOULDER ORIENTATION, SHAPE, AND AGE ALONG A TRANSECT OF THE HICKORY RUN BOULDER FIELD, PENNSYLVANIA

by

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ABSTRACT

The boulder field at Hickory Run State Park in Pennsylvania is the largest such feature in the eastern United States and has been designated a National Natural Landmark. It has generated considerable interest among Quaternary scientists, and many college and university earth science field trips visit the boulder field each year. Beginning with H.T.U. Smith's pioneering study in the early 1950s, most scientists have regarded the field as a relict of different frozen ground and freeze-thaw processes due to the close proximity of the Laurentide Ice Sheet during the late Pleistocene. Although the boulder field is included in many regional studies, relatively little quantitative data regarding its sedimentary properties have been published to date. This thesis describes a quantitative study of boulder orientation, shape, and relative age collected from 14 samples along a central parallel transect extending over the boulder field's length. The first two rounds of field sampling used traditional field instruments including a Brunton compass, inclinometer, tape measure, and Schmidt hammer to collect data on boulder orientation, plunge, shape, size, and hardness. A third round of field sampling used ground-based Light Detection and Ranging (LIDAR) to obtain detailed topographic data from three 10 m by 10 m plots along the study transect. The LIDAR data were filtered and used to construct elevation, slope, and aspect models for comparison with the aforementioned manually collected field data. The LIDAR data provides a quantifiably more useful dataset than traditional field methods using a Brunton compass, and the resultant Digital Elevation Models (DEMs) are a robust and data-rich approach to evaluating boulder fabric. The results of this thesis suggest a spatial trend in boulder roundness and *a*-axis length along an east-west trend of the boulder field. Conversely, no spatial trends were identified in the orientation, plunge, sphericity, flatness, and size data. The implications of spatial trends in sedimentary characteristics are discussed relative to four possible formation processes of the Hickory Run Boulder Field.

Chapter 1

INTRODUCTION

A boulder field is an extensive accumulation of loose and unsorted rock material attributed typically to periglacial climatic conditions. It is defined as an area covered by angular clasts with either a gentle or nonexistent gradient (Washburn, 1973) or more specifically, with a slope of less than 10° (Fritz and Meierding, 1989). Block deposits are characterized as areas that contain more than 50% of the block material on the landscape (Michalek, 1968). Boulder fields contain little presence of fines, and can be found on either flat or sloped land with a size variance from centimeters to meters and no arrangement of clasts (Tricart, 1970). Mid-Atlantic boulder fields have been used as an indicator of paleoclimatic conditions and processes in that area, the result of collected debris from the frost shattering of rock (Tricart, 1970).

The Hickory Run Boulder Field, referred to henceforth as simply Hickory Run, located in Carbon County, Pennsylvania, is of particular interest to scientists because it has been noted as the most remarkable and best example of a boulder field in the eastern United States. This is because of its large size, low gradient (1°), and lack of vegetation and interstitial matrix. Previous researchers have examined Hickory Run fabric to better understand its origin and formation. However, fieldwork involving manual fabric measurements is time-consuming, and studies have thus far focused on a small number of transects heavily concentrated in the western end of the field, as seen in the fabric map displayed in Braun et al., (2003) and Sevon et al., (1975). These studies do not constitute a systematic sample of fabric across the field.

Several mechanisms have been proposed to describe the formation of boulder fields. Sevon (1969) listed three main criteria for boulder field formation: distinct source rock characteristics, the presence of an appropriate mechanism for boulder production, and the presence of an appropriate mechanism of boulder movement. The source rock characteristics include an outcrop of sufficient size, bedrock of resistant lithology, and the presence of planes of weakness or separation. The mechanism for boulder production is frost action caused by freeze-thaw cycles. Lastly, a mechanism for movement, such as gelifluction or creep, must be active.

Evidence to identify the origin and process by which Hickory Run formed has been weak, despite the field's inclusion in numerous studies of formation process and climate. The original work by Smith (1953) considered four different hypotheses. The first regarded boulder deposits as resulting from direct glacial deposition or glacial meltwater processes. The second hypothesis attributed boulder accumulation to *in situ* residual mechanical weathering by frost action either in periglacial or cold climate conditions. The third hypothesis expanded on the second to include the later removal of less resistant rock, most likely by fluvial processes, to leave the more resistant boulders. The fourth hypothesis suggested accumulation by mass movement from the surrounding valley sides under periglacial conditions. Smith (1953) assigned Hickory Run development to his fourth hypothesis, supporting the theory that the boulder field formed under periglacial climate conditions. Mills and Delcourt (1991) cautiously agreed with Smith's fourth hypothesis by stating that block streams are likely of periglacial origin, especially those occurring on low gradients and comprising large clasts. However, they warned also that “patterned ground is the only widespread feature in the Appalachians that is considered unquestionably diagnostic of past periglacial environments.”

The purpose of this study is to revisit analyses of Hickory Run and to conduct a more comprehensive study of boulder fabric and characteristics to identify the likely mechanism for its formation and the timing and extent of different formation processes acting at the site. Inspired by Smith’s (1953) original four hypotheses, four possible boulder field formation processes are reworked:

1. glacial deposition as a result of proximity to the glacial-fluvial margin and a significant source of water (Figure 1),

2. *in situ* breakup and subsequent movement of underlying bedrock via the action of periglacial processes, with mechanical weathering by frost action and slow mass movement by gelifluction; this requires the presence of permafrost and indicates long-distance travel of boulders over millennia (Figure 2),

3. *in situ* breakdown of bedrock by fluvial or frost action under cold climate conditions without requiring the presence of permafrost (Figure 3), and

4. *in situ* undermining of the underlying geologic unit, or valley widening, over time by fluvial or frost action and subsequent gelifluction, or a combination of periglacial and cold climate processes, with a shorter time-scale and travel distance implication than the second hypothesis (Figure 4).

In this study, these four formation processes are evaluated by first completing a set of traditional field measurements to quantify approximate boulder orientation, shape, and age. For comparison with the traditional field methods, a ground-based Trimble GX Light Detection and Ranging (LIDAR) was used to obtain centimeter-scale models of elevation, slope, and aspect at three 10 m by 10 m plots along the survey transect. These detailed field studies, together with visual observations of more rounded boulders in the west, are used to evaluate each of the proposed hypotheses. These analyses also provide insights into the climate and processes responsible for the development of Hickory Run with subsequent implications for the climatic significance of other Mid-Atlantic boulder fields.

It is noted that the results of this thesis may not reflect the interpretations of Nelson et al., (in preparation) using some of the data presented in this thesis. The interpretations presented herein are to supplement this research at the study site with no intent to supplant other interpretations using the same dataset. However, Frederick E. Nelson of the University of Delaware is credited for suggesting the original sampling strategy regarding the traditional field methods and some of the analytic strategies.

Chapter 2

BACKGROUND

Appalachian Work

Appalachian boulder fields are well-recognized phenomena with hundreds of boulder fields having been reported from Pennsylvania to North Carolina. However, any casual observer will quickly realize that many boulder fields are obscured by forest cover, making their identification and study more difficult towards the southern extent of the range. Fritz and Meierding (1989) assigned a late Pleistocene or Wisconsinan development age to existing boulder fields in eastern North America based on their conclusion that these fields are relicts no longer undergoing development. A boulder field might be considered as relict either by the presence of lichen, which indicates long-term inactivity, or by the confirmed exclusion of alternate formation theories (Washburn, 1973). The following summary of boulder field research performed in the Appalachians begins with studies in Pennsylvania and continues south.

Hickory Run was first studied and described by Smith (1953), in which he presented his four aforementioned hypotheses. He credited the formation of the field to periglacial processes, and his analysis of Hickory Run is the most thorough available today. Potter and Moss (1968) studied the clasts at the Blue Rocks Block Field in Berks County, Pennsylvania, along a longitudinal transect and determined no trends in mean long axes of boulders although they noticed vertical sorting with larger boulders on top. They also presented the first published description of the fabric of large clasts at Blue Rocks, up to 20 ft. in length. Psilovikos and Van Hounten (1982) measured and analyzed the long axes of clasts at Ringing Rocks Barren Blockfield in Bucks County, Pennsylvania. Their results showed clasts of rectangular or cubic shape scattered in random orientations. They attributed these shape and orientation characteristics to the lack of downslope movement after initial breakage.

Sevon (1967) highlighted Bowmanstown Boulder Field, also located in Carbon County, Pennsylvania. His report included rock units, structure, overall description of the boulder field, and origin. Most notably, he stated, “The high number of boulders in point contact and the low matrix quantity of the present deposit suggest that the internal friction would probably have been too high to allow movement by solifluction,” and therefore the deposit can be attributed to “[r]ock-glacier creep as a result of freezing and thawing of interstitial water.”

In a brief paper highlighting periglacial features in Pennsylvania, Ciolkosz (1978) discussed mostly colluvial deposits located south of the Wisconsinan glacial boundary. A map of these features includes boulder fields, grezes litees (shale-chip deposits defined by Ciolkosz et al., (1986)), ice wedge casts, patterned ground, and involutions. From east to west, Ciolkosz (1978) identified the Pennsylvania counties that contain boulder fields as Bucks, Carbon, Berks, Dauphin, Northumberland, York, and Adams. Carbon County contains two boulder fields: Hickory Run and the Bowmanstown Boulder Field. Ciolkosz et al., (1986) identified two more boulder field locations in Centre and Lycoming Counties. The latter field is believed to be the same field as shown in Northumberland County (Ciolkosz, 1978) because the most recent map shows more detail. Ciolkosz et al., (1986) listed the names or locations of the following boulder fields: Hickory Run, Lehighton, Bald Eagle Mountain, Hamburg, Ringing Rocks, Iron Springs, and Montoursville South. The remainder of the paper focused on colluvium and loess deposits and the authors stressed the importance of identifying periglacial features for identifying soils and their ages and recognizing the variability in soils caused by periglacial activity.

Denny (1956) reported on boulder fields, boulder rings, boulder stripes, and terraces in Potter County, Pennsylvania, which is in the north central part of the state near the Wisconsin drift border, and described the general physical characteristics of boulder fields. He stated that although most boulder fields are fully or partly covered by vegetation, fields containing large clasts, a lack of interstitial material, and depths of six feet have never been forested. Hickory Run follows this description and shows no sign of having been vegetated since formation.

Wilshusen (1983) provided a comprehensive list of geologic sites along the Pennsylvania portion of the Appalachian Trial. Described by some as the rockiest portion of the trail, this portion holds some of the most remarkable periglacial sites. Although Hickory Run is not discussed because its location is too far north, other such boulder fields and streams are listed. The guide is an excellent general resource on general geology and glacial and periglacial relicts throughout a small part of Pennsylvania.

Walters (1984) explained that although northern New Jersey is home to at least 40 boulder fields, little has been done to describe them in detail. He summarized eight of these fields based on dimension, vegetation, interstitial material, slope, and morphometry. Walters concluded that New Jersey boulder fields mirror Pennsylvania boulder fields in terms of both formation age and type, but are smaller overall.

Smith and Smith (1945) summarized rock streams from southern Pennsylvania to West Virginia along the Blue Ridge Mountains. They described them in terms of field and clast size and shape, water audibility, gradient, sedimentary characteristics, and lichen presence. They attributed the formation of these landforms to Pleistocene periglacial conditions.

Moving southward, Hupp (1983) examined boulder fields at Massanutten Mountain, Virginia that were considered to have been formed during the Pleistocene periglacial climate but are still active due to steep slope runoff events. Hupp mapped and correlated the spatial distribution of freshly exposed rock to areas with no lichens present on the Massanutten Sandstone to determine recent clast movement. He also performed a size analysis of the clasts by measuring the long axes of both weathered and unweathered rocks along a transect. Hack (1965) mapped and described scree deposits in Virginia and West Virginia and concluded that scree deposits do not necessarily require a periglacial climate but that they formed faster during the Pleistocene than today.

Kerwan and Hancock (2002) tested theories relating the formation of the Central Appalachians to periglacial processes using cosmogenic radionuclide ^{10}Be results from tor surfaces and analysis of periglacial features in Dolly Sods, West Virginia. Although the ^{10}Be analysis is still in progress, the authors determined that the presence of boulder streams is not always indicative of past periglacial conditions.

Clark and Torbett (1987) summarized characteristics found across various boulder fields in the Great Smoky Mountains National Park, which spans both North Carolina and Tennessee. Clark (1968) referred to seven large-scale boulder fields from Pennsylvania, West Virginia, and Virginia in a report on new locations of sorted patterned ground, but did not describe them individually.

Also in North Carolina, Shafer (1988) used thermoluminescence (TL) on a blockstream, a colluvial fan, and a fluvial terrace at Flat Laurel Gap, all in the Blue Ridge Mountains, to provide absolute ages for the formation of periglacial features in the area. The TL date for the blockstream revealed an age of 7,400±1,000 yr B.P., whereas active blockstreams and boulder fields are generally thought to form between 16,500 and 12,500 yr B.P. He attributed this disagreement to a displacement in a previously formed boulder field. Michalek (1968) noted "reworking of the deposits could have caused piping and redeposition of the matrix," and Shafter (1988) concluded, a "resetting of the TL signal."

