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THE NATURE OF BOULDER-RICH DEPOSITS IN THE UPPER BIG FLAT BROOK DRAINAGE, SUSSEX COUNTY, NEW JERSEY

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ABSTRACT*: The upper reaches of the Big Flat Brook drainage, northwest of Kittatinny Mountain, contain a variety of glacial, pro-glacial, and periglacial deposits from the Late Quaternary. The area is dominated by recessional moraines and ubiquitous ground moraine, along with meltwater deposits, drumlins, and possible post-glacial periglacial features. We have identified a curious boulder-rich deposit in the vicinity of Lake Ocquittunk and Lake Wapalanne on upper Big Flat Brook. The area where these boulder deposits occur is mapped (1:24,000 surficial geology) as till. As mapped and observed, larger cobbles and boulders within the till are quartz-pebble conglomerate, quartzite, sandstone, and shale. The boulder-rich deposits differ from the typical till, however. Unlike the local till, which is more mixed in lithology, the boulder deposits are nearly exclusively Shawangunk conglomerate. The deposits are discontinuous, but appear to occur at a topographic level above the meltwater stream terraces. The boulders in the deposits lie partially embedded in soil, but are very closely spaced. The boulders range in size from ~20cm to over 100cm, and present a subrounded to subangular shape. There appears to be a fabric orientation of the boulders, NE-SW, with subsidiary orientations. As the boulder deposits differ from other mapped features in the area, we attempt to ascertain the origin for the deposits. Unique moraine dynamics, meltwater flood, periglacial slope movement, and slope-snow bank processes are possible explanations. Detailed examination of these boulder deposits will provide a finer explanation of the glacial and post-glacial geomorphic history of the area.*

Keywords*: Glacial geomorphology, Big Flat Brook, Late Quaternary*

INTRODUCTION

Recent geomorphic mapping at the quadrangle scale (1:24,000) reveals a complex glacial and postglacial environment in northwestern New Jersey (Witte and Epstein, 2005; Witte, 1997 and 2008). In the upper reaches of the Big Flat Brook drainage, bound by Culvers Gap to the south, Kittatinny Ridge to the southeast and Wallpack Ridge to the north and northwest, a variety of deposits include recessional moraine, blanket ground moraine, drumlins, meltwater and stream sediments, and colluvial deposits. Stream incision is evident by the terraces and ravine channels cut through glacial and fluvial sediments. With the overall geomorphic picture established, we are able to look closer at the smaller scale features which can reveal details on the glacial and post-glacial history.

One feature of interest is a bouldery deposit that appears as an armored surface bed, mainly on one terrace level in the vicinity of Lake Wapalanne and Lake Ocquitunk, along Big Flat Brook near the New Jersey School of Conservation (NJSOC, Montclair State University's field campus). A casual look might attribute the boulder bed to ground moraine, and the area is mapped, at a coarse scale, as such (Witte and Epstein, 2005 and Witte, 2008). A closer examination reveals several possible origins, including glacial processes. The single lithology and organization of the boulders suggests a periglacial-slope formation, similar to that at the much larger Hickory Run Boulder Field, Pennsylvania (Sevon, 1987). On the other hand, the apparent sorting and rounding of the boulders implies a possible fluvial origin or modification. In order to gain a better understanding of this landscape component, we undertook a detailed particle size, fabric, and lithologic analysis of the boulder bed. Two objectives for this study are to 1) establish the boulder bed in the larger context of the local geomorphic history; and 2) initiate the first geomorphic mapping and investigation at the School of Conservation, as a baseline study to assist future field research and education programs at the field campus. We report the initial findings in this paper.

Geographic and Geologic Setting

The study area is on and near the NJSOC property, located within Stokes State Forest. Big Flat Brook, a 166 km^2 tributary of the Delaware River, traverses the site. Lake Wapalanne and Lake Ocquitunk are two small lakes formed from dammed tributaries adjacent to Flat Brook. The area is within the Valley and Ridge physiographic province, and lies just two kilometers from the crest of Kittatinny Mountain, the first prominent ridge of the Appalachian front. Local elevation at the study site is around 260m AMSL, with relief not exceeding, 60m. Nearby Sunrise Mountain, on Kittatinny Mountain reaches 504m AMSL.

As part of the Ridge and Valley province, the underlying geology is of steeply folded lower Paleozoic sedimentary rocks (Drake et al., 1996). Kittatinny Mountain owes its relief to the resistant Shawangunk quartzite and quartz-pebble conglomerate. Eroded clasts from this formation are nearly ubiquitous in the Quaternary sediments. The Flat Brook valley itself (and study site) is underlain by Bloomsburg Red Beds, a softer sandstone and shale. No bedrock is exposed at the study area, however. Wisconsinan-aged glacial and pro-glacial sediments dominate the landscape, 8-15m thick (Witte and Epstein, 2005 and Witte, 2008). Fluvial processes redistribute these sediments in and near Big Flat Brook and its tributaries. Witte (2008) maps the Culvers Gap-Ogdensburg recessional moraine crest bordering the study area to the south and southwest. Sparse radiocarbon dating brackets the age of this recessional moraine between 20 years B.P and 18 years B.P (Witte, 1997).

