Spring 1997

Elevation as a Control of Boulder Stream Formation in the Blue Ridge Province of Virginia

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ELEVATION AS A CONTROL OF BOULDER STREAM FORMATION IN THE BLUE RIDGE PROVINCE OF VIRGINIA

by

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B.S. December, 1992, Bloomsburg University

A Thesis submitted to the Faculty of
Old Dominion University in Partial
Fulfillment of the Requirements
for the Degree of

Master of Science

GEOLOGY

OLD DOMINION UNIVERSITY
May, 1997

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ABSTRACT

Within four study areas in the Blue Ridge Mountains of Virginia, boulder streams formed by periglacial processes carpet the bottoms of most high-altitude first-order valleys. The geomorphic indicators of periglacial formation in these long, linear accumulations of bouldery colluvium - the presence of vertical clasts, gradational upper contacts with talus deposits, confinement within valleys, and hump-like cross sectional profiles - were present in all areas mapped and in most individual boulder streams. The minimum critical elevation for boulder stream formation increases from north to south across Virginia, from 150 m in elevation in northern Virginia to 1500 m in southwestern Virginia. Thus, as predicted by the periglacial hypothesis, boulder streams should be expected in many small high-altitude valleys above the elevation critical for boulder stream formation.

The presence of near vertical clasts found in all boulder streams mapped implies that this characteristic is useful in differentiating periglacial boulder streams from other colluvial debris. Statistical analysis on the distribution of the near vertical clasts suggests these features are randomly dispersed within the boulder stream. Rose diagrams reveal a large number of the near vertical clasts oriented subparallel, and a lesser number perpendicular, to the main axis of the boulder stream. Differential flow velocities within the boulder stream could produce these preferred orientations.

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ACKNOWLEDGMENTS

I would like to express my appreciation to several people who helped me accomplish this work. I would like to thank Dr. Whittecar for assisting in this research and his endless guidance. I would also like to thank Dr. John Leftwich and Dr. Dennis Darby for their review of this paper and their suggestions. Thanks also go to Cliff Nelson for his help in the field.

My endless gratitude also goes out to my parents, Walter and Jane. Without their love, support, and encouragement, none of this would have been possible.

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INTRODUCTION

Throughout the southern and central Appalachian mountains, surficial features exist that formed due to frost action more intense and longer lasting than produced by present conditions. Talus slopes, boulder streams, solifluction lobes, cryoplanation terraces, patterned ground, and other periglacial landforms have been reported from sites peripheral to the margins of Pleistocene ice sheets and at high altitudes (e.g., Flint, 1971; Pewe, 1983; Clark and Ciolkosz, 1988). Geomorphic studies in modern periglacial settings suggest that these landforms result from frost cracking, frost heave, frost sorting, and related processes (e.g., Washburn, 1980; Williams and Smith, 1989).

Paleontologic evidence also strongly suggests that periglacial conditions existed during much of the Pleistocene in the southern Appalachians, especially along the highest altitudes of the Blue Ridge and Appalachian Plateau. Delcourt and Delcourt (1981) discuss palynological data which support the presence of periglacial conditions in the central and southern Appalachians during the time of glacial advances. Fossil remains of Pleistocene mammals and birds in North America have also suggested the presence of a tundra - like environment in the Appalachians (Flint, 1971). Other studies on Pleistocene mammals and birds by Eschelman and Grady (1986) and Holman (1986) also support the conclusion that tundra - like conditions existed over much of the Appalachians of Virginia. Boulder streams (block streams) have been documented in many high altitude valleys throughout the Appalachians (e.g., Smith and Smith, 1945; Michalek, 1968;

The journal used as a model for this paper was Geology.

Sevon, 1987; Mills, 1988; Shafer, 1988). Interpretations of boulder stream processes are based on data, mostly from Pennsylvania and North Carolina, which suggest that boulder streams are periglacial landforms and that in the mountains of Virginia, they should be present in most, if not all, high elevation valleys immediately downhill of talus slopes (Fig. 1). In addition, previous studies suggest that, due to increasing severity of frost action towards the Pleistocene ice margin, the lowest elevation where periglacial landforms may develop in a given area should increase towards the south (Fig. 2). For these studies,elevation is used as a proxy for paleotemperatures averaged over many periglacial events during the Pleistocene. Thus, we would expect to see the elevation at which boulder streams form (in the heads of first order valleys) to increase to the south. This study tests these two hypotheses.

Previous studies on active and relict boulder streams suggest that the recognition of near vertical clasts (i.e., tabular boulders aligned with the A - B plane in a vertical position) and analysis of their spatial distribution can aid in evaluating the origin and evolution of boulder streams. However, as the following literature review demonstrates, many aspects of the spatial distribution and fabrics of boulder streams in the central and southern Appalachians have not been addressed.

In addition to the formative considerations of boulder streams and their distribution on slopes, this study will also examine the fabric of the clasts that compose the boulder streams, particularly near vertical clasts that have been observed within the streams. A detailed analysis will be made at each site regarding one boulder stream and the presence and distribution of near vertical clasts within it. This analysis will suggest