Climatology

Tricart (1970) estimated that Quaternary glaciers have produced at least 10 million square kilometers of glaciated terrain globally, or approximately 40% of total land areas. The Laurentide Ice Sheet had an enormous effect on the shaping of the north central and eastern portion of the United States. Delcourt and Delcourt (1981) dated the peak in Late Wisconsinan continental glaciation at 18,000 yr B.P. The Laurentide Ice Sheet caused cooling of the air directly above the ice and subsequently a low-level outflow of cold air along the ice perimeter. The presence of the continental ice sheet also created two jet streams: the first along the Arctic cold air to the north and the second along the southern ice front. The latter was located more southward than the current single jet stream (Kutzbach and Webb, 1991). The ice sheet caused the extended duration of winter air extending farther southward and consequently the decreased advancement of sub-tropical air north. The latter was also less frequent during the summer months (Peltier, 1949).

In addition to the reworking of atmospheric circulation, the presence of the ice sheet caused large-scale surface changes, including surface erosion, moraine construction, and disruption of drainage systems. Within a sizeable distance of the ice margin, the reduction of air and ground temperatures created a periglacial zone. The interaction between ice, land, and climate along the continental ice margin determined the conditions that acted upon land surfaces. South of the ice sheet, some areas developed seasonally frozen ground and tundra vegetation. Braun (1989) reported a 50-150 km band of tundra along the ice edge in Pennsylvania, which extended into West Virginia and Virginia at high elevations. Delcourt and Delcourt (1981) estimated the width of tundra as 60-100 km wide and Péwé (1983) wrote that a permafrost zone of approximately 100 km wide might have existed adjacent to the glacier. Relative to the study area of this paper, Peltier (1949) suggested that all of Pennsylvania should have been considered a tundra climate based on the presence of rubble deposits across the state. Tricart (1970) stated that boulder fields are common features found in moist climates with severe Arctic winters or where solifluction flows exist. This would have been common amid freeze-thaw debris and snow meltwater in the ice-sheet-covered northeastern United States.

The climatic influence of the Laurentide Ice Sheet extended farther south than its immediate border. During the last glacial maximum, periglacial and cold climate environments existed not only along ice margins, but continued south throughout high altitudes of the Appalachian Mountains (Fritz and Meierding, 1989). Peltier (1949) estimated that during glaciation, more intense freeze-thaw cycles occurred in the midlatitudes than occur in the high latitudes of today. The cold climate probably extended at least 500 mi. south of the glacial margin, over the Piedmont and Southern Appalachians, as indicated by the occurrence of boulder fields in the Blue Ridge area (Smith and Smith, 1945). However, it is important to distinguish landforms influenced by periglacial activity from those that could have formed under cold climate conditions without the presence of permafrost.

By 12,000 yr B.P., regions downwind and within proximity of the ice border remained cold, despite warming west and far south of the ice sheet. Isotopic research has dated the melting of the Laurentide Ice Sheet in North America between 17,000 and 11,500 yr B.P. (Friedman, 1983). By 9,000 yr B.P., the ice sheet's climatic influence decreased, according to climatic models. By 6,000 yr B.P., the size of the ice sheet was reduced to one grid cell in climatic models (4.5° latitude by 7.5° longitude in models of the period) (Kutzbach and Webb, 1991).

Chapter 3

STUDY AREA

The Appalachian Plateau extends from Alabama to Ohio and Pennsylvania (Mills and Delcourt, 1991). In northeastern Pennsylvania, the local name is the Pocono Plateau. The Appalachian Plateau has the highest average slopes in the Appalachians, and the bedrock comprises mostly horizontal sandstones and shales of the late Paleozoic age (Mills and Delcourt, 1991). Rodgers (1970) characterized the rocks in the Appalachian Plateau as mainly Carboniferous and Devonian Age. Many geomorphologic features typically tied to alpine tundra, such as patterned ground and boulder fields, developed from the Appalachian crest to the Great Smoky Mountains approximately 18,000 yr B.P., and their formation corresponds to the last glacial maximum (Clark, 1968; Michalek, 1968). Mills and Delcourt (1991) stated that periglacial features have been mostly studied in the Valley and Ridge physiographic province of the Appalachians.

In Pennsylvania, three glaciations are recognized: Woodfordian (Late Wisconsin), Altonian (Middle Wisconsin), and Illinoian. Hickory Run lies approximately 1.5 mi. from the Late Wisconsinan glacial border as marked by the Olean District End Moraine (Sevon, 1990) and is contained within the geographic extent of the penultimate Late Illinoian glaciation (Figure 5). The Olean District End Moraine is characterized by the thick accumulation of undifferentiated till (unsorted clay, silt, sand, pebbles, cobbles, and boulders) and minor sand and gravel. The moraine topography is described as hummocky, or uneven and rolling, with 10 ft. of relief. These moraine border deposits are easily distinguished from their surroundings on the ground because of their high relief and are identifiable on aerial photographs as distinct ridges on the landscape (Crowl and Sevon, 1980). Behind the Olean District End Moraine lies a band of Olean ground moraine and local colluvium. This paper focuses on those conditions existing during the presence of the Olean glacial border of the Woodfordian (Late Wisconsin) age.

Hickory Run is located in Hickory Run State Park, Kidder Township, Carbon County. Current aerial imagery reveals that the boulder field and its surrounding environment have remained unchanged in recent history (Figure 6). The boulder field is oriented east-west, measuring 518 m by 122 m, or 16.5 acres (6.7 ha). The boulder field is situated at the head of the Hickory Run Stream, which ultimately drains to the Lehigh River. Although water can be seen and heard running through the boulder field, it is not indicated on any official mapping effort.

The boulder field lies atop the Duncannon Member of the Catskill Formation (DcD) (Figure 7). This formation is assigned an Upper Devonian age. The lithology of the DcD that supplies Hickory Run includes grayish-red sandstone and conglomerate. Sevon (1975) provided three geologic formations: the red sandstone and conglomerate of the DcD, and gray sandstones and conglomerates of the Pocono Formation and Spechty Kopf Formation. The sandstones are fine to coarse-grained, quartzitic, and generally compose the main portion of the boulder field. The conglomerates are a coarse to very coarse-grained sandstone matrix, include 80% pebbles, and compose the southeastern portion of the main boulder field and the entire small boulder field. Sevon et al., (1975) and Braun et al., (2003) displayed maps depicting bedrock source location, type, and direction as described by Smith (1953).

For the main boulder field, sandstone outcrops are located northeast and east of the eastern fishtail and the direction of movement is downslope, to the southwest and west. The smaller boulder field has sandstone and conglomerate outcrops located southeast, and are shown to have moved in a northwest direction. The boulder field clasts range in size from a few centimeters in diameter up to 30 ft. (10 m) (Sevon, 1987). The boulder field surface relief, although appearing extremely flat, is actually a complex microrelief, or surface irregularity (Sevon, 1969). Tricart (1970) observed that stone circles can appear on the flat portions of boulder fields where groundwater is abundant.

Sevon (1975) published surface and bedrock geological maps of the Hickory Run and Blakeslee Quadrangles. The named boulder field is surrounded by boulder colluvium. The distinction between field and colluvium is recognized because each has certain characteristics. The boulder colluvium is defined as a thin surface cover deposit, with the presence of interstitial material and vegetation, and a lack of point contact between boulders. The boulders are not fitted, ground or polished, and generally occur on steeper slopes. The boulder field, therefore, is characterized as a thick surface cover deposit, without the presence of interstitial material and vegetation, with point contact between boulders. The boulders are fitted, ground or polished, and generally occur on gentle slopes.

In general, the age of Hickory Run can be described as being analogous to the age of the last glacial maximum, or the advance of the Laurentide Ice Sheet in Pennsylvania, at about 15,500 yr B.P. (Mickelson et al., 1983). Sevon et al., (1975) stated that deglaciation "started not earlier than 15,000 years ago." Fritz and Meierding (1989) stated that relict boulder fields formed greater than 100,000 years ago would contain severely weathered stones and fines, and additional wind-blown fines initiating forest growth.

Hickory Run is mentioned frequently in literature regarding Appalachian boulder fields, because of its distinguishing physical characteristics: large size, low gradient, and lack of interstitial material. Sevon (1969) listed three brief earlier studies (Ver Steeg, 1930; Ashley, 1933; and Leverett, 1934) of boulder fields in Pennsylvania, but noted that Smith's (1953) was the most detailed. The field has been mentioned in other publications. The boulder field is highlighted on a map of periglacial features in Pennsylvania, as summed by Ciolkosz (1978). No authors have described Hickory Run in such detail as Smith (1953) or have attempted a complete quantitative analysis of the boulders to support the periglacial formation hypothesis. Following H.T.U. Smith (1953), however, W.D. Sevon provided a wealth of descriptive information regarding Hickory Run by publishing many reports on the subject and including descriptions in geologic mapping projects.

Sevon (1969) wrote a short but descriptive piece about Hickory Run as part of the Geological Society of America guidebook of excursions. He summarized its physical characteristics and provided some unpublished mapping completed by Alan Adler. Adler mapped a part of the surface morphology, including mounds of varying sizes, highs, stone rings, depressions, and trees. This work, although thorough, only covers a small part of the western, downslope part of the field. A subsequent map by Adler featured a description of flows, once again containing only a small part of the main field.

Sevon (1975) also published surface and bedrock geological maps of the Hickory Run and Blakeslee Quadrangles, where he described in great detail the boulder field, surrounding boulder colluvium, and the Catskill Formation. Sevon (1990) also published a guide for the Eastern Section of the National Association of Geology Teachers, condensing the material to less than four pages. The content is a condensed version of his (1969) work. Sevon et al., (1975) once again used the same two surface maps created by Adler and an additional fabric study produced by students in a geology class at Lehigh University in 1974. The 1974 fabric map and Adler's two maps are also used in Braun et al., (2003).

Chapter 4

METHODS

The first phase of fieldwork, supervised by Frederick E. Nelson, was conducted during the summer and fall of 2004. A 35 m by 35 m sampling grid was overlaid on aerial imagery. A sub-parallel transect, trending east-west, was drawn along the longitudinal axis of the boulder field. From this transect, 14 consecutive sample locations with spacing of 35 m were selected from the grid (Figure 8). The imagery and grid data were used to obtain coordinates so that the exact sample locations were identified in the field with GPS. Using GPS locations in the field, four radii of 2 m length were measured in N, S, E, and W directions and all boulders encountered were selected for study. If a sample size of 50 boulders was not met within these transects, additional boulders identified in NW, SW, SE, and NE directions were used in an alternating fashion.

Sampling measurements included azimuth (measured in plunge direction), plunge, three axes lengths (*a*, *b*, *c*), and hardness (Figure 9). All measurements were collected using a Brunton compass, inclinometer, tape measure, and Schmidt hammer (Figure 10). Ten Schmidt hammer readings were taken per boulder, five parallel and five perpendicular to the boulder bedding-plane to best represent clast sides. Schmidt hammer position angle was ignored since boulders are positioned in all directions. Only stationary boulders were measured; unsteady boulders might alter plunge and hardness values.

A second phase of fieldwork, supervised by Frederick E. Nelson, was conducted in 2006 at the same 14 sample locations. In this survey, only the 25 largest boulders were sampled to improve the likelihood of encountering more stable boulders less susceptible to movement by anthropogenic activity at the site. Sampling measurements included three axes (*a*, *b*, *c*) lengths and roundness. Schmidt hammer measurements were not made during the 2006 field season.

Morphometry analysis of the individual boulders involved five main components: size, volume, sphericity, flatness, and roundness. Note that Frederick E. Nelson suggested the use of these commonly applied techniques. Size and volume were calculated using the three axis lengths, *a*, *b*, and *c* (Figure 11). Size was simply an analysis of the length of the *a*-axis (long axis). Volume was calculated as follows:

$$V = a \times b \times c$$

Sphericity and flatness are expressions of how closely boulder shape approaches that of a sphere, or one in which the *a*, *b*, and *c* axes are equal (Leeder, 1982). The sphericity equation (Krumbein, 1941) was calculated as follows:

$$\psi = \sqrt[3]{\frac{b \times c}{a^2}}$$

The flatness equation (Cailleux, 1947) was calculated as follows:

$$\varphi = \frac{a + b}{2c}$$

Roundness (Figure 11) is an expression of clast smoothness (Leeder, 1982) and can be determined using illustrative diagrams (McLane, 1995) or a roundness calculation based on radii of curvature. The roundness equation (Wadell, 1932) was calculated as follows:

$$\delta = \frac{\sum(r/R)}{N}$$

where r is the radii of individual corners, R is the radius of the maximum inscribed circle, and N is the total number of corners measured. Roundness measurements were always taken on the largest, upward facing plane of a boulder.