The study area is covered by mixed hardwood forest, mostly oak (*Quercus* spp.), maple (*Acer* spp.), beech (*Fagus* spp.), and birch (*Betula* spp.). Eastern hemlock (*Tsuga canadensis*) is found in the cooler, shaded ravine valleys; pines have been planted in some areas as part of forestry projects. Boggy areas are common in Flat Brook's tributaries. All of the area is secondary growth forest; historic aerial photographs from the late 1920's indicate areas of cleared pasture and fields. Field stone fence lines throughout the area are evidence of this agricultural history. The area remains sparsely populated, and the primary economic activity revolves around recreation. The New Jersey School of Conservation is an original camp constructed by the Civilian Conservation Corp in the 1930s.

METHODS

Boulder beds were identified by reconnaissance survey of the area, on foot and by automobile. The extent of the boulder beds became more evident as the lack of vegetation in the autumn revealed the ground surface. Of eleven sites surveyed around the Lake Wapalanne area, ten are reported here on the basis of completeness and quality of the data. Sites were later grouped according to topographic similarity (refer to map on Figure 1): "Lakeside" included sites immediate to the present shoreline of Lake Wapalanne (sites 1, 3, 7); "Cabin Hill" included sites along the slope of the drumlin hill east of Lake Wapalanne (sites 5, 9, 10); "Molly Pitcher" included sites in the vicinity of the recreation area by that name along a shallow footslope, northeast of Lake Wapalanne (sites 2 and 4); and "Across Flatbrook" (sites 8a and 8b), on an elongate deposit on the terrace, ~300 m northwest of Flat Brook. Additional boulder beds were identified, but not surveyed, on the terrace escarpment northwest of Flat Brook, and northwest of Lake Ocquitunk adjacent to Skellinger Road.

Fifteen to 30 boulders with a minimum size of 40cm were selected for measurement at each site. From a central reference point (such as a notable tree), the first 15 or 30 boulders were selected at an increasing radius from the reference point. This type of survey typically encountered enough boulders within a 10m radius from the reference point. Boulders that were buried too deeply to be measured properly were excluded, as were boulders that were obviously split due to weathering.

The following data were recorded for each boulder: long axis length (x), intermediate axis length (y) (both taken with a meter stick or tape), orientation of the long axis in degrees azimuth (0-360°, taken by compass), lithologic description, boulder shape (based on a six-step ordinal classification similar to Blott and Pye (2008) and Powers (1953) and estimated percentage of lichen or moss coverage. General notes on weathering were made if relevant. Measuring methods, and the appearance of the boulders, is illustrated in Figure 2. Differences in grouped data were assessed using analysis of variance or the Kruskal-Wallis tests.

Separately, a second set of size measurements were made on 146 additional clasts in order to obtain an accurate representation of the size distribution for all particles pebble and larger (>4mm). This secondary survey provided data without the selective over-40cm boulder size bias present in the larger survey. A linear transect, similar to a Wolman (1954) pebble count, was followed at three representative locations: Lakeside, Molly Pitcher, and Cabin Hill. At each transect the first 50 clasts >4mm were measured along x, y, and z axes (four clasts at the Lakeside transect were omitted due to data errors). Using these data, a sorting index (SI) was calculated using the following formula (Prothero and Schwab, 1996):

$$SI = [(\Phi84 + \Phi16)/4] + [(\Phi95 - \Phi5)/6.6]$$

where Φ is the grain size in phi units ($\Phi = -\log_2 x$, x being the long dimension in millimeters), and Φ(number) notation represents the statistical percentile (Φ84 is 84^{th} percentile, Φ16 is the 16^{th} percentile, etc.). A sorting index <0.35Φ is considered "very well sorted", 0.35Φ to 0.50Φ is "well sorted", 0.50Φ to 0.71Φ is "moderately well sorted", 0.71Φ to 1.00Φ is "moderately sorted", 1.00Φ to 2.00Φ is "poorly sorted", and >2.00Φ is "very poorly sorted" (Prothero and Schwab, 1996).