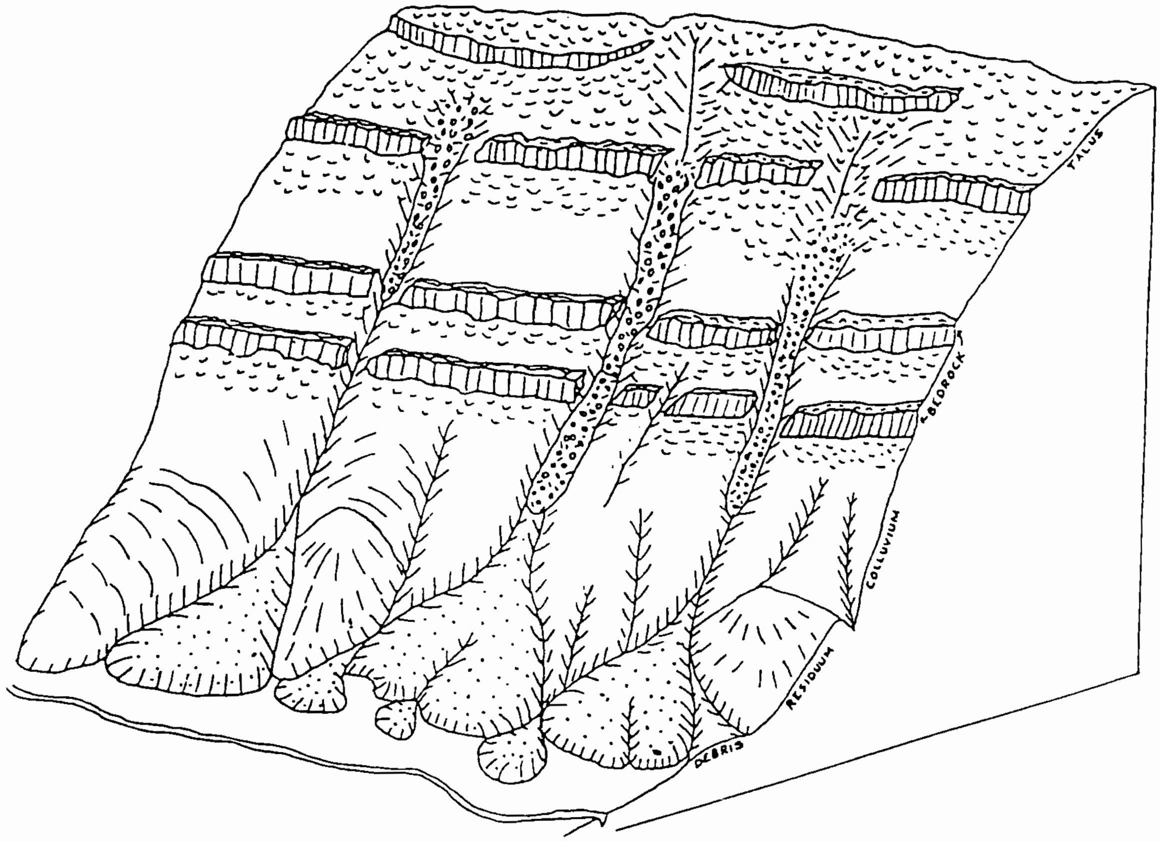


Figure 1 Sketch showing the hillslope features for a site in the Blue Ridge mountains of central Viriginia. Note the gradation of periglacial boulder streams into talus at their upper ends (Whittecar and Ryter, 1992).

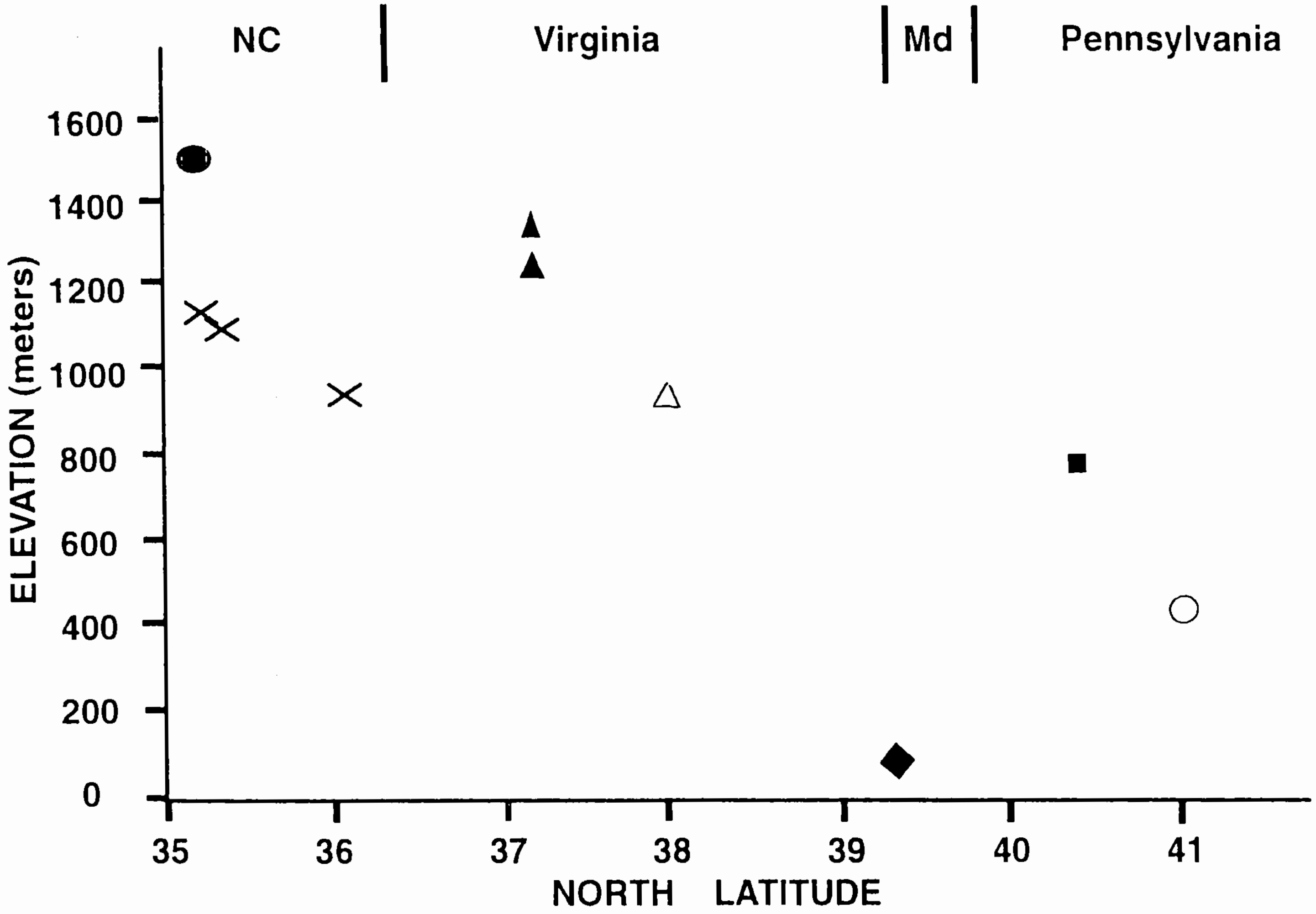


Figure 2 Latitude and approximate elevation of boulder streams previously documented in the Appalachians. Open circle=Sevon(1987); closed square=Potter and Moss(1968); closed diamond=Clark(1992); open triangle=Ryter(1989); closed triangle=Mills(1988); closed circle=Shafer(1988); X=Michalek(1968).

either that near vertical clasts are common (and perhaps expected) in periglacial boulder streams and may be regarded as a significant characteristic for such features, or that the presence of near vertical clasts is random among surface deposits.