Fabric is defined as the two or three-dimensional representation of boulder orientation in space. Such data can be used to determine the overall alignment of boulders with regard to the direction of downslope flow in sedimentary environments. For this thesis, fabric was determined by taking two measurements with a Brunton compass, azimuth and plunge (Figure 12). Plunge was always taken in the boulder down-dip direction. Shafer (1988) found clast orientation to be consistent with general patterns regarding fabric: long axes were parallel to blockstream axes and intermediate axes were vertical. He also noted that tabular clasts show imbrication of 0° to 10°, which demonstrates frost heave of boulders or upending upon boulder settlement. Millar and Nelson (2003) suggested that measurements of fabric should be taken on clasts with an axial ratio ≥ 1.5:1 to quickly identify long boulders. The current study used all boulders encountered along the N, S, E, and W sampling radii because only measuring boulders with an axial ratio ≥ 1.5:1 would have drastically enlarged the sampling location areas and misrepresented the physical characteristics of the local boulder population. Note again that Frederick E. Nelson suggested the use of these commonly applied techniques for measuring clast fabric.

A third phase of fieldwork was conducted in August 2011 at three sample sites that correspond to samples 2, 7, and 14 from the original dataset. A LIDAR unit was used to obtain detailed topographic data at these locations along the main transect of the boulder field (Figure 13). LIDAR calculates the distance to features in the study area by measuring the time-of-flight of emitted pulses of green light (532 nm) with a factory-tested accuracy of ±1.3 mm at a distance of 100 m. The distance measurements are coupled with azimuth and zenith data of the emitted pulse to place each point in a local Cartesian coordinate system that originates at the instrument. In general, resolution of LIDAR data depends on the spacing of successive points at a given distance and the size of the laser spot on an object. These two measurements can affect the ability to detect small features in the point clouds and dictate spacing of far-field data, which influences the type and/or resolution of the surface model developed from the point clouds. For this study, scans were assigned a horizontal spacing of 20 cm at a distance of 100 m, which results in a laser footprint of approximately 1 cm at that distance.

The three LIDAR sampling locations were selected to represent boulder conditions by quantifying observations of the upended, tabular boulders in the east as compared to the more rounded boulders in the west. At each location, the exact grid location was selected based on field observation of site conditions. For example, areas that had misplaced boulders from excavation pits were avoided to best represent natural formation processes. Additionally, sites with upended boulders that could block the LIDAR line-of-sight were avoided, with the exception of the eastern margin of the study area where upended boulders are clearly *in situ*.

For each of the three LIDAR surveys, a 10 m by 10 m sampling area was defined and oriented to magnetic north. The LIDAR was placed outside of the grid at four locations around the sample area to improve the likelihood of collecting data from all sides of the boulders. Table 1 reports the sample number, scan, and resolution of each of the LIDAR surveys.

Because quartzites typically do not produce weathering rinds and the radiometric dating of rocks is expensive, a Schmidt hammer was used to determine how rates of hardness were spatially distributed throughout the field. E. Schmidt created his hammer in 1948 to measure the strength of concrete (Day, 1980; Greene, 1954). It was designed for the rapid, inexpensive, and nondestructive testing of concrete—characteristics lacking in previous testing equipment such as the compression machine. The hammer measures the R-value of concrete or rock surfaces, or the distance of rebound of spring-loaded mass impacting a surface, to provide an estimate of surface hardness or strength. Greene (1954) and Kolek (1958) provided detailed descriptions of the mechanical components of the hammer, presented compression, rebound, and calibration curves, and offered proper preparation and handling methods for optimum performance.

The first published use of the Schmidt hammer in geomorphology was by Yaalon and Singer (1974), who tested the strength and porosity of calcrete in Israel (McCarroll, 1987). This technique has been applied to a number of geomorphological studies (Campbell, 1991; Matthews and Shakesby, 1984; Sheorey et al., 1984; Sjoberg and Broadbent, 1991). Most of these authors recommended the hammer for relative dating of rock surfaces under the assumption that decreased rock hardness corresponds to increased exposure to age and weathering. Sjoberg and Broadbent (1991) praised the tool for relative dating in geomorphology in conjunction with other methods such as lichenometry. Day (1980) stated that the hammer not only provides meaningful data about relative hardness, but can also be used to understand weathering processes, the effect on rock properties of those processes, and differential landform development.

Chapter 5

RESULTS

All results for boulder orientation (excluding LIDAR), shape, and age are listed in Table 2. Boulder mean orientations show that six sample locations (1, 6, 9, 10, 11, and 14) are aligned parallel to the long axis of the boulder field (Figure 14). The remaining eight sample locations are not aligned with the parallel orientation of the boulder field. Rose diagrams match the mean orientation data (Figures 14-15). LIDAR orientation data matches field methods at sample locations 2, 7, and 14 and confirm that manual orientations are correct (Figure 16). Although some pockets of fabric are revealed, such as the grouping of samples 9, 10, and 11, no general fabric characterizes the entire site.

Images that display the LIDAR surface data at each survey site within the boulder field are presented in Figure 16 along with DEMs and rose diagrams depicting the elevation and boulder surface aspects. The boulder aspect data indicate a dominance of surfaces with northwest-to-southeast trending aspects. Comparison of the LIDAR-based aspect data with boulder orientation data from Smith (1953) indicates that the majority of reflected surfaces aspects are perpendicular to his long axis boulder alignments. This juxtaposition of aspects vs. long axis orientations is likely due to long tabular clasts with large surface areas on their sides. Such clasts may align in a direction that reinforces long-term flow directions while simultaneously providing large surfaces areas on the sides so that the LIDAR collects a majority of points with aspects that are perpendicular to the fabric.

Based on visual interpretation, the boulders upslope (east) at Hickory Run are larger, angular, and less spherical; those downslope (west) appear to be smaller, smoother, and rounder (Figure 17). Roundness reveals the strongest spatial trend in the data, with boulders being more angular in the east and more rounded in the west for the 25 boulder dataset (Figure 18). The *a*-axis data also display an east-west relationship, with boulder length decreasing to the west for the 25 boulder dataset (Figure 19). These results match visual observations when traversing the boulder field from east to west. However, sphericity and flatness indices reveal somewhat uniform data and no spatial relationships for both the 50 boulder and the 25 boulder dataset (Figures 20-21). Volume measurements also reveal somewhat uniform data and no spatial relationships for both the 50 boulder and the 25 boulder dataset (Figure 22). Relative resistance data obtained from Schmidt hammer tests show that there is a grouping of more resistant, i.e., younger, boulders in the west, but the correlation is weak (Figure 23). Overall, the boulders display similar rates of rock weathering ages, implying they are of similar age.

Researchers often describe boulder fields as inactive because of the presence of vegetation. Although some boulder fields have no vegetation, the surrounding forest can obscure portions of a boulder field on aerial imagery, potentially excluding them from identification for study (Figure 24). Missing vegetation is typically caused by the removal of interstitial matrix by running water. Hickory Run is one such instance; water is visible in various depressions and audible when standing on the field. On an average day, water is visible at depths of a few meters and is mainly located in the western, downslope part of the field.

During the first phase of fieldwork in September 2004, approximately one week after intense rains following a southeastern United States hurricane, the western half of the boulder field was flooded (Figure 25) with clear and sediment free water. The water level reached the uppermost boulders but left enough surfaces for hiking. Despite the high water levels, the visible water decreased and was eventually absent approaching the eastern, upslope end. Speculating on the possible occurrence of flooding, Smith (1953) wrote, “The possibility that the surface of the boulder field might be flooded at times of heavy rainfall was suggested by the presence of debris draped around tree trunks in the area immediately down valley from the boulder field.” His estimates were confirmed by the September 2004 field investigation.

Chapter 6

DISCUSSION

This study analyzed quantitative results of trends in boulder characteristics, as measured using both traditional and modern field measurements, to provide insight on the possible formation process of Hickory Run. The purpose of these measurements was to evaluate and compare the relative likelihood of four different explanations of the origins and processes of boulder field creation. This section covers each theory in turn.

The first formation process considered is glacial deposition. An illustration in a Pennsylvania park guide (Geyer, 1969) depicts glacial meltwater eroding local rock debris and depositing an apron down valley. However, one would expect glacial outwash to produce different grain sizes and different materials. Also, a glacial moraine lies north of the boulder field and contains these same physical characteristics. Hickory Run does not fit the characteristics of glacial moraine deposits for the following reasons. The boulders at Hickory Run appear to be of mostly uniform size and comprise two types of material derived directly from local bedrock: quartzitic sandstones and conglomerates. Therefore, it is not likely that the boulder field was formed by direct glacial deposition.

The second formation process considered is gelifluction, the most popular theory among researchers. Gelifluction is a form of mass movement in periglacial environments where a permafrost layer exists. It is characterized by the movement of waterlogged soil over the permafrost layer. A boulder field produced by this process should show evidence of the motion in the boulder shapes and fabrics, evidence of differing ages based on distance from the source region, and evidence of the appropriate waterlogged soil material. Embleton and King (1968) asserted that the presence of both angular and rounded boulders (the latter being farther away and downslope of source region) indicate that movement of boulders has occurred and therefore a boulder field was not formed *in situ*. Boulders in Hickory Run do fulfill this requirement somewhat, showing below-median roundness near the source region and above-median roundness farther away from it (Figure 18).

Smith (1953) and others have postulated that boulder flow at Hickory Run was facilitated by shallow permafrost acting as an impermeable layer and causing saturation of the near-surface layer. Thaw of ice-rich permafrost would cause considerable settlement, with many of the elongated boulders becoming upended in the process. Smith's (1953) hypothesis required that the two-dimensional fabric, or the azimuth data, of the boulder field show correlation with the local slope, and that three-dimensional fabrics are without a preferred direction because the boulders were strongly modified by thaw settlement, or melting of the permafrost and supportive ground layer during the last rapid climatic amelioration. Washburn (1973) observed that alignment of the long axes of clasts parallel to the boulder field orientation was a sign of past gelifluction.

Studies of similar processes have been undertaken in other locations. In a study of Mt. Barrow, Tasmania, Caine (1968) found long axes aligned parallel with local slope with a tendency toward upslope imbrication; he noted, however, that the size and shape of clasts seemed to have no influence on fabric. Fabric analysis by Caine (1968) noted that unimpeded flow resulted in clast alignment with local slope, whereas in areas of impeded flow, such as on blockstream toes, the clast alignment was normal to the direction of greatest stress. Bertran et al., (1997) summarized previous research by stating that the wealth of solifluction fabric data has indicated that clasts typically have a preferred orientation parallel to slope direction. They also furthered Caine's (1968) argument by reinforcing the observation that lobe fronts revealed non-parallel trends with downslope direction by lacking a preferred orientation, or that slow movement near lobe fronts causes transverse clast orientation (Benedict, 1976). Bertran et al., (1997) stated that of the three cohesive particle movements, solifluction, debris flows, and grain flows, solifluction deposits have the highest fabric strength as supported by Mills (1991) and Nelson (1985). Bertran et al., (1997) also noted that the main complications with fabric analysis are the lack of knowledge on post-depositional changes to fabric and the general imprecision of interpretation.

The current analysis of Hickory Run data collected for several different boulder characteristics revealed no large-scale fabric trends governing boulder orientations throughout the entire site. Six sample locations (1, 6, 9, 10, 11, and 14) did reveal pockets of fabric aligned with the east-west orientation of the boulder field, but samples 9, 10, and 11 compose the only grouping with a similar orientation parallel to the boulder field (Figures 14-15). Sample locations 1, 6, and 14 are aligned with the parallel orientation of the boulder field, but are situated alone (Figures 14-15). The roundness and *a*-axis data display an east-west relationship, with boulder roundness increasing and boulder length decreasing to the west. Boulder roundness box plots display seven sample medians (symbolized as horizontal red lines) at sample locations (2, 3, 4, 5, 6, 7, and 10) below the median line (Figure 18). Six sample medians at sample locations (1, 9, 11, 12, 13, and 14) are above the mean line (Figure 18). Boulder *a*-axes box plots display no spatial relationship for the sample of 50 boulders. The sample of 25 boulders displays two groups of sample locations (2 and 3) and (5, 6, 7, 9, 10, 11, 12) and a single value at sample location 14, with sample medians below the mean line (Figure 19). Only three sample locations (1, 4, and 13) display sample medians above the mean line (Figure 19). No other shape indices, such as sphericity, flatness, or volume reveal spatial trends (Figures 20-22).

The Schmidt hammer data were used to evaluate whether an exposure age gradient exists across the boulder field. In general, higher R-values indicate stronger, less weathered, and younger rocks. Weathering is defined as the breakdown of solid rock at or near the Earth's surface. Mechanical weathering in particular is the physical abrasion inflicted on rocks due to the action of water, ice, and wind. It is thought that a type of mechanical weathering, frost wedging, is responsible for the breakdown of local rock at Hickory Run. It is also supposed that mechanical weathering is responsible for the general decrease in boulder size and increase in sphericity and roundness with downstream distance at Hickory Run, due to the movement and abrasion on the surfaces of the boulders. Chemical weathering is described as the chemical reaction of rock minerals with water and oxygen in the atmosphere. During boulder field formation, movement, and equilibrium status in place, the boulders have most likely undergone some form of chemical weathering. Analyzing boulder R-values revealed no spatial trends along the boulder field transect.