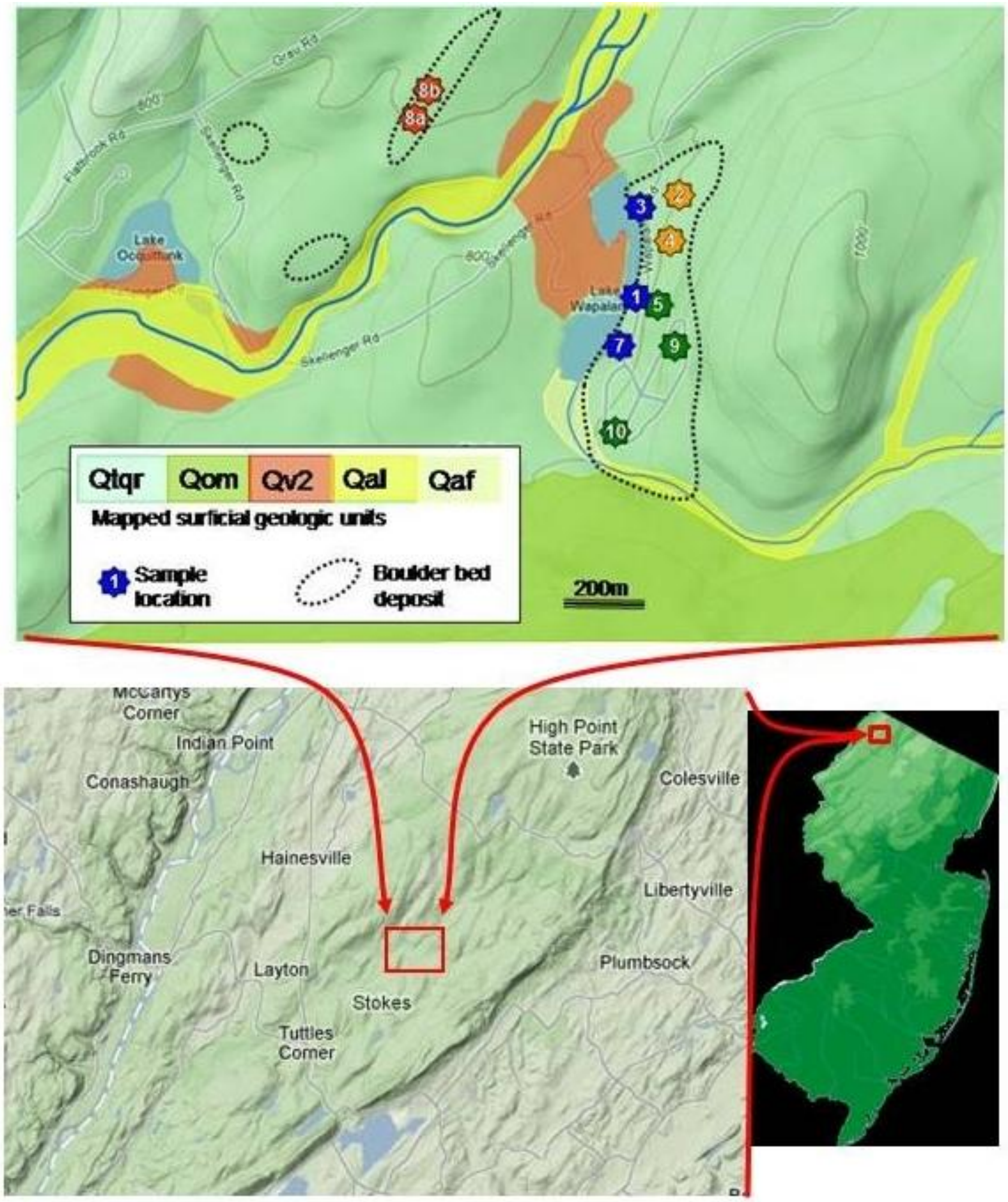

Figure 1. Study location in Stokes State Forest, northwest New Jersey. Geomorphic units mapped as follows: Qtqr = till (ground moraine), Qom=Ogdensburg/Culvers Gap recessional moraine; Qv2 = valley train deposits, Qal = alluvium, Qaf = alluvial fan. The hill just east of Lake Wapalanne is one of several oriented drumlins in the area. Base map from Google Maps.

Figure 2. Close up of the boulder bed, and an example of the measurement procedure. Two clear fabric orientations are apparent in this site within the "Lakeside" group (site 1). Figure 2b. Though partially covered in leaves, soil, and moss, the density of interlocking boulders is apparent here at the "Across Flatbrook" site (8a).

Two additional locations were included in the study for comparison to the boulder beds. At Big Flat Brook, Wolman pebble counts were taken at five locations within the study area in order to assess fluvial particle sizes. Lithology of measured Flat Brook stream pebbles was also noted. At Culvers Gap, 6.5km to the southwest of the study area, the lithologies of representative clasts within the Culver Lake-Ogdensburg recessional moraine were recorded.

Numerous soil pits (~1m x 1m in area and ~0.5-1.5m in depth to the C horizon) have been excavated at the New Jersey School of Conservation since 1998 as part of ongoing field exercises for courses in soil science and geomorphology at Montclair State University. Where reasonably dependable descriptions exist, data from these field exercises are referenced in order to arrive at near-surface soil and sediment characterizations.

RESULTS

Boulder Bed Lithology and Particle Size

The composition of the boulder beds was overwhelmingly represented by Shawangunk quartzite and conglomerate (Table 1). This is interesting because the bedrock immediately below the study area is Bloomsburg sandstone and shale. There is no obvious downslope influx of Shawangunk colluvium or talus from the nearby Kittatinny Mountain, as a small hill, mapped (Witte, 2008) as a drumlin and probably bedrock cored, lies between the study area and Kittatinny Mountain. The drumlin feature blocks the direct downslope contribution of colluvium from Kittatinny Mountain. The boulders must therefore have come from locations up Flat Brook valley, brought in by fluvial or glacial transport (discussed later).