Although not specifically designed for an in-depth study of aspect (hillslope orientation), this report will examine if aspect has any significant control on boulder stream formation. Aspect, along with other environmental factors, may provide information into the formation of boulder streams and their distribution.

PREVIOUS STUDIES

A boulder stream is defined as an accumulation of boulders or angular blocks with no fines in the upper part (Bates and Jackson, 1987). Although some have very low slope angles (e.g., Smith and Smith, 1945; Sevon, 1987), most boulder streams form in steep mountainous valleys. These features are commonly 30 m to 1000 m in length and 10 m to 300 m in width (Clark and Ciolkosz, 1988; Whittecar and Ryter, 1992). The clasts are often tabular, range in size from 0.3 m to 15 m in diameter, and are tightly wedged together (Clark and Ciolkosz, 1988). Boulder streams rarely contain sand or pebbles in their upper parts but often have such fine material between the boulders at depth (White, 1976; Mills, 1988).

Several periglacial mechanisms are thought to have formed boulder streams in the Appalachians during the Pleistocene, principally frost wedging, gelifluction, frost heaving, and related freeze-thaw processes (Smith and Smith, 1945; Flint, 1957; Washburn, 1973; White, 1976). Boulder streams form from talus slopes derived at outcrops of source rock immediately upslope from the stream (Fig. 1). Water that infiltrates cracks in the parent rock will expand upon freezing and enlarge the crack. Angular clasts that subsequently break from an exposed cliff may roll downhill and accumulate as talus. This shattering mechanism, known as frost wedging, is believed to be the major cause for the growth of coarse detritus on the hillslope (Washburn, 1973; White, 1976).

The subsequent movement of the angular blocks further downslope has been frequently attributed to processes of solifluction. Solifluction is the slow downslope movement of water - saturated sediment under the influence of gravity (Andersson, 1906). It can occur in many settings, including those devoid of permafrost, but it is most commonly seen in arctic and sub - arctic environments (Williams and Smith, 1989). Saturation is necessary because water not only decreases the cohesion of the material but also adds additional weight that increases shear stress (Embleton and King, 1975). Saturation of the soil occurs commonly in periglacial regions where the downward percolation of rain or meltwater ceases due to an impermeable permafrost layer at depth (Washburn, 1973).

Gelifluction is solifluction associated with ground that is frozen seasonally or permanently (Washburn, 1980). Large amounts of slope debris move downhill due to the combined effects of gelifluction and frost heave. Frost heave is the process by which the growth of ice crystals causes the upward movement of overlying debris (Williams and Smith, 1989). Gelifluction occurs when, on some slopes, thawing causes the ice to melt and the material that was raised settles further downslope from its original position (Washburn, 1973) (Fig. 3).

In boulder streams, solifluction processes are believed to take place near the bottom where the pores between matrix particles could retain water. Very large pores higher in the deposit would drain and would not freeze. The boulder stream surface could be "rafted" downhill by the heaving and thawing caused by freezing in the finer-grained matrix at the bottom of the deposit (French, 1976). In most circumstances, the amount of movement due to solifluction decreases with depth. This differential motion is believed to

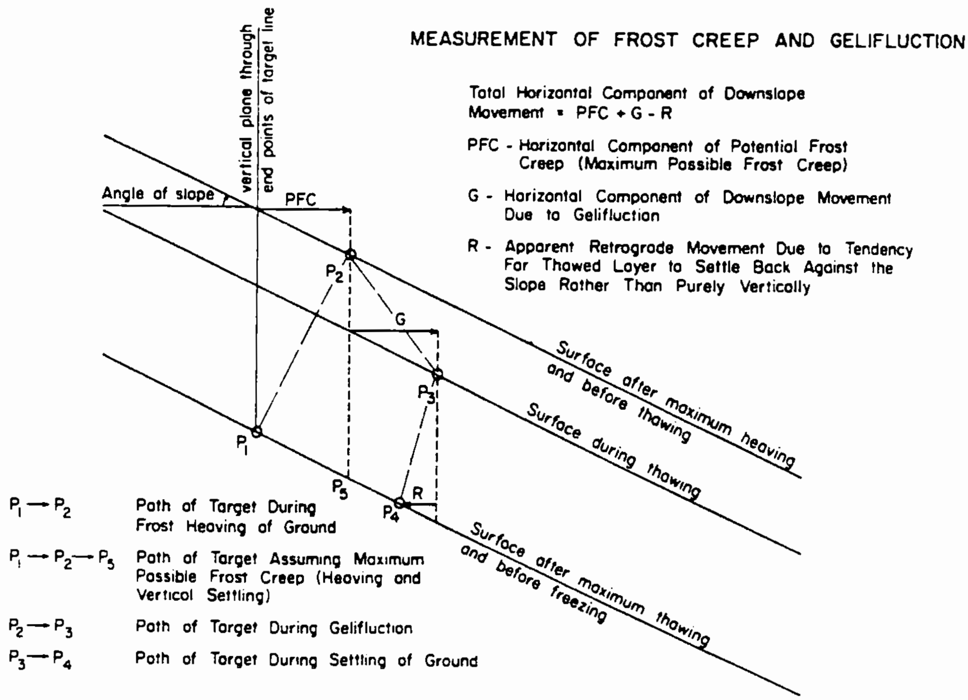


Figure 3 Diagram illustrating the movement of a particle downslope by the process of frost creep and gelifluction (from Washburn, 1973).

cause tabular oriented boulders to become parallel to the hillslope (Embleton and King, 1975).