If hardness displays a decreasing trend with increasing distance from source area, this can suggest that chemical weathering processes have had more time to act on the older, farther boulders. No observable distinct trend of hardness with distance from source area supports two conclusions. One, that after the boulders were deposited downslope from the source area, enough time has passed that chemical weathering is essentially equally represented in all portions of the field, regardless of the distance from source area. A second possibility is that physical irregularities, climatic influences, and errors introduced from the instrument and/or the experimenter overwhelm the ability to detect any trends in hardness. A third possibility, one tentatively ruled out, is that the boulder field is still sufficiently active and that new surfaces are regularly being exposed.

Relative age data determined from Schmidt hammer hardness measurements suggest that Hickory Run boulders display no particular age distribution (Figure 23). This refutes the hypothesis of an east-west transfer of boulders over millennia that would have been caused by gelifluction over a great distance. Note that some supporters of this relative-dating method warn of problems with geomorphological use of the Schmidt hammer. Matthews and Shakesby (1984) applied the Schmidt hammer to approximate the extent of weathering on glacial moraines in conjunction with lichenometry in southern Norway. Their results showed a decrease in overall mean R-values taken from inside glacial moraines, along the outer moraine, and then outside the moraine, thus supporting the theory that higher R-values correlate to less weathered rocks. In this case, the outside rocks had more exposure time than the inside glacial deposits. However, they discouraged using the method for dating early or pre-Holocene age materials because long-term surface exposure places surface weathering in equilibrium so R-values would not necessarily reveal different hardness values. Campbell (1991) warned that methods for using the Schmidt hammer in relative geomorphic dating have not been standardized, so that varying techniques are used. McCarroll (1989) recommended the Schmidt hammer for merely preliminary assessment of relative dating. This study did not seek to obtain objective hardness values from the Schmidt hammer data at Hickory Run, but rather used these data to identify any gross trends. As such, these relative hardness data provided a useful negative result, showing that there is no long (multiple millennia) age difference across the boulder field. It is noted that the R-values could have been altered by different hammer position angles, boulder moisture, different field assistants handling the instrument, and general wear and tear. Hence, it would be more accurate to say that the Schmidt hammer data did not demonstrate an age difference, rather than to say that they prove that there was no age difference across the boulder field.

Finally, gelifluction requires the presence of fabric material, such as soil or sand, and Hickory Run is without a matrix. The previously mentioned running water presence at Hickory Run also does not support gelifluction because it prohibits soil accumulation, which is necessary for gelifluction. Peltier (1949) observed a lack of fabric orientation on Bald Eagle Mountain in Pennsylvania, which he attributed to the washing-out of interstitial material causing subsequent subsidence. While the boulder roundness increasing and boulder length decreasing to the west support some influence of gelifluction in the formation of the boulder field, the lack of an obvious boulder orientation fabric, lack of evidence for a deformable matrix, and lack of evidence of an age gradient all point against gelifluction as an explanation for the boulder field.

The third formation process considered is *in situ* weathering of bedrock, or the breakdown of bedrock in place. This process does explain the adjacent sampling sites displaying strong fabric differences and no overall spatial trends. But, *in situ* weathering does not support the boulder roundness increasing and boulder length decreasing to the west. The localized fabric can be attributed to the jointing of rocks and not necessarily to boulder movement. The overall lack of fabric is consistent with the *in situ* weathering formation process. Therefore, *in situ* weathering is likely a necessary part of the overall process of Hickory Run formation, but is not sufficient to explain the entire formation of the field since it does not address the east-west changes in roundness and *a*-axis lengths.

The fourth formation process considered is valley widening and/or scarp retreat. This process is less of a new entry and more of a coupling of several previously mentioned mechanisms. A valley widening and/or scarp retreat model requires an initial phase of freeze-thaw cracking of the bedrock or the migrating vertical failure of jointed and fractured rock walls over time. Subsequently, frost-heave lifting of the boulders and gelifluction moves the boulders downslope. This formation process, which combines many of the characteristics of those mentioned earlier, provides a more sufficient mechanism than any single process.

Chapter 7

CONCLUSION

Relict periglacial features are of particular interest because they can indicate paleoenvironment and paleoclimate within proximity to the ice-sheet margin. Few other land features can provide such data. Although studying boulder field formation is an important contribution to climate research, assigning a paleoclimatic implication requires the physical processes acting on a site to be revealed in spatial trends. Because none of the boulder parameters of orientation, shape, and age at Hickory Run work in concert, suggesting that the boulder field is a good indicator of past paleoclimate environments is a bold assumption. The *in situ* and valley widening formation processes could have occurred in a cold climate and thus relied on freeze-thaw processes, but do not necessarily require permafrost to form. One cannot assign a known temperature to a relict physical landscape feature that could have potentially formed with or without the presence of permafrost. Hickory Run site formation is therefore not a good indicator of paleoclimate conditions.

Future studies of Hickory Run should include a systematic sampling method to obtain and identify the best spatial representation of the boulders. Additionally, observations in this study of running water present under the matrix, and the implications of seasonal flooding events such as hurricanes, present further opportunity for exploring modern conditions and their effects on boulder weathering and potential movement.

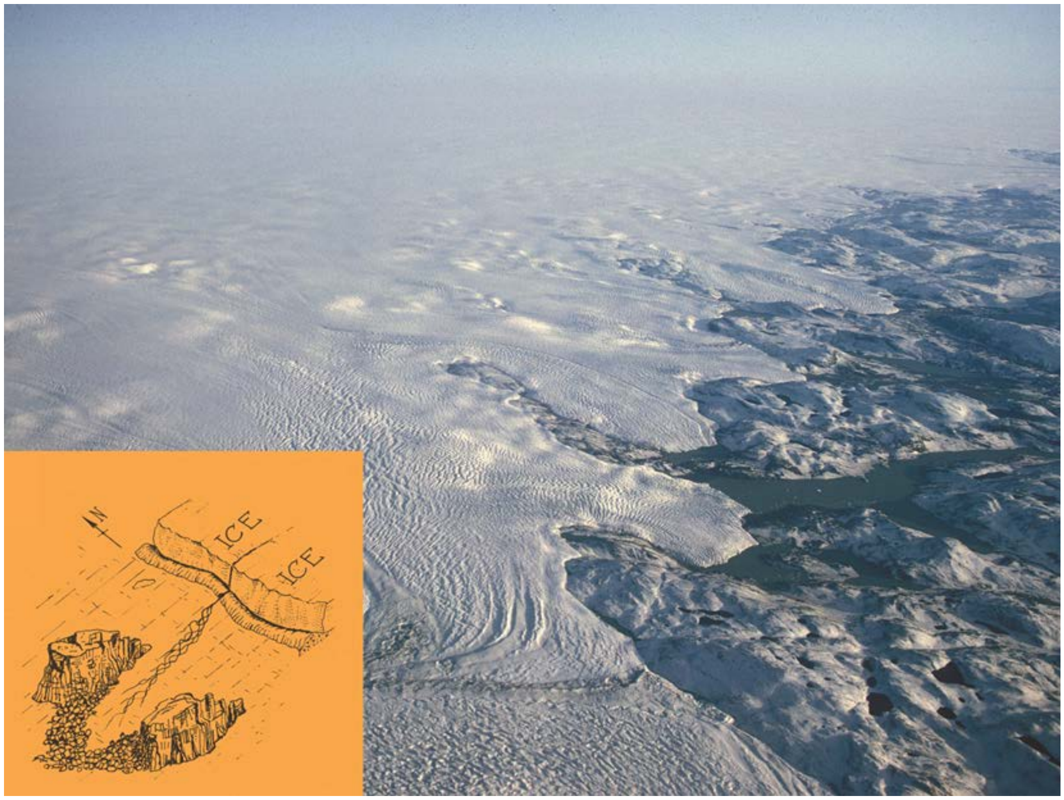


Figure 1 Photograph of a glacier in Greenland (Hannes, 1995) and an illustration of glacial deposition (Geyer, 1969).

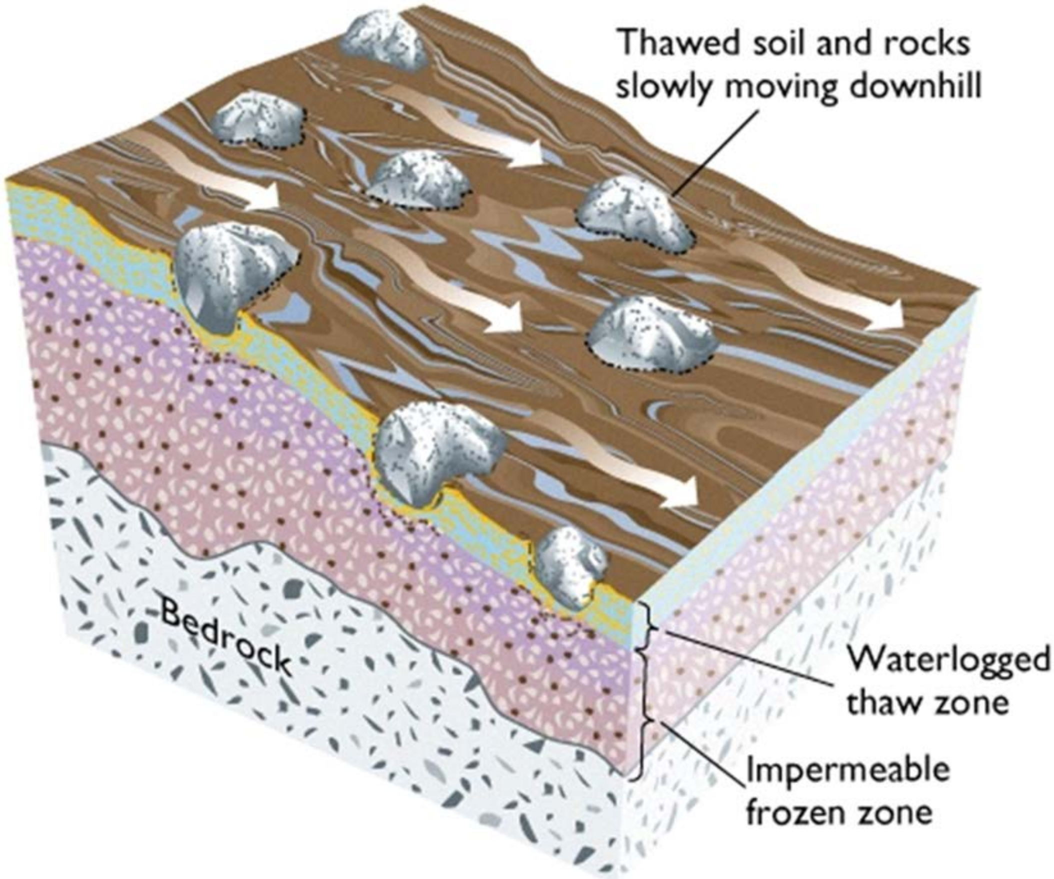


Figure 2 Illustration of gelifluction. *http://learningglaciers.blogspot.com*. Retrieved April 13, 2013.

Figure 3	Photograph of *in situ* erosion of bedrock surface in Sandy Cove, Labrador (House, 2002).

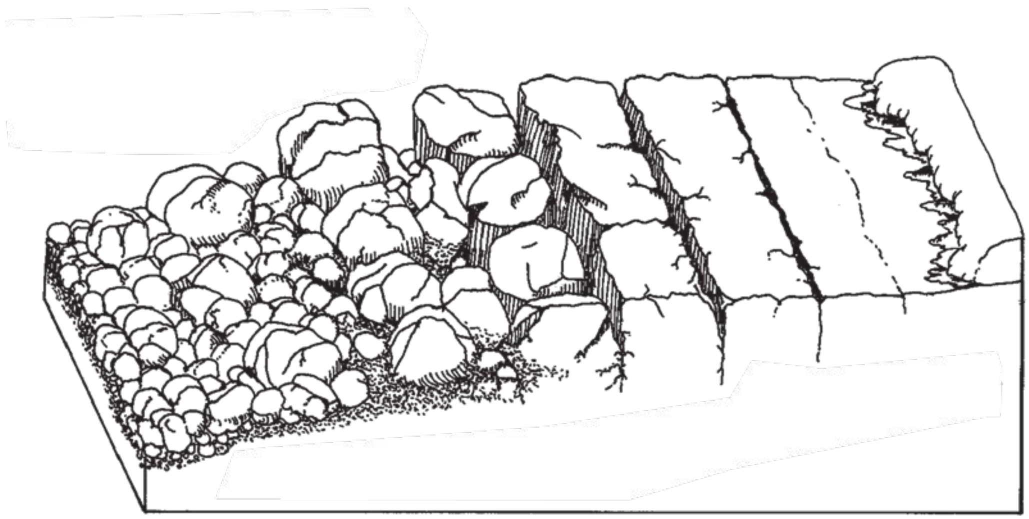


Figure 4 Illustration of valley widening or scarp retreat found on the informational sign at the entrance to the Hickory Run Boulder Field, Pennsylvania (Sign date unknown).