Table 1. Lithology of Boulders Counted at the Study Area

Rock type	Number of boulders
Quartz pebble conglomerate (Shawangunk)	209
Quartzite (Shawangunk)	43
Red conglomerate (Bloomsburg?)	6
Brown sandstone (Bloomsburg?)	5
Red sandstone (Bloomsburg?)	4
Gray sandstone	1
Slate	1

The composition of the boulder beds is similar to that of the larger sediments in the active Flat Brook channel, but differs from that of the nearby Culver Gap Moraine. In Flat Brook, particles larger than 20cm are overwhelmingly (>90%) Shawangunk conglomerate and quartzite. A pebble count of smaller cobbles on two gravel bars yielded a somewhat more varied lithology, and more dominantly Bloomsburg sandstones. It is possible that the softer Bloomsburg sandstones do not survive long as large particles in the stream or glacial geomorphic system; thus, large Bloomsburg sandstone boulders are rare, though small cobbles and pebbles common. At the Culver Gap recessional moraine (6.5 km to the southwest), lithologies are more mixed, but the red and brown sandstones of the Bloomsburg formation (40%) slightly outnumber the conglomerates of the Shawangunk (33%).

The subset of measurements used to assess the total particle size for the boulder beds (all particles pebble size and larger) indicate a relatively uniform range of sizes. One-way analysis of variance verified no statistically significant difference in particle sizes between the three sample sites ($F = 0.92$, $p = 0.401$, $N = 146$). Visually, the boulder beds looked reasonably sorted, and the sorting index bears this out (table 2). Sorting index values for samples taken ranged from 0.701-0.782, within the range of “moderately well sorted” to “moderately sorted” (Prothero and Schwab, 1996).

Table 2. Descriptive Statistics for All Pebble-and-larger Clasts (>4mm long axis) at Three Locations Representative of the Sample Sites

Site	N	Mean long axis (cm)	Median long axis (cm)	Maximum (cm)	Minimum (cm)	sorting index
Molly Pitcher	50	31.90	26.5	103	9	0.779
Lakeside	46	30.72	28.5	71	10	0.701
Cabin Hill	50	36.62	31.5	116	10	0.782

Boulder Bed Morphology

The boulder bed seems to appear on one elevated terrace above Big Flat Brook, approximately 20 meters above the flood plain. The boulder bed is found on either side of Big Flat Brook, but is discontinuous (Figure 1). The shape of the deposits is roughly oriented along the strike of the valley, northeast to southwest. The largest extent recognized thus far is draped along the northwest footslope of a drumlin hill and along a platform that parallels the eastern shore of Lake Wapalanne. This lake was built in the 1930s, so the shoreline association is coincidental. Some boulders probably extend into the lake's eastern shallows, though still on a terrace above Wapalanne Brook dammed to form the lake (Kile, 1968). The opposing western shore line of the lake is a different geomorphic deposit, composed of faintly stratified and occasionally imbricated gravels and cobbles evident in soil profiles (from a soil surveys conducted in Spring 2009). This western shore deposit is contiguous with the high terrace above Flat Brook (Figure 1), and mapped as a fluvial valley train deposit (Witte, 2008).

The shape of the boulders ranges from angular to rounded, though 61% of all boulders assessed for shape (N = 184) fall within the subrounded category. There is some variation in the boulder shape between locations, but not statistically significant based on the Kruskal-Wallis test (χ^2=4.80, p = 0.440) (Figure 3). Boulders along the drumlin hill to the east of Lake Wapalanne (Cabin 7 and Cabin 10 sites) appear to have the least variation in shape, with more than average in the rounded category. The Molly Pitcher site had very large variation in shapes. Many of the angular boulders are so because of post-depositional physical weathering. Post-depositional weathering is obvious from the angular fractures and edges when compared to the morphology of the boulder, and boulders split into two or more segments are common. Ice shattering is probable in the post-glacial periglacial environment and continues even today. Root growth also exerts mechanical pressures on the rocks in some instances.

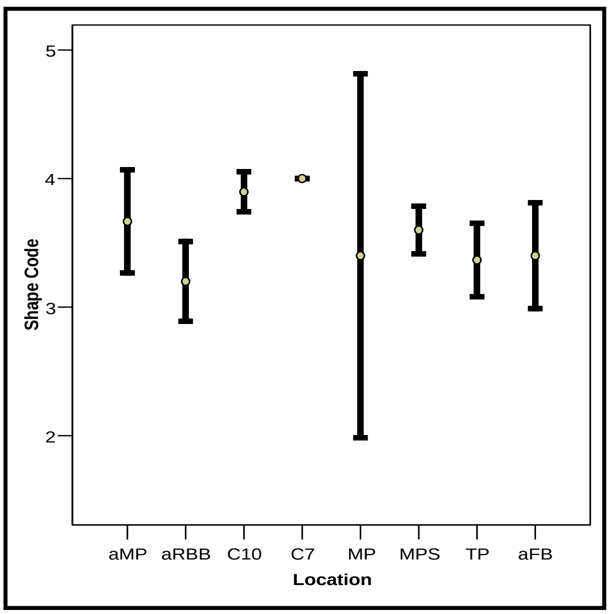

Figure 3. Boulder roundness ranges across sample locations. Roundness scale (shape code): 2=angular, 3=subangular, 4=subrounded, 5=rounded; bars represent the 95% confidence interval surrounding the mean value. Site locations abbreviated (site number in parentheses): aMP = across Molly Pitcher (3), MP= Molly Pitcher (2), MPS = Molly Pitcher South (4), aRBB = across Rainbow Bridge (5), TP = Trading Post (7), C10=Cabin 10 (10), C7 = Cabin 7 (9), aFB = across Flat Brook (8).