Although many boulder streams are believed to be formed under periglacial conditions, bouldery deposits form on hillslopes by other means. Mills (1988) contended that coarse valley bottom colluvium could form by simple gravity processes, by debris flows, and by periglacial processes. He studied boulder streams formed under different situations and analyzed certain criteria for each type. Bouldery deposits formed by simple gravity processes (e.g. rolling) were observed as being found at the base of generally steep slopes (>35°) and had loosely packed clasts with low slope stability. Boulder streams forming under debris flow activity had weak fabrics, lay relatively far from ridge crests, and sometimes had fine material in the interstices of the upper boulder layer. Aside from the presence of steeply dipping clasts, boulder streams formed under periglacial conditions were also noted as having intermediate stability, weak to moderately strong fabric strength, and deposition on moderately steep slopes (10° to 30°).

Washburn (1973) noted the presence of steeply dipping and sometimes vertical clasts on boulder streams in North America and Europe. He concluded that the only reasonable explanation for such an orientation is the process of frost heaving. The same conclusion for the presence of vertical clasts in boulder streams was reported by Flint (1971) and Ryter (1989). Frost heaving is believed to occur when freezing of a soil occurs around stones. The heaving pressure originates from the expansion of the soil due to the development of ice lenses within the soil (Williams and Smith, 1989). Since stones have a greater heat conductivity, they are not as susceptible to freezing as other soil constituents. The freezing of the soil pushes the stones upward and a small gap is left behind where the stone once lay. This gap is subsequently filled in by sediment in the soil and the stone is no longer capable of returning to its original position (Fig. 4) (Washburn, 1973).

The exact mechanism by which the tabular boulders are tilted to a near vertical position is not clearly understood. One theory suggests that there are differential frost heaving pressures at either ends of the blocks. For example, as the ground freezes from the surface downward, the freezing front holds onto the side of the boulder closest to the surface. This side of the stone is then subjected to frost heaving pressures while the opposite side is not. A pressure differential then exists between both sides of the block and a rotational movement is applied. This results in the tilting of the block to a vertical orientation (Fig. 5) (French, 1976). Smith and Smith (1945), Potter and Moss (1968), Sevon (1987), Mills (1988), and Whittecar and Ryter (1992), also reported near vertical clasts in Appalachian boulder streams.

Potter and Moss (1968) studied the presence of near vertical clasts at the Blue Rocks boulder field in Pennsylvania. By plotting the poles to the planes of the near vertical clasts on equal area nets and visually observing the orientation of the clasts, they identified the presence of several lobes within the structure of the boulder field (Fig. 6). They concluded that these lobes formed by viscous flow movement of the boulder field.

In addition to the near vertical clasts, Mills (1988) concluded that in most bouldery colluvium, tabular clasts commonly had their A - B planes (A being the long axis and B being the intermediate axis) lying almost parallel to the slope with a dip

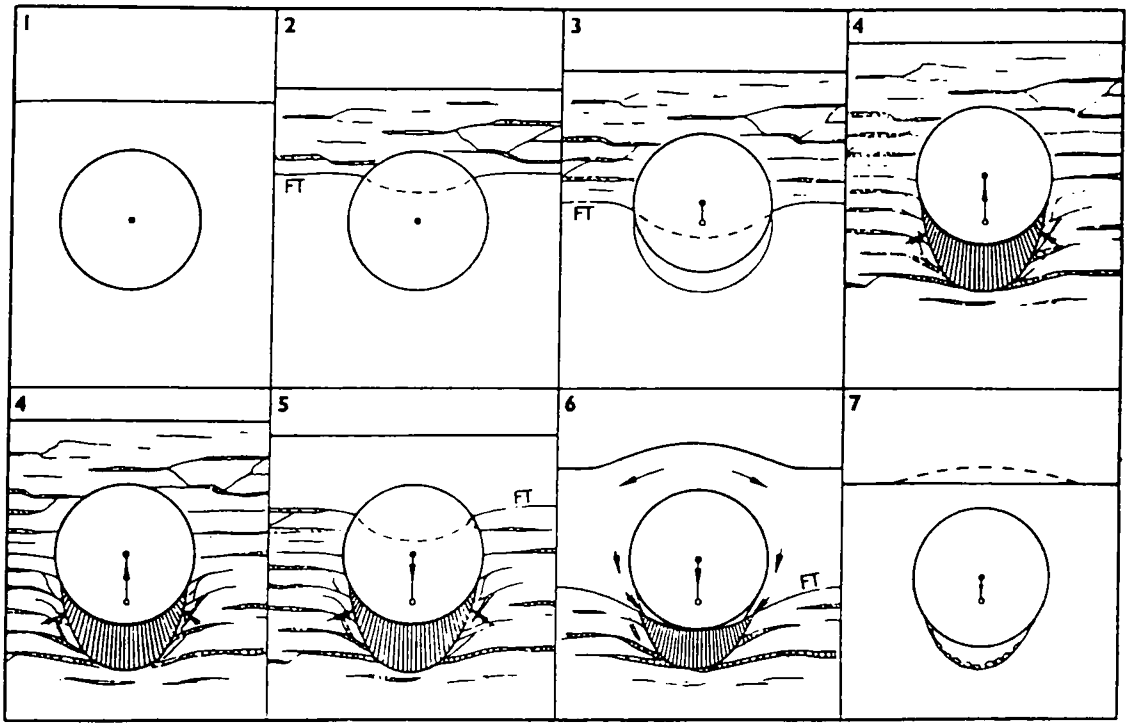


Figure 4 Diagram illustrating the upward movement of a stone through a soil by the process of frost heaving (Washburn, 1973).