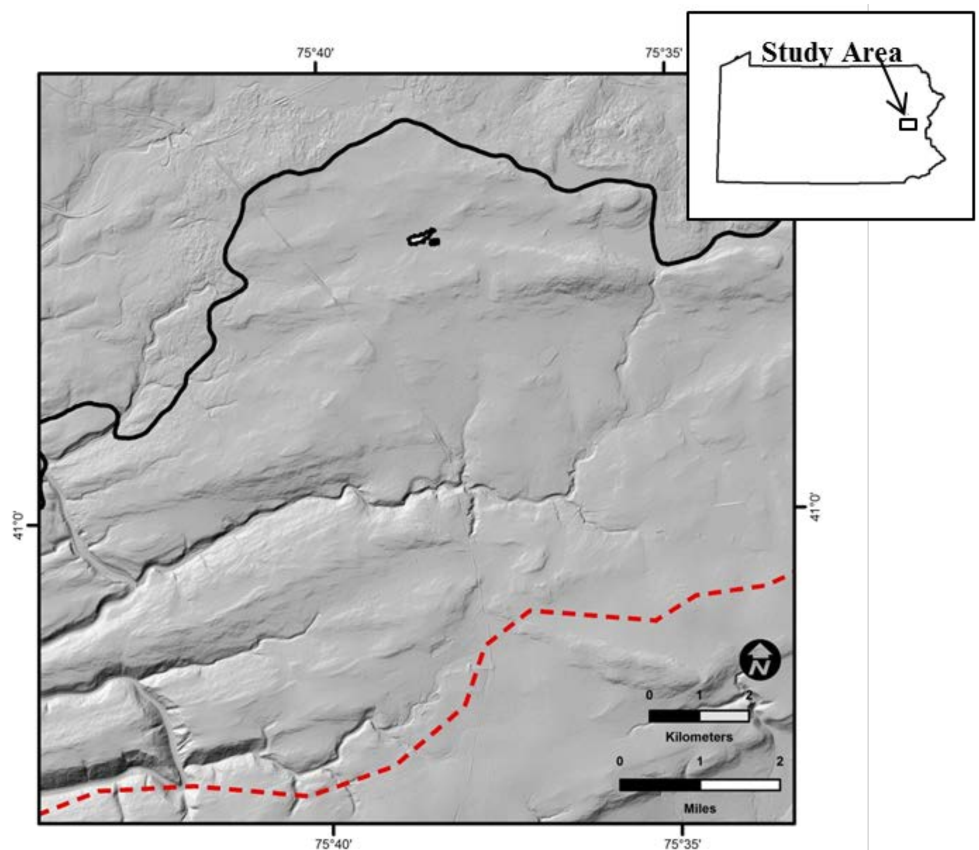


Figure 5 Hickory Run Boulder Field location south of the Late Wisconsinan Glacial border (black) and north of the Late Illinoian border (red) and general study area location within Pennsylvania. Background image is LIDAR Digital Elevation Model (DEM) (PAMAP Program, 2006).

Figure 6 Image is orthorectified digital raster aerial image (PAMAP Program, 2007).

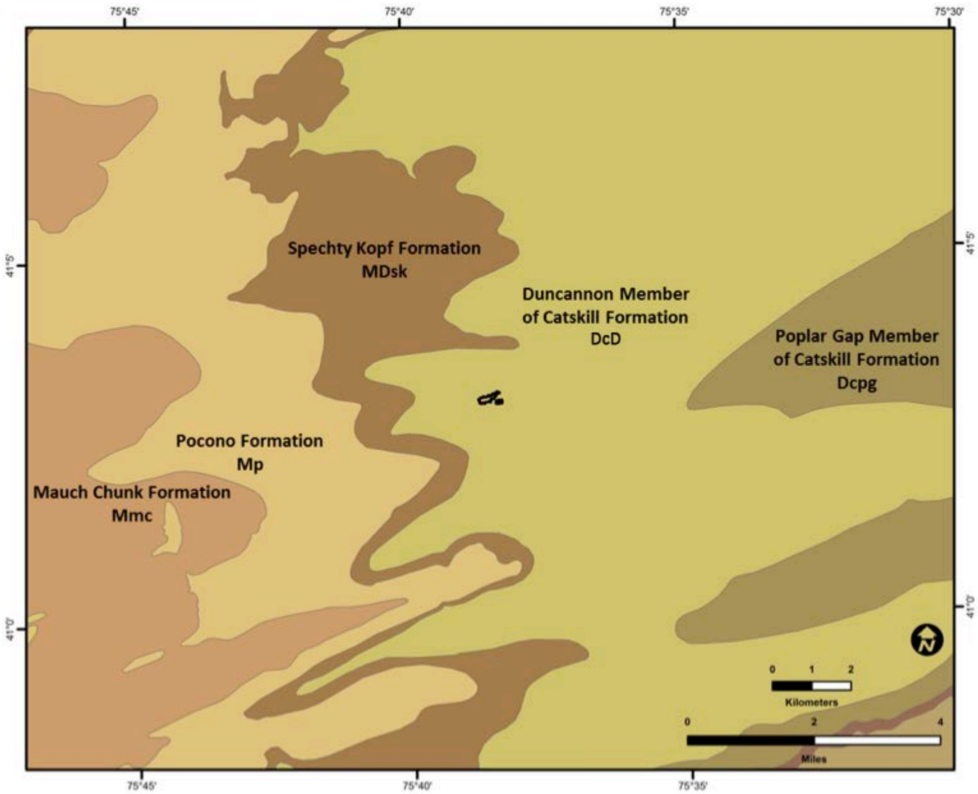


Figure 7 Bedrock Geology of Pennsylvania (PA DCNR, 2001). The Hickory Run Boulder Field, located in the center of the map, sits within the Duncannon Member of Catskill Formation (DcD).

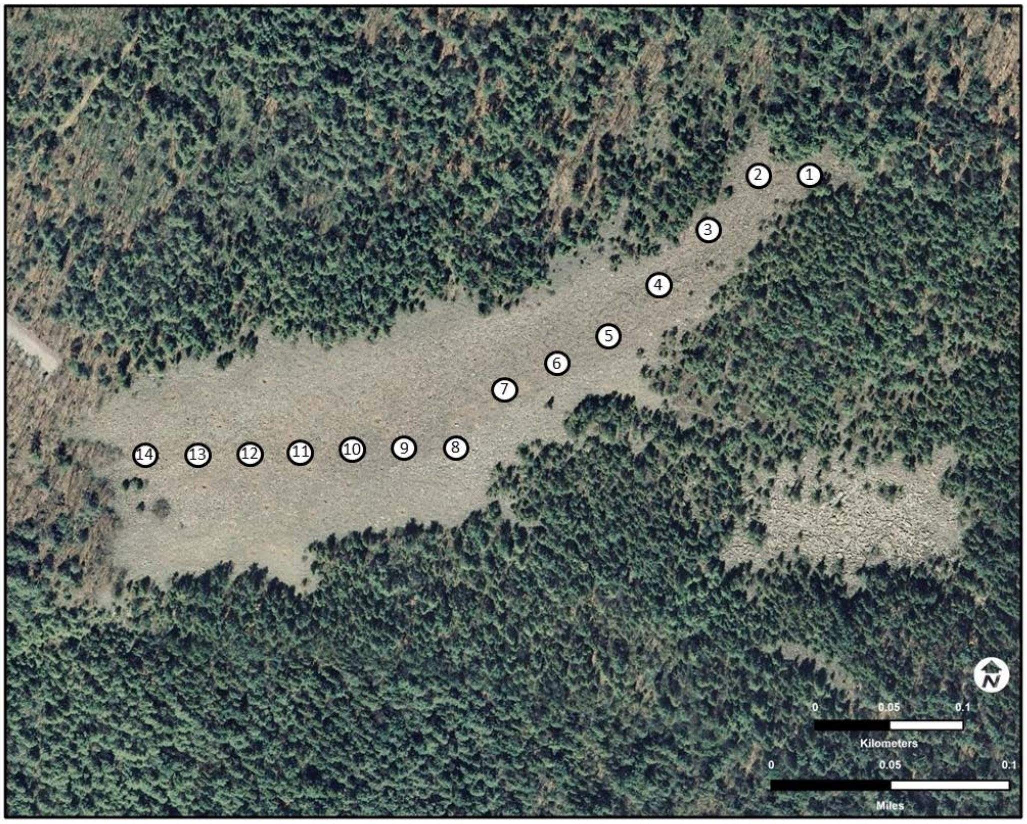


Figure 8 Sample locations 1 through 14 at the Hickory Run Boulder Field. Background image is orthorectified digital raster aerial image (PAMAP Program, 2007).

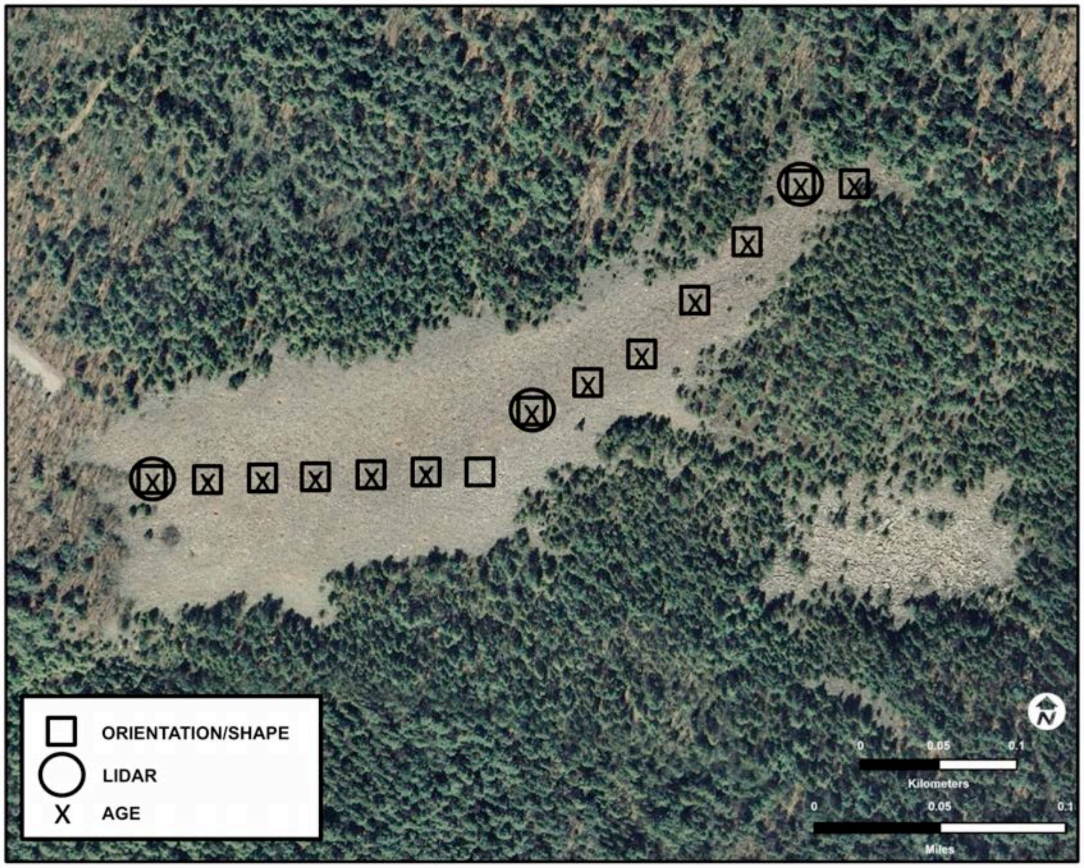


Figure 9 Sampling location types at the Hickory Run Boulder Field. Background image is orthorectified digital raster aerial image (PAMAP Program, 2007).

Figure 10 Photograph of a Schmidt hammer (taken by the author, August, 2004).