All boulders exhibit chemical weathering as well, in the form of pitting, staining, and minor surface disaggregation. The abundant lichen and moss covering as well as mulch and humus in the forest account for an aggressive chemical weathering environment. Such weathering would tend to obliterate features such as striations that would suggest transport environments. Even so, most boulders are solid and intact, owing to the durable silica matrix and quartz clastics.

Most boulders appear to be stable, only a few boulders on steeper slopes are wobbly. Clasts in the boulder bed are partially buried in soil or resting just above the soil surface atop lower boulders. Several soil profile pits excavated in the area above Molly Pitcher indicate that the boulder deposit is a surface feature, resting on a cobbley-gravelly soil. Similarly, large boulders are concentrated at the surface at a cross section exposed by the eroding northern escarpment of Flat Brook ravine, where it intersects a boulder bed outcrop. There is a need for more soil profile data at other locations to ascertain whether the boulder bed is similarly limited to the surface. In all locations, boulders are closely spaced, in contact with one another or with small areas of soil separating the boulders (Figure 2). Where the boulder bed exists, it effectively armors the surface.

The population of boulders surveyed indicates orientation fabrics in the boulder beds. The polar plot of percent frequency for the entire data set, n=210 (Figure 4), indicates a slightly higher frequency of boulders oriented E-W (18% of all boulders) and NE-SW(16% of all boulders); the lowest frequency of orientation was in the S and SE to N and NW. An analysis of variance test indicate marginally significant differences in boulder orientation between sample sites (F=2.01, p=0.067). Separating the frequency plots by location confirms these differences and reveals stronger fabric relationships dependent on site (Figure 4). Sample locations were grouped by similar topography: "Lakeside" included three sites immediately adjacent to Lake Wapalanne (the edge of the former stream terrace); "Molly Pitcher" included two sites in the slightly upland but gradually sloped area northeast of the lake; "Cabin Hill" included three sites along the relatively steep drumlin hill slope southeast of Lake Wapalanne; and "Across Flatbrook" had two sites on the broad, flat terrace northwest of Flat Brook and Lake Wapalanne. Polar frequency plots (Figure 4) reflect these groupings. "Lakeside" boulders show a pronounced east-west orientation (26%). "Molly Pitcher" boulders are dominantly oriented NE-SW (15%). "Cabin Hill" has tri-modal orientation to the N-S (10%), E-W (9%), and SE-NW (9%). "Across Flatbrook" is also trimodal, but the SSE-NNW orientations dominate (12%) over the secondary E to ENE-W to WSW (7% and 8% respectively) and NNE-SSW (7%) orientations.

DISCUSSION

Several geomorphic scenarios explain the formation of the boulder bed, though none are perfect, and it is likely that more than one process is possible. These hypotheses are detailed here.

Periglacial Colluvium

Boulder fields are recognized in this region, the best known being the Hickory Run boulder field in Carbon County, Pennsylvania. Sevon (1987) hypothesizes that boulders at Hickory Run are split from bedrock outcrops by weathering, and then slowly moved down very gradual slopes (1°) with the aid of ice, water, and sand. White (1972) describes comparable processes in a mountainous environment in Colorado. Slow down-slope movement imparts a fabric orientation of oblong boulders in a down gradient direction, and grinds sharp edges into subrounded shapes. Similar processes may be taking place at the Upper Flat Brook boulder beds. The boulder source differs: there is no direct bedrock source in Upper Flat Brook, the material may derive instead from glacial material, such as lateral moraines (mentioned above). The Hickory Run boulder field is expansive, nearly 6 ha. While the boulder beds at Upper Flat Brook are presently discontinuous, they may have been one large, continuous feature prior to the incision of Flat Brook and its tributaries.

As in Hickory Run, fabric orientations at Upper Flat Brook tend to orient with the slope: the Lakeside sites (east:west down-slope of the drumlin hill), Across Flatbrook (northwest:southeast down a very gradual gradient), and Cabin Hill (a secondary east:west orientation, down-slope). Fabric at Molly Pitcher appears to be perpendicular to the slope, but does strongly parallel a small drainage immediately to the northwest. In addition to the flow fabric, Hickory Run exhibits an organized surface morphology (pits, rings, and mounds) attributed to periglacial sorting (Sevon, 1987). Subtle surface undulations seen in the boulder beds at Upper Flat Brook are difficult to assess, and may be the result of tree throw or simple erosion as well as periglacial action. Nevertheless, there are several suspected sorted rings (particularly at Molly Pitcher and Across Flatbook), with fine material devoid of boulders surrounded by a perimeter of boulders, sometimes turned vertically on edge. Careful microtopographic survey may reveal additional organization in future studies.

Witte and Epstein (2005: 17) note the existence of boulder fields in the Culver Gap quadrangle, in areas of low relief at slope bases. These are not mapped per se, but are considered part of talus, meltwater lag deposits, or glacier-concentrated boulder till.