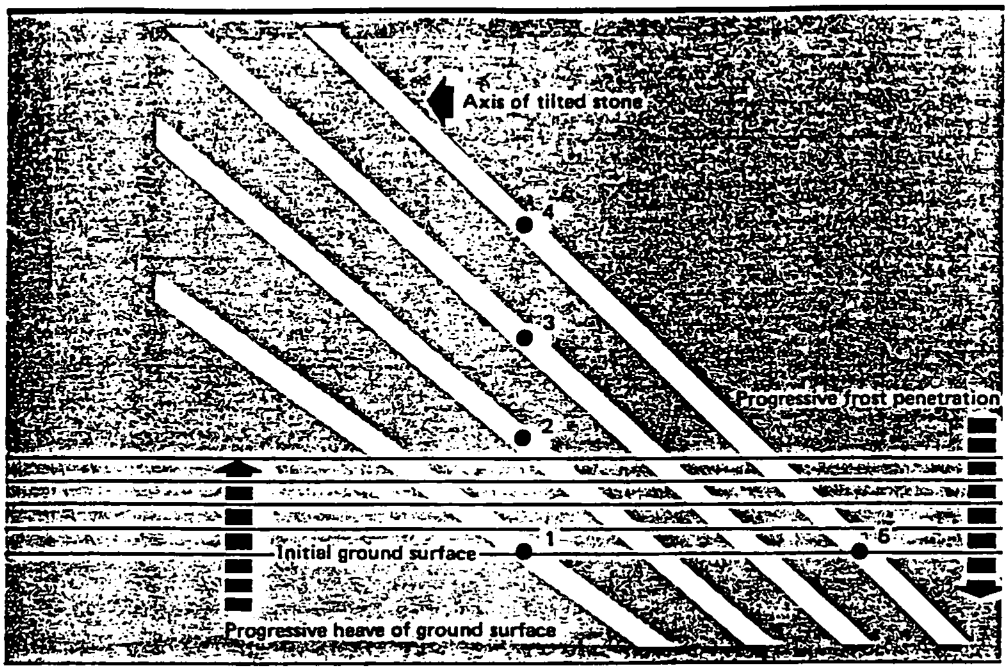


Figure 5 Illustration showing the rotation of a block to a near vertical orientation by the process of frost heaving (from French, 1976).

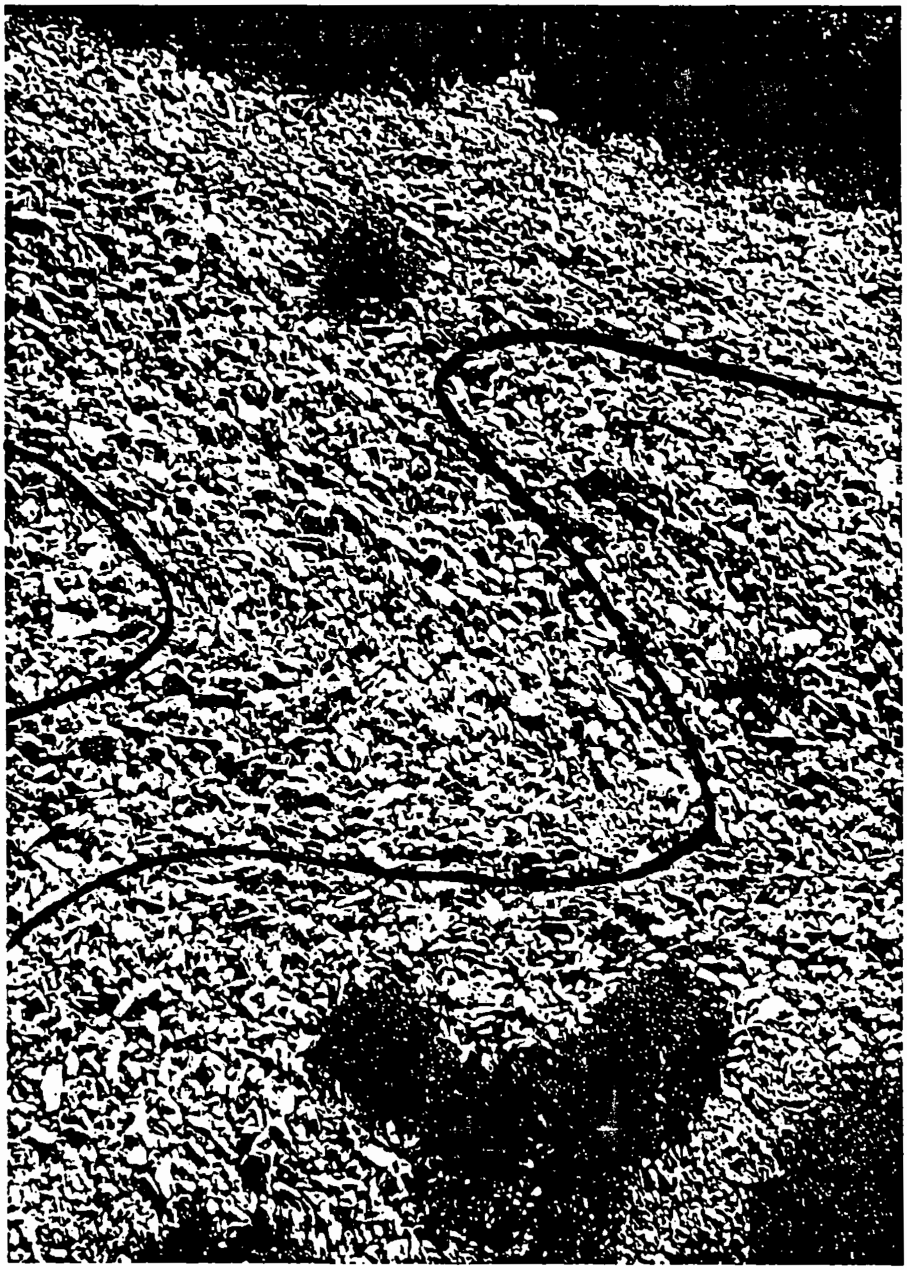


Figure 6 Oblique aerial photograph of the Blue Rocks boulder field. Note the lines that are drawn in the picture that show the lobate pattern of the near vertical clasts. The largest blocks in the photograph are approximately 15 feet long (from Potter and Moss, 1968).

slightly less than that of the hillslope. This "standard fabric pattern" existed throughout deposits formed by debris flow and periglacial processes.

Whittecar and Ryter (1992) observed boulder streams in Nelson County, Virginia and concluded their formation to be due to periglacial processes, mostly by evaluating and eliminating other potential processes such as debris flow activity, simple gravity processes, and rock glacier activity. The boulder streams observed by Whittecar and Ryter (1992) were not thick enough to warrant the rock glacier hypothesis because the calculated shear stresses at the bases of the boulder streams were much less than what would be expected for rock glaciers. The process of their formation by simple gravity activity was also disregarded because the boulder streams were too stable, being made of tightly wedged clasts, on slopes that were too gradual. The formative process of debris flow activity was also dismissed because many boulder piles deposited during debris flows commonly have erosional chutes just above them on the slopes. The boulder streams observed gradually widened into talus toward the upper ends (Fig. 1). Also, the deposits were quite continuous throughout the length of the stream valleys; debris flow deposits are usually much more sporadic. These observations support the idea that the boulders were deposited by periglacial activity instead of debris flows (Whittecar and Ryter, 1992).