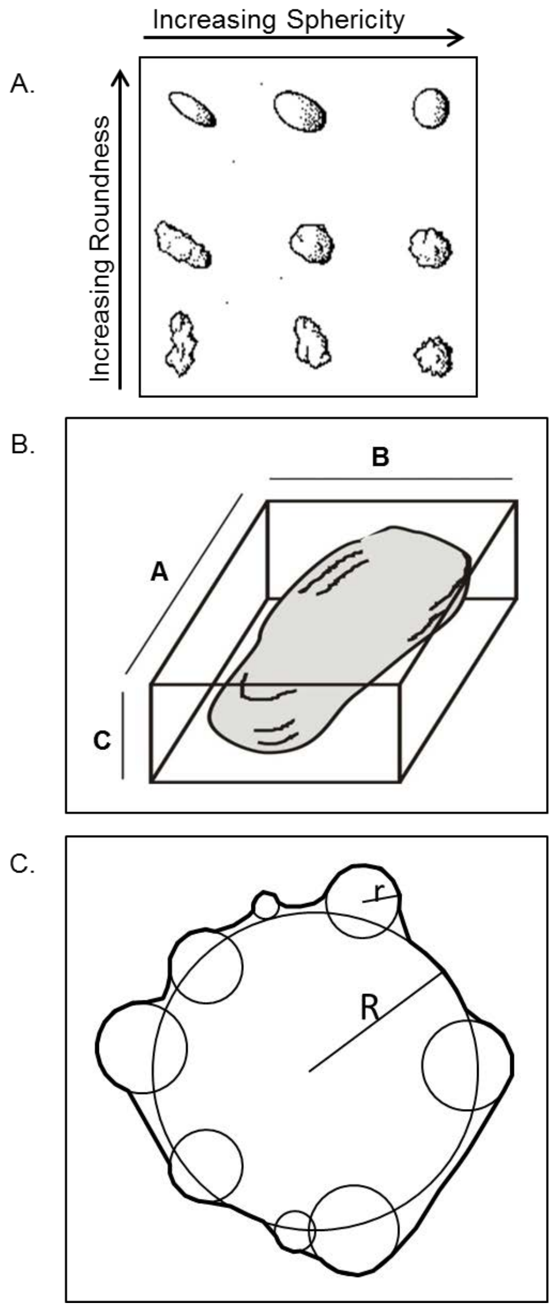


Figure 11 Illustrations of boulder shape. A. Roundness and sphericity, modified from Selley (1976) B. Three axis lengths, *a, b, c*, modified from McLane (1995) C. Roundness, modified from Boggs (1995).

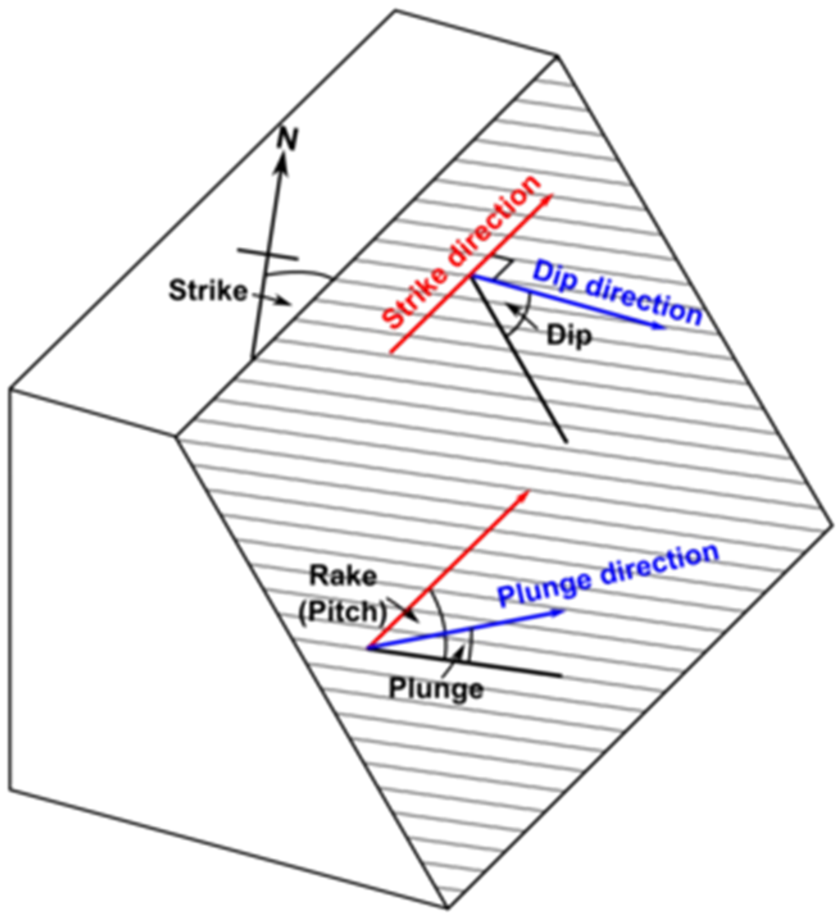


Figure 12 Illustration of boulder orientation. Field measurements include azimuth (strike) and plunge (Norton, 2010).

Figure 13 Photograph of University of Delaware Geography Department students using a Trimble GX LIDAR at sample location 14 (taken by Dr. Michael O'Neal, August, 2011).

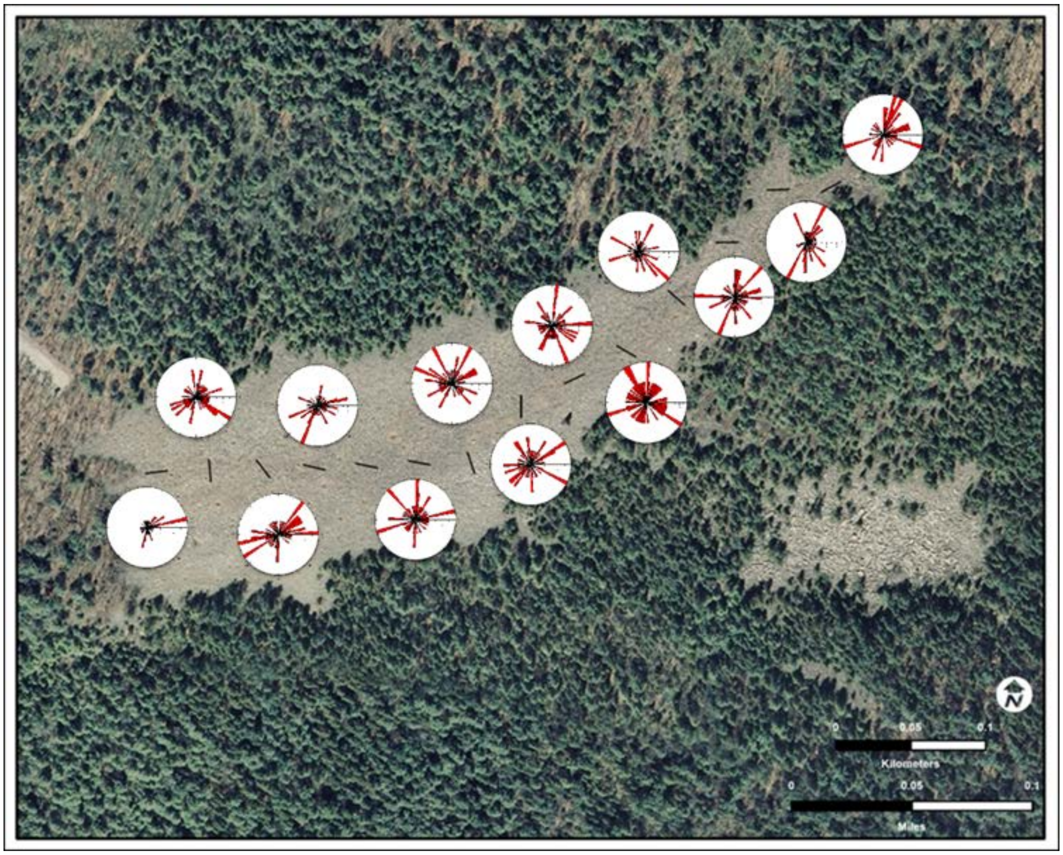


Figure 14 Average directions (black lines) and rose diagrams of *a*-axes. Background image is orthorectified digital raster aerial image (PAMAP Program, 2007).

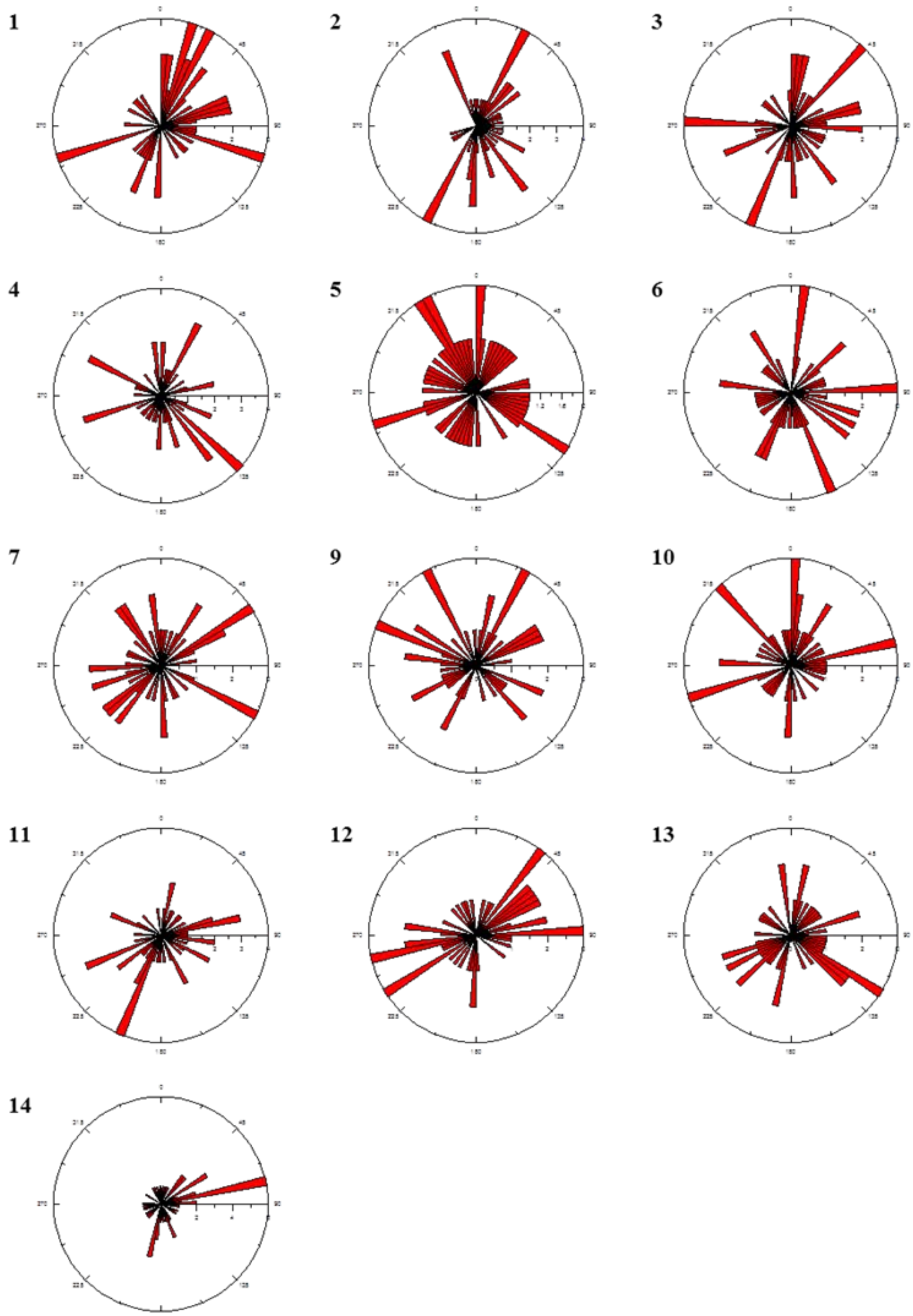


Figure 15 Rose diagrams of *a*-axes.