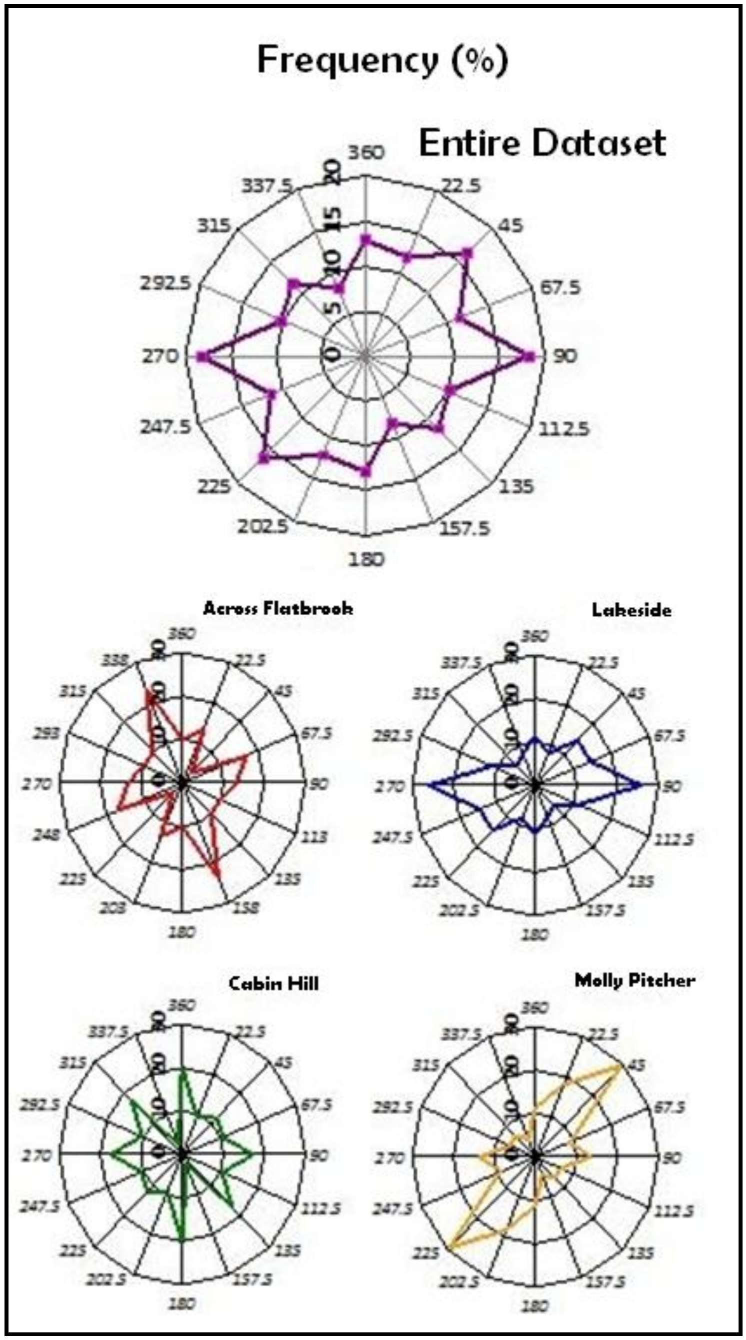

Figure 4. Polar plots (0-360° azimuth) showing percent frequency along 16 subordinal sectors (North = 360°, North-northeast = 22.5°, Northeast = 45°, etc.); each subordinal coordinate represents the centroid of a sector 22.5° wide. Percent frequency, indicated along the radial axes (and labeled along the 360° axis), is for the percent of the total number of boulders oriented within a given sector.

Till

Witte's (2008) description of the Qkmq till deposit in the Branchville quad, "…unstratified, poorly sorted…silty sand and sand containing 10-20 percent gravel", matches the material found below the boulder bed. While it does not mention boulder beds, large boulders would be typical within the till, as evidenced throughout northern New Jersey. Witte and Epstein (2005: 6) further describe the same unit in the Culvers Gap quad as containing "subangular to subrounded, faceted, and striated [clasts]" with "a preferred long axis orientation that generally parallels the regional direction of glacier flow". Witte and Epstein presume this oriented till to be subglacial lodgement till.

The shape and fabric orientation described by Witte and Epstein (2005) match the boulders in the boulder bed deposits. Lodgement till tends to congregate in the subrounded to subangular shape, more so than any other type of supra-, en-, or subglacial till (Hambrey, 1994); this corresponds with our observations. As for fabric, the north:south orientation apparent in the in the fabric at the Cabin Hill locations coincides with the glacial flow during the terminal Wisconsinan glacial maximum, in which the larger ice mass over-ran the local topography. The northeast:southwest orientation seen at Molly Pitcher, as well as secondary orientations at Lakeside and Across Flatbrook locations, are all congruent with the glacier flow during the later, recessional deglaciation, where the regional valley and ridge structure enforced more control on glacier flow (Witte, 1997). Drumlins in the vicinity are also oriented in this direction. Subglacial lodgement till could have been reworked into the new glacial flow, except where sheltered by topography, which may explain the persistence of north:south orientation at the Cabin Hill locations.