Whittecar and Ryter (1992) also examined the fabric of several boulder streams and observed that the changes in the fabric of the clasts were influenced by the hump - like profile across a boulder stream. That is, the fabric for the clasts in the center of the streams were lying almost horizontally whereas clasts closer to either side of the streams were dipping away from the center of the streams (Fig. 7). Only a few near vertical clasts were noted at these sites, widely dispersed amidst the numerous gently - dipping tabular clasts.

In addition to the previously mentioned evidence that supports a periglacial origin for boulder streams (near vertical clasts, continuity, etc.), other criteria have also been used to determine such an derivation. Potter and Moss (1968) studied the Blue Rocks boulder field in Berks County, Pennsylvania and concluded a periglacial origin for it due to lack of evidence for recent movement and that the deposit was directly overlying what is believed to be Sangamon -aged soil. Michalek (1968) studied boulder streams in the North Carolina - Tennessee Blue Ridge area and concluded that they formed under a periglacial environment based on lack of deposition below the 2300 foot (767 m) elevation level and the fact that the number of deposits decreased to the south. White (1976) noted that many boulder streams are believed to be caused by periglacial activity based on relative abundance in high latitudes and at high altitudes and their association with other periglacial features.

The first investigations into critical elevations for glacial and periglacial features began in the late 1800's. One of the first correlations between glaciers and latitude was documented by Paschinger (1912). He noted that on a global scale, the regional snowline is influenced by latitude, thus indicating a correlation between glacier altitude and latitude (Sugden and John, 1976). Ostrem (1964) and Flint (1971) noted that a "glacial limit" separates peaks that have elevations high enough to accommodate glaciers from peaks that do not have glaciers (Fig. 8). Meier (1960) demonstrated for the western

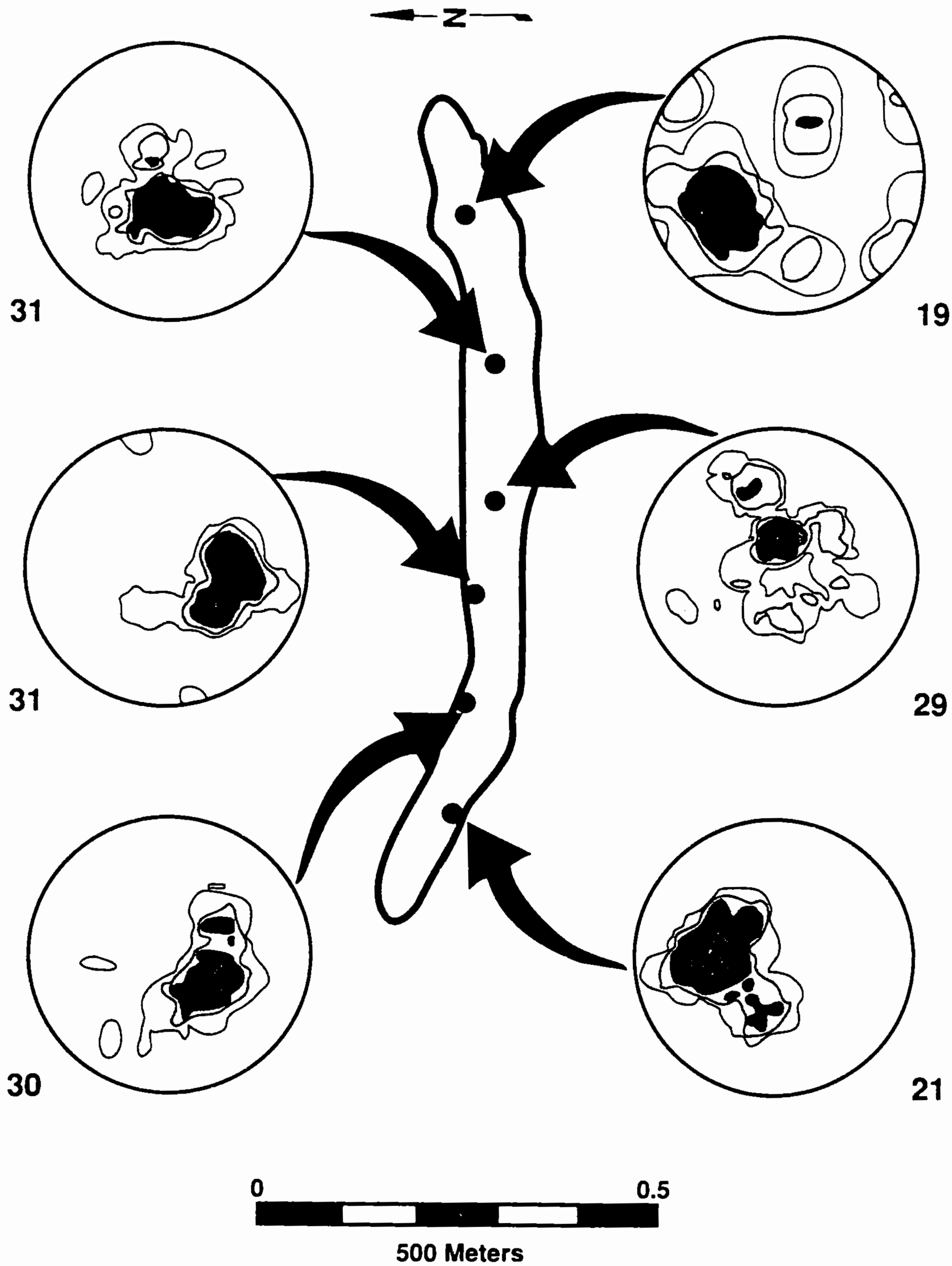


Figure 7 Fabric plots for a boulder stream in the Blue Ridge of Virginia. Plots are poles to A-B planes and stereonets are rotated so downslope is toward the bottom of the page. Values for the data are : black=>20%; dark gray=15-20%; light gray=10-15%; white=5-10% (Whittecar and Ryter, 1992).