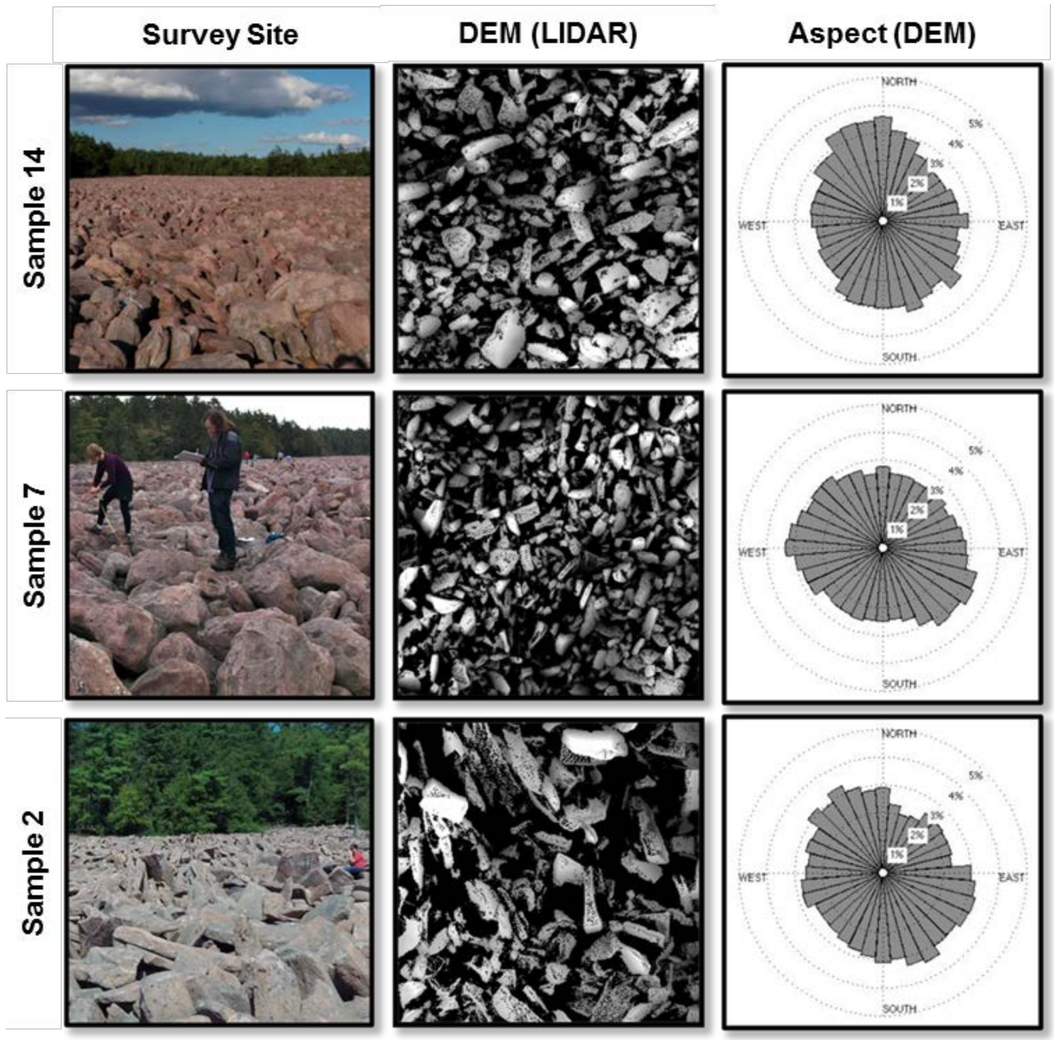


Figure 16 LIDAR data displaying sample location photographs, LIDAR DEMs, and rose diagrams of orientation data for selected samples.

Figure 17 Top photograph of the western end of the Hickory Run Boulder Field containing rounded boulders. Bottom photograph of the eastern end containing angular boulders. Construction hat for scale (taken by the author, August, 2004).

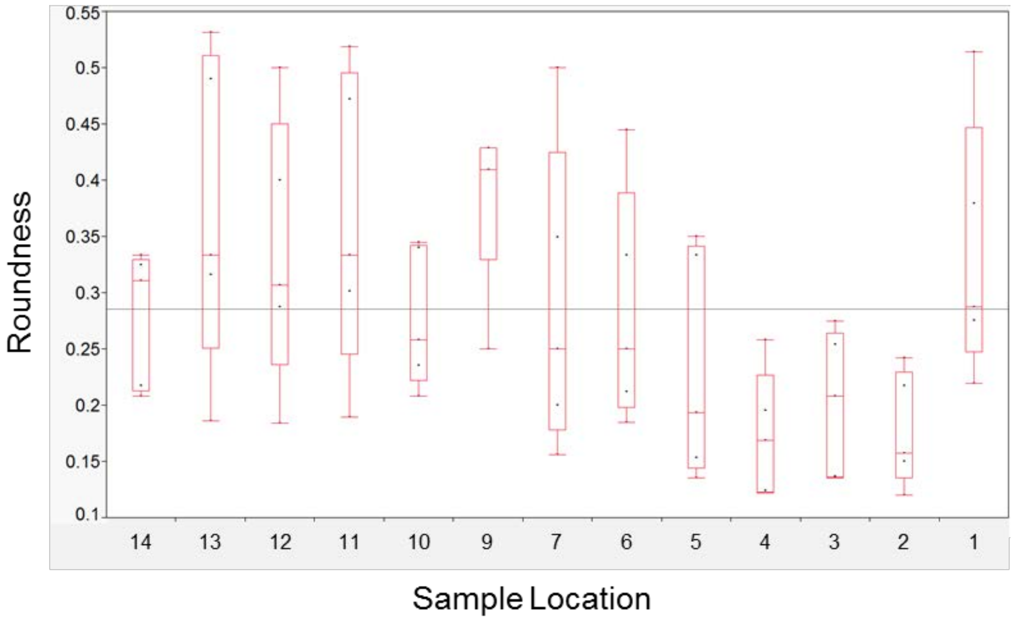


Figure 18 Box plot of boulder roundness at each sample location. Sample 1 is east and sample 14 is west. Graph displays 25 largest boulders sampled, with roundness sampled every fifth boulder.

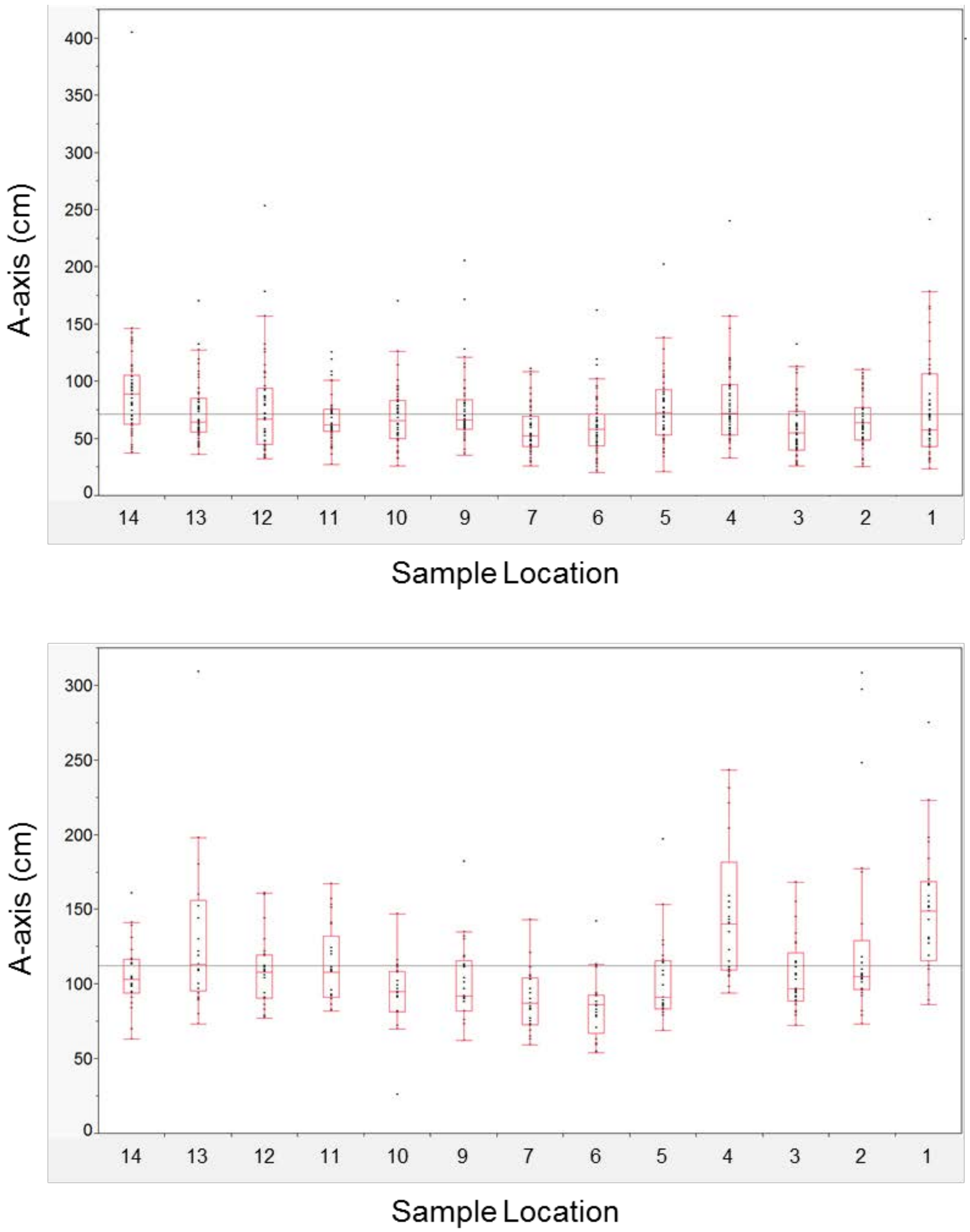
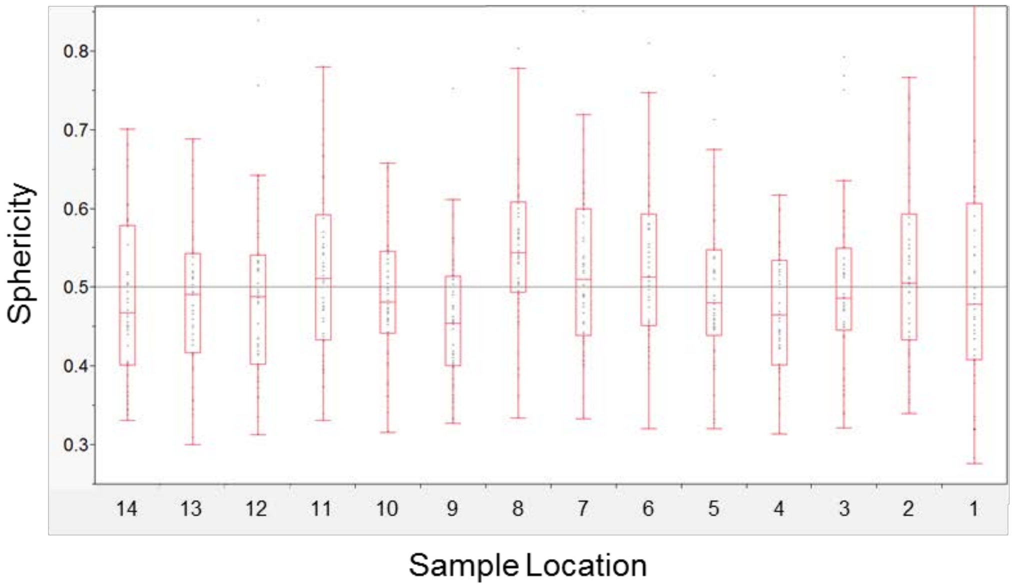


Figure 19 Box plot of boulder *a*-axes at each sample location. Sample 1 is east and sample 14 is west. Top graph displays 50 boulders sampled. Bottom graph displays 25 largest boulders sampled.



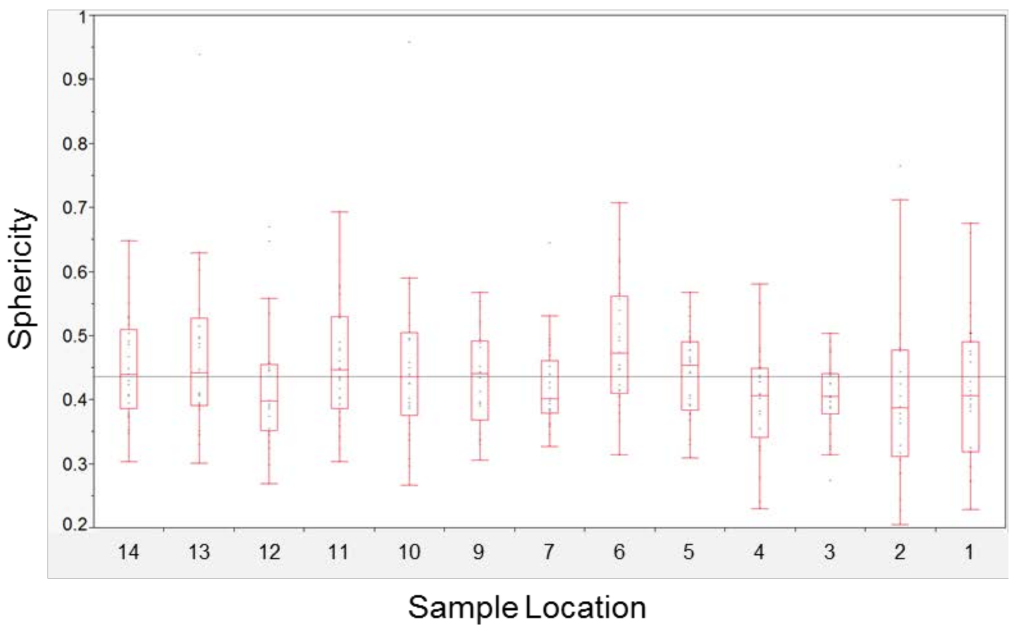
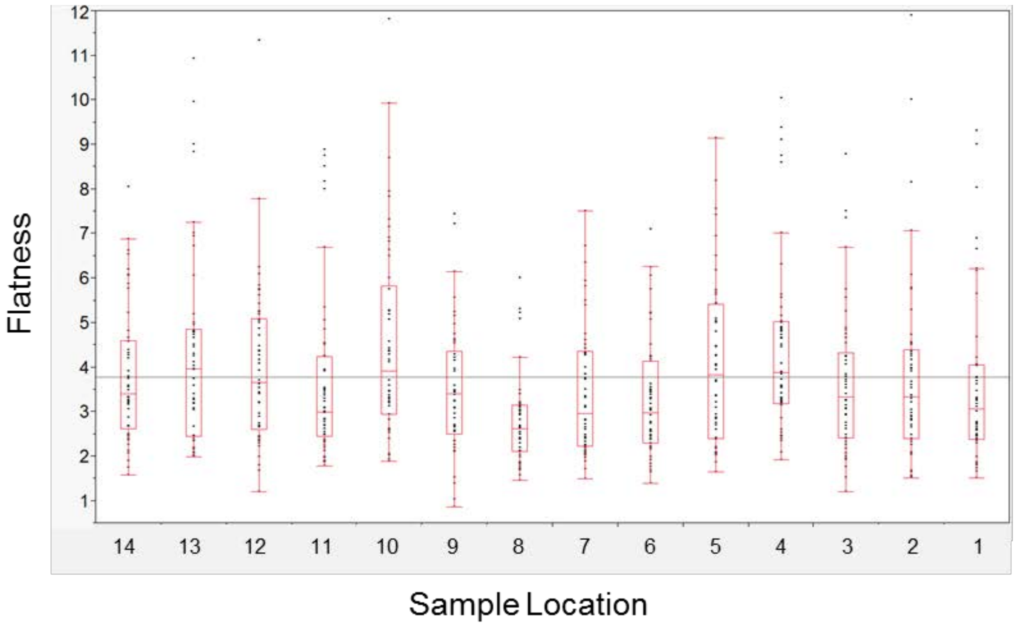


Figure 20 Box plot of boulder sphericity at each sample location. Sample 1 is east and sample 14 is west. Top graph displays 50 boulders sampled. Bottom graph displays 25 largest boulders sampled.