The uniform lithology in the boulder bed material contradicts the homogeneity normally expected with till (evident at Culvers Gap, for instance). However, lateral moraines, owing to their local influx of valley-side mass wasting material, would exhibit a strong dominance of one lithology. Lateral moraines are also dominant in coarse material, lacking fines (Hambrey, 1994), also similar to the boulder beds. The boulder beds overlie Bloomsburg sandstones and are separated from Kittatinny Mountain by small intervening ridges and drumlins, but slope-sourced Shawangunk conglomerate could have been entrained into lateral and medial moraines up valley. Two points contradict a lateral moraine origin, however. First, lateral moraines tend to contain angular to very angular clasts with highly variable sphericity (Hambrey, 1994), owing to the local mass wasting influx. All sample sites apart from Molly Pitcher were narrowly defined as subrounded to subangular in shape. This study did not detect any change in boulder shape, size, or lithology in a valley side to valley center direction, as might be expected with supraglacial material. Second, lateral moraines would be prominent and thick, as opposed to the boulder beds which seem to be shallow and limited to the surface. It is possible, however, that the boulder beds represent a subglacial lodgement of former lateral moraine material.

Glaciofluvial Deposit

Flowing water is responsible for sorting and fabric orientation of sediments. It is likely that fluvial regimes in Upper Flat Brook were considerably larger than present during deglaciation; proglacial and subglacial fluvial processes should be considered in interpreting the boulder beds.

Meltwater is sometimes responsible for removing fines from lodgement or other subglacial till (Hambrey 1994), resulting in "boulder pavement" lag deposits. White (1972) and Hara and Thorn (1982) suggest a comparable process, but under persistent snowbanks rather than glaciers. Both cases recognize preferred orientation due to the flow. Witte and Epstein (2005: 15) note that "valley floors are typically covered by a lag of boulders and cobbles chiefly derived from meltwater-washed till", along the slopes and steep valleys of Kittatinny Mountain. This description resembles the boulder beds covered in this study. Meltwater may have been proglacial or subglacial. Like the present large clasts in Flat Brook, Shawangunk conglomerate/quartzite could have dominated the meltwater paleochannel.

Rounding and sorting of the boulders suggests possible large scale and turbulent fluvial transport processes, as opposed to the more *in situ* processes of lag deposits which would have little subsequent effect on rounding and size segregation (apart from winnowing away fines). Russel (2009) and Marren et al. (2009) describe proglacial outwash plains in which boulder-sized sediment bars and beds derive from large glacial outburst floods, or *jökulhlaups*, These authors describe hyperconcentrated flows (similar to debris flows) and extreme turbulent fluid flows capable of transporting and "floating" large particles to the surface. Sedimentary profiles from Iceland and Greenland illustrate large clasts (>1m) supported above finer material and oriented to flow. There is a general valley-parallel orientation in the clast fabric, but local variations due to braiding and turbulent flow and non-Newtonian debris flow may impart different orientations.

There is resemblance to the Upper Flat Brook deposits from a superficial view. While further studies would be needed for a more complete vertical stratigraphic profile at numerous locations in upper Flat Brook, the glacial flood origin for boulder beds is intriguing. Multiple fabric orientations suggest braiding in a stream channel, while the sorting, bedding, and clast size suggest transport and deposition by high-volume flow. Deposits found on the footslope of the drumlin hill are difficult to rationalize, however. The existing mapped geomorphology is consistent with the possibility of glacier meltwater floods. Valley train glaciofluvial deposits are already recognized in Flat

Brook valley (Witte and Epstein 2005, Witte 2008), including the Lake Wapalanne area. These include coarse material (pebbles and cobbles), described as well to moderately sorted. Boulder beds are sorted, but less so, perhaps evidence of more chaotic flow. Deep ravines are evident in several locations at Upper Flat Brook, suggesting episodes of rapid incision during a flood, far in extreme of the present fluvial regime. Ravines and valley train deposits lie downstream from a known recessional glacier terminus. Finally, the nature of middle latitude recessional glaciers would be conducive toward production of considerable meltwater, which could have been constant and occasionally episodic.

In all scenarios, the age of the boulder beds is probably no older than the Ogdensburg/Culver Gap ice margin, and if the proglacial fluvial origin is valid, possibly contemporary with the Augusta-Montague ice marginal position (a few kilometers northeast of the study area). Witte (1997) constrains these recessional events to between 19,300 and 17,500 years B.P. The possibility of a periglacial origin brings the age later still, as long as cold climate conditions prevailed.

CONCLUSIONS

The Upper Flat Brook boulder beds are a discontinuous, surface-armoring deposit found primarily on the upper terrace of Flat Brook. They are composed of moderately sorted, dominantly subrounded clasts of mostly Shawangunk conglomerate and quartzite, with a median long-axis dimension of ~30 cm. The beds show fabric orientations dependent on location. Each location has a primary or at least secondary orientation approximately northeast:southwest, parallel to the valley, though other orientations (east:west, north-northwest:south-southeast, north:south) are evident as well. Down-slope movement may account for re-orientation of previously deposited boulders, accounting for the fabric variation.