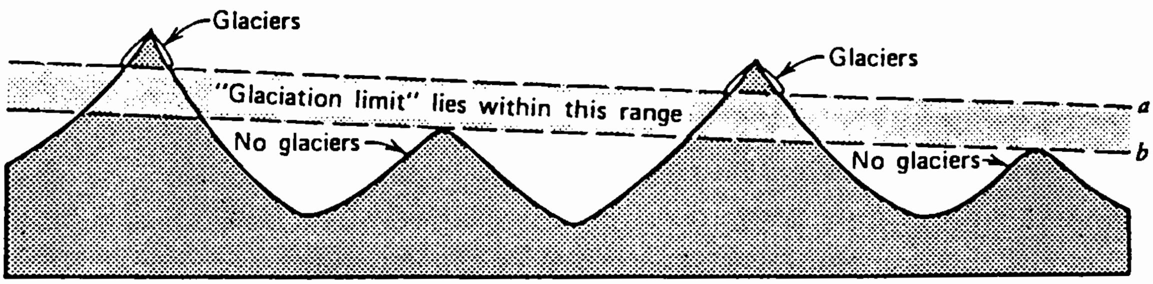


Figure 8 Diagram illustrating the concept of a glacial limit. This region lies between the base of glaciers on the lowest peaks which bear glaciers and the highest peaks that are capable of retaining ice and snow but have no glaciers (from Flint, 1971).

United States that as the latitude decreases the elevation at which glaciers are found increases (Fig. 9) (Sugden and John, 1976). In another study, Pewe (1983) documented several reports of existing permafrost in the western cordillera. His findings show that the elevation at which permafrost is observed increases in a southerly direction.

In analyzing the distribution of relict periglacial landforms in the central and southern Appalachians, Delcourt and Delcourt (1985) constructed a graph which shows the relationship between the latitude at which the landforms formed (in this case, patterned ground) and the minimum altitude at which they are found (Fig. 10). According to this analysis, the critical elevation for the formation of the particular periglacial landform decreases towards the north. This trend suggests that lower elevations are necessary for the formation of patterned ground at higher latitudes south of the maximum Wisconsin ice margin.

Delcourt and Delcourt (1985) have suggested that a critical elevation exists for the formation of patterned ground that increases with a decrease in latitude. If this theory proves correct, then boulder streams should be expected in all regions that meet certain criteria (namely the topography to support the presence of boulder streams). If this theory does not prove correct, then the distribution of, not only boulder streams, but other periglacial landforms will have to be reevaluated.

To summarize, very coarse colluvial landforms in valley bottoms, collectively called boulder streams, have formed in the central and southern Appalachians by one or more processes - simple gravity action (rolling), debris flow activity, and periglacial mechanisms. Existing fabric data suggests periglacial boulder streams formed by frost

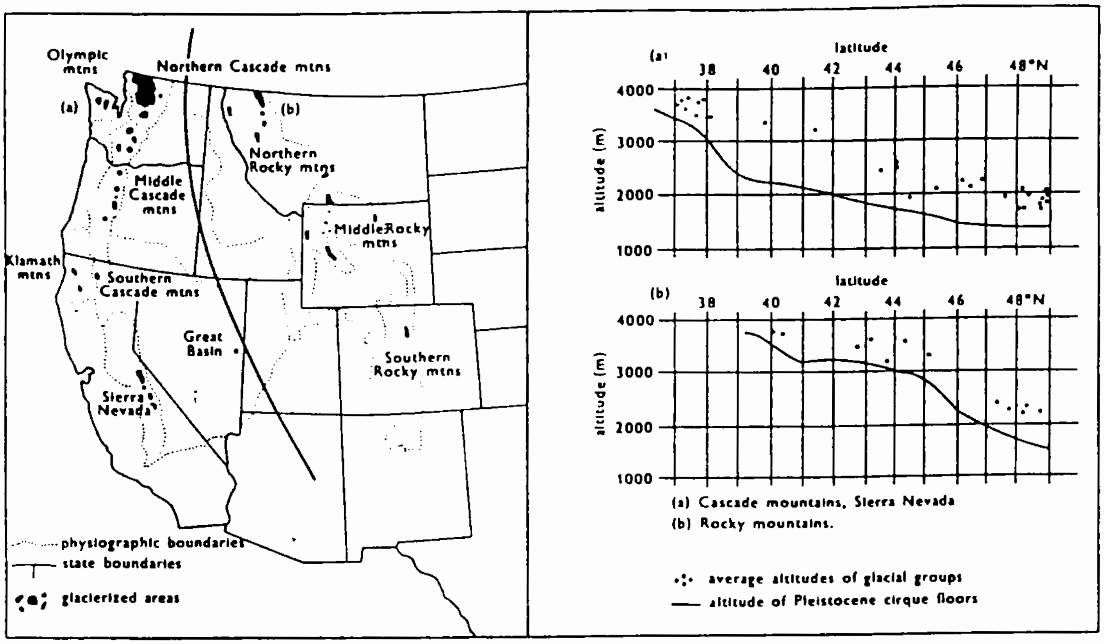


Figure 9 The map on the left shows two regions with glacial highlands. The graphs on the right show a relationship between the latitude of the glaciers and the altitude at which they are found (from Meier, 1960).

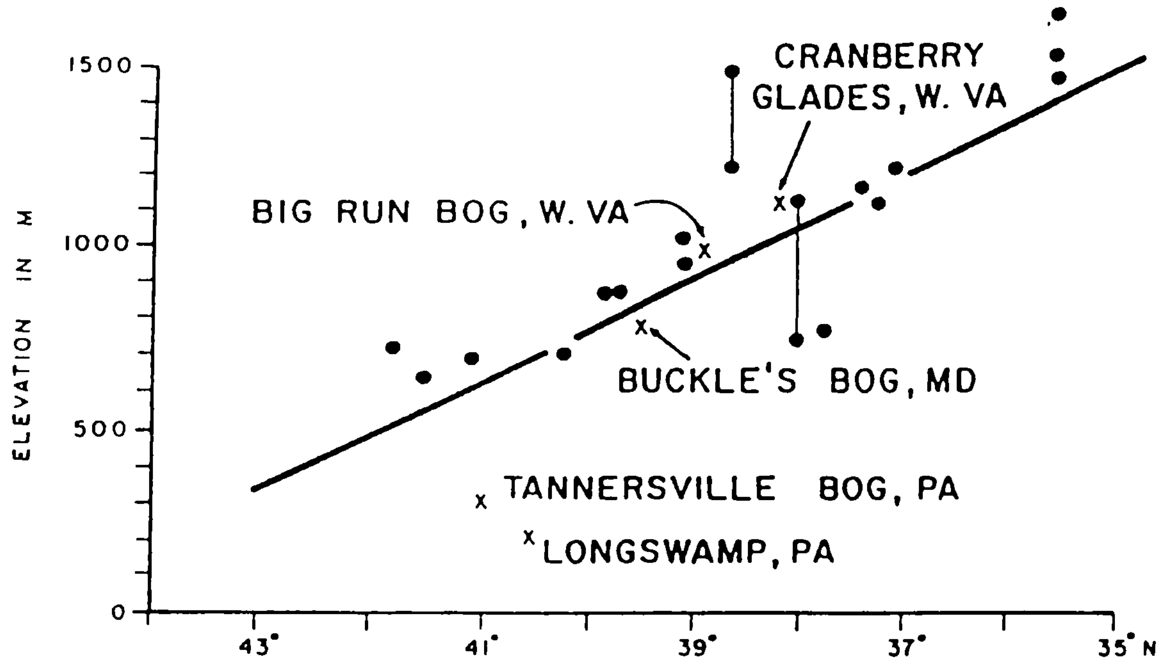


Figure 10 Latitude versus elevation plot for minimum elevations (dots) of polygonal landforms at sites in the Appalachians south of the glacial border (from Delcourt and Delcourt, 1985).

action at several locations in the substrate. Frost wedging breaks angular blocks of rock from a source outcrop which then accumulates in a talus slope. Blocks are transported farther downslope via the steepest path by additional frost heave and solifluction. Frost heaving also brings clasts to the surface and acts to orient tabular clasts into near vertical positions. Thus, in theory, one should be able to distinguish well - developed periglacial boulder streams from other bouldery accumulations by their uniform thickness and continuity along the valley, by gradation of their upper ends into talus slopes, by presence of near vertical clasts, and by a convex cross - sectional profile, particularly in narrow boulder streams.

However, the results of research on Appalachian boulder streams raise the following questions. If "periglacial" boulder streams, as described above, are indeed of periglacial origin, then the answers to these questions should all be "yes" :

A. Are boulder streams so common as to be the "expectable landform" in a given geomorphic setting? Most previous Appalachian studies were done on boulder streams selected more for their special qualities (e.g., size, dramatic appearance, etc.) and less for their ubiquity. Existing observations and theories of their formation suggest that boulder streams should be found in small valleys directly downhill of large talus accumulations at high altitudes, but that generalization has yet to be tested directly with an unbiased selection of field areas.

B. Does a critical minimum elevation exist for periglacial boulder streams within a given area? Does that critical elevation increase southward from the glacial margin? Elevations of previously studied boulder streams do increase to the south (Fig. 2) but previous workers did not determine if these boulder streams were the lowest ones in the area. Systematic mapping of the presence or absence of boulder streams in valleys at different elevations would test these hypotheses.

C. Are near vertical clasts common in Appalachian boulder streams? Existing fabric studies measured only a few vertical clasts and most researchers say nothing about their spatial distributions. Maps of their occurrence in individual boulder streams may reveal significant details about their formation.

PURPOSE AND OBJECTIVES

The purpose of this research is to test the hypothesis that boulder streams in the central and southern Appalachians formed under periglacial climatic conditions. Review of the existing studies suggests the minimum elevation at which boulder streams form should increase to the south, reflecting a north - south paleoclimatic gradient across the region. At least three implications of the periglacial hypothesis have yet to be tested systematically. One is that boulder streams should be common features, formed where proper conditions exist. A second inference is that the lowest elevation at which boulder streams may form decreases toward the south. A third implication of the periglacial hypothesis is that near vertical clasts should be a common characteristic of boulder streams in the central and southern Appalachians.

In order to address these research goals, the following objectives were established :

1) Determine if boulder streams may be regarded as an “expectable” landform in a given geomorphic setting (i.e., in small valleys downhill of talus slopes and source cliffs) in a limited geographical area..

2) Determine if critical minimum elevations exist for boulder streams in separate areas distributed across a broad region (e.g., the state of Virginia) and, if they do exist, whether or not they increase in altitude to the south.

3) Determine if near vertical clasts are common within boulder streams and analyze what their distribution and orientation may signify.

METHODS

The first two research objectives were addressed by detailed examination and mapping in a series of widely-dispersed high-altitude field sites. Four sites were chosen in the Blue Ridge province of Virginia (Fig. 11). Three criteria governed which sites were chosen.

1. *A wide range of elevations at which boulder streams might be found.* Each study area contains a ridge with valleys that start at a variety of elevations. Some areas have several ridges while others have a long ridge with a descending crest line.

2. *Rocks that mechanically weather in a similar manner.* Each site is dominated by rocks that are thickly bedded or massive and fracture in outcrop to large tabular fragments. The weakly metamorphosed volcanic or igneous rocks (metabasalt, metarhyolite, charnokite) in the chosen areas appear to physically weather in very similar fashions. Thus, although the rock types differ, this consistency in weathering products would alleviate the effects of using terrains with markedly different rock strengths and fissility.

3. *A widespread spatial distribution.* A large number of tall peaks with boulder streams are distributed across the Blue Ridge in Virginia.

Large areas of highlands in the Blue Ridge extend above elevations where earlier workers found boulder streams (Fig. 2). From these areas, four large regions were selected that gave a wide latitudinal spread (Fig. 11). The specific study area in each region was selected after reconnaissance mapping of several sites in each region. The

Study Area	Rock Type
Short Hill	Metabasalt
Wintergreen	Charnokite
Peaks of Otter	Charnokite
Whitetop Mtn.	Metarhyolite