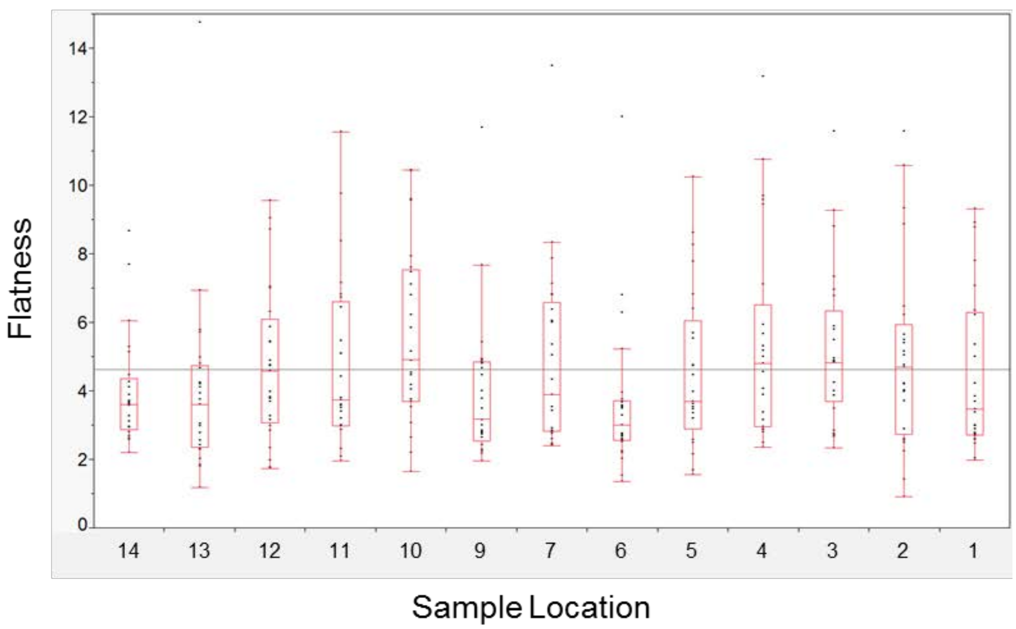
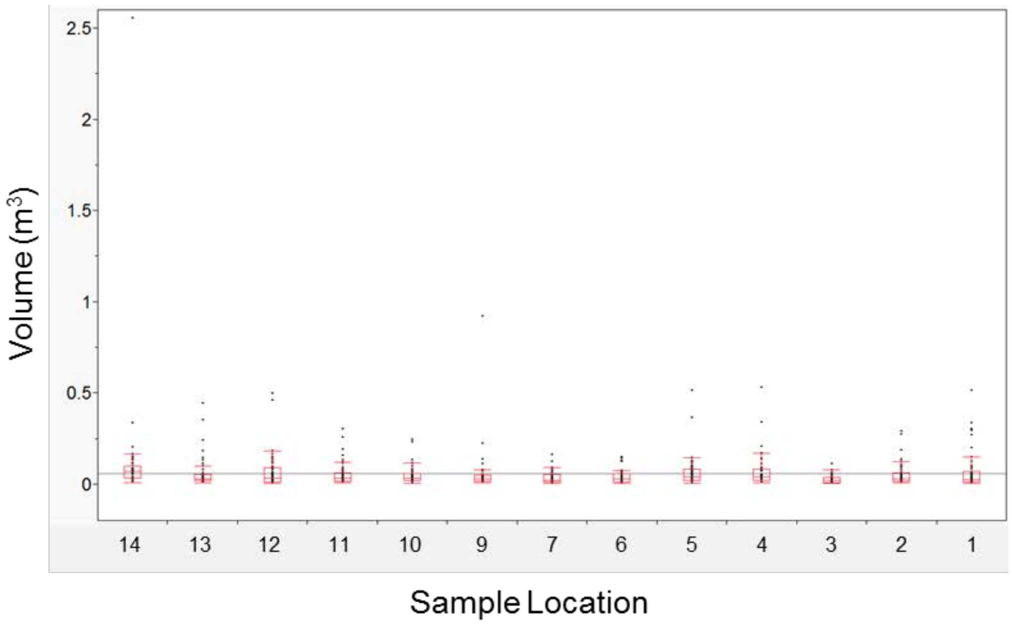


Figure 21 Box plot of boulder flatness at each sample location. Sample 1 is east and sample 14 is west. Top graph displays 50 boulders sampled. Bottom graph displays 25 largest boulders sampled.



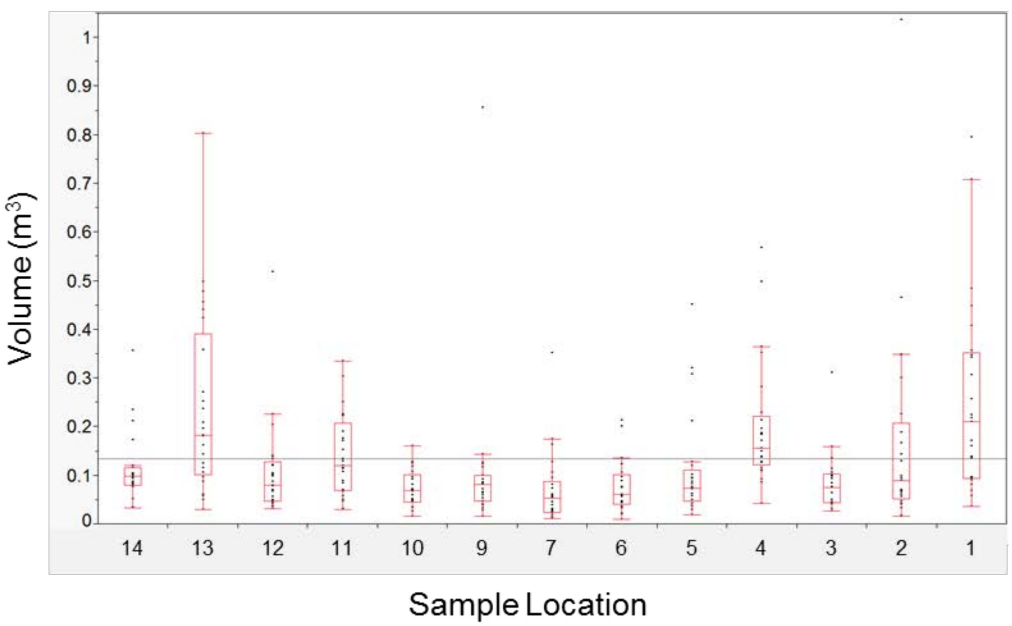


Figure 22 Box plot of boulder volume at each sample location. Sample 1 is east and sample 14 is west. Top graph displays 50 boulders sampled. Bottom graph displays 25 largest boulders sampled.

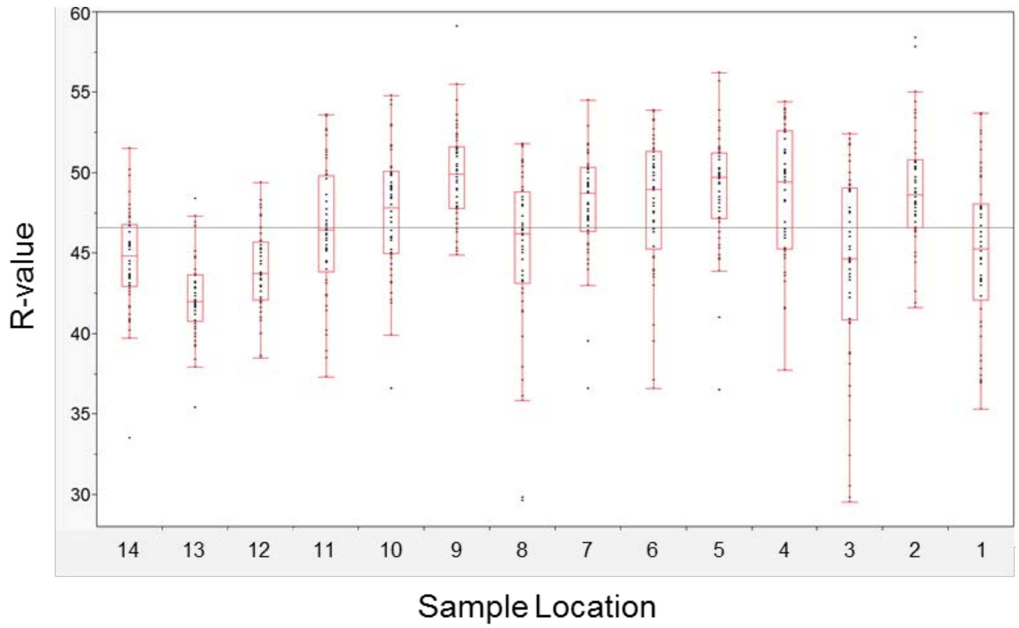


Figure 23 Box plot of boulder Schmidt hammer R-values at each sample location. Sample 1 is east and sample 14 is west. Graph displays 50 boulders sampled.

Figure 24 Photograph of the Hickory Run Boulder Field perimeter showing rocky material in the surrounding woods (taken by the author, August, 2004).

Figure 25 Photographs of the flooded Hickory Run Boulder Field approximately one week after a hurricane in September 2004. Both images captured at western end of the field (taken by the author, September, 2004).

Table 1 LIDAR sample, scan, and resolution.

Sample	Scan	Resolution		
14	A, C, D	200	200	100
	B	100	100	100
7	A, B, C, D	100	100	100
2	A, B, C, D	200	200	200

Table 2 Data tables.

DATA COLLECTION - 1						
SAMPLE	A-AXIS (cm)	VOLUME (m^3)	SPHERICITY	FLATNESS	SCHMIDT HAMMER (R)	DIRECTIONAL MEAN
1	76	0.07	0.50	3.57	45	242
2	65	0.05	0.53	3.77	49	88
3	59	0.03	0.50	3.64	44	89
4	81	0.07	0.47	4.43	49	311
5	76	0.06	0.49	4.10	49	120
6	60	0.04	0.53	3.25	48	65
7	58	0.03	0.52	3.43	48	180
8	87	0.24	0.55	2.78	45	161
9	75	0.06	0.46	3.50	50	101
10	70	0.05	0.49	4.54	48	102
11	68	0.06	0.52	3.65	47	103
12	76	0.07	0.49	3.97	44	142
13	74	0.06	0.48	4.26	42	175
14	92	0.12	0.48	3.80	45	263

DATA COLLECTION - 2					
SAMPLE	A-AXIS (cm)	VOLUME (m^3)	SPHERICITY	FLATNESS	ROUNDNESS (R)
1	148	0.25	0.42	4.49	0.34
2	129	0.17	0.41	4.98	0.18
3	106	0.08	0.40	5.19	0.20
4	148	0.20	0.40	5.40	0.17
5	102	0.11	0.44	4.57	0.23
6	85	0.08	0.49	3.59	0.28
7	90	0.07	0.42	4.92	0.29
8	N/A	N/A	N/A	N/A	N/A
9	101	0.11	0.43	3.92	0.39
10	95	0.07	0.45	5.62	0.28
11	111	0.14	0.46	4.80	0.36
12	108	0.11	0.42	4.75	0.34
13	130	0.24	0.47	4.01	0.37
14	106	0.11	0.45	3.97	0.28

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