Three process scenarios could explain the origin of the boulder beds. 1) Post-glacial frost and permafrost action, including colluvial creep and organization, could explain the sorting of large clasts and orienting them gradually parallel to slope creep, explaining the local variations in fabric, similar to other boulder fields in the region. Periglacial mechanisms do not easily explain the source of the dominant rock type (Shawangunk conglomerate and quartzite), in that the source rock is not adjacent to the study area. 2) Direct glacial deposition, as some form of till, accounts for fabric orientations parallel to known glacial flow directions. Subglacial lodgement till tends to be subrounded, as the boulder bed stones trend toward, and meltwater winnowing of finer sediments gives the impression of sorting. The dominant lithology can be explained by nearby slope contribution to lateral moraines. The glacial deposition theory does not explain the local variation in fabric departing from the larger north-south to northeast-southwest trend. No glacial marks (striations or other physical damage) were noted on the well weathered boulders. 3) A glaciofluvial deposition accounts for sorting and rounding. Large scale meltwater events could be responsible for transporting the boulders and, with turbulent and hyperconcentrated flows, permit a matrix-supported deposit at the surface. Variations in fabric orientation may be due to stream braiding and small scale turbulence. Conclusive support for a glaciofluvial origin requires study of a detailed stratigraphic profile for the area. Glaciofluvial deposition does not easily explain the existence of deposits on the sides of hills. Finally, it is possible that the boulder beds are the result of multiple processes, and all three scenarios are partially valid. Originally deposited and presorted as subglacial lodgement till could have been reworked by proglacial meltwater. During and immediately after deglaciation, permafrost and periglacial slope processes further altered the boulder bed, imparting site-specific fabric orientation.

This study accomplishes an initial quantification of the nature of the boulders beds as a sedimentary and geomorphic feature, and therefore sheds light on a subtle but unusual feature in the landscape. The study has a geographic limit to the Lake Wapalanne and Lake Ocquitunk vicinity; further field studies may reveal more extensive deposits (which will need to be differentiated from known fluvial, glacial, and periglacial features). One goal will be to establish a stratigraphic profile, perhaps exposed on the stream terrace escarpment or by road cut, which will reveal a more definite temporal sequence of geomorphic events. It is hoped that future studies will add to the story of environmental change in the Upper Flat Brook valley.

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REFERENCES

Blott, S.J. and Pye, K., 2008. Particle shape: a review and new methods of characterization and classification. *Sedimentology* 55: 31-63.

Drake, A.A., Volkert, R.A., Monteverde, D.H., Herman, G.C., Houghton, H.F., Parker, R A., and Dalton, R.F., 1996. Bedrock Geological Map of Northern New Jersey. Trenton, NJ: New Jersey Geological Survey (1:100,000).

Hambrey M. J., 1994. *Glacial Environments.* Vancouver. British Columbia: UBC Press.

Hara, Y., and Thorn, C. E., 1982. Preliminary quantitative study of alpine subnival boulder pavements, Colorado Front Range, USA. *Arctic and Alpine Research* 14(4): 361-367.

Kile, D.P., 1968. Mapping of Lake Wapalanne at the New Jersey School of Conservation, Branchville, New Jersey. Unpublished report and map, on file with New Jersey School of Conservation, Montclair State University.

Marren, P.M., Russel, A.J., and Rushmer, L.E., 2009. Sedimentology of a sandur formed by multiple jökulhlaups, Kverkfjöll, Iceland. *Sedimentary Geology* 213: 77-88.

Powers, M.C., 1953. A new roundness scale for sedimentary particles. *Journal of Sedimentary Petrology* 51: 611-624.

Prothero, D.R., and Schwab, F., 1996. *Sedimentary Geology: An Introduction to Sedimentary Rocks and Stratigraphy*. New York: W.H. Freeman.

Russel, A.J., 2009. Jökulhlaup (ice-dammed lake outburst flood) impact within a valley-confined sandur subject to backwater conditions, Kangerlussuaq, West Greenland. *Sedimentary Geology*, 215: 33-49.

Sevon, W.D., 1987. The Hickory Run boulder field, a periglacial relict, Carbon County, Pennsylvania. In *Geological Society of America Centennial Field Guide – Northeast Section*, ed. D.C. Roy, pp. 75-76. Boulder: Geological Society of America.

White, S.E., 1972. Alpine subnival boulder pavements in Colorado Front Range. *Geological Society of America Bulletin* 83(1): 195-200.

Witte, R.W., 1997. Late Wisconsinan glacial history of the upper part of the Kittatinny Valley, Sussex and Warren Counties, New Jersey. *Northeastern Geology and Environmental Sciences* 19(3): 155-169.

Witte, R.W., 2008. *Surficial Geology of the Branchville Quadrangle, Sussex County, New Jersey.* Geologic Map Series GMS 08-2. Trenton, NJ: New Jersey Geological Survey (1:24,000).

Witte, R.W., and Epstein, J., 2005. *Surficial Geology of the Culvers Gap Quadrangle, Sussex County, New Jersey.* Geologic Map Series GMS 04-1. Trenton, NJ: New Jersey Geological Survey (1:24,000).

Wolman, M.G., 1954. A method of sampling coarse river-bed material. *Transactions, American Geophysical Union* 35(6): 951-956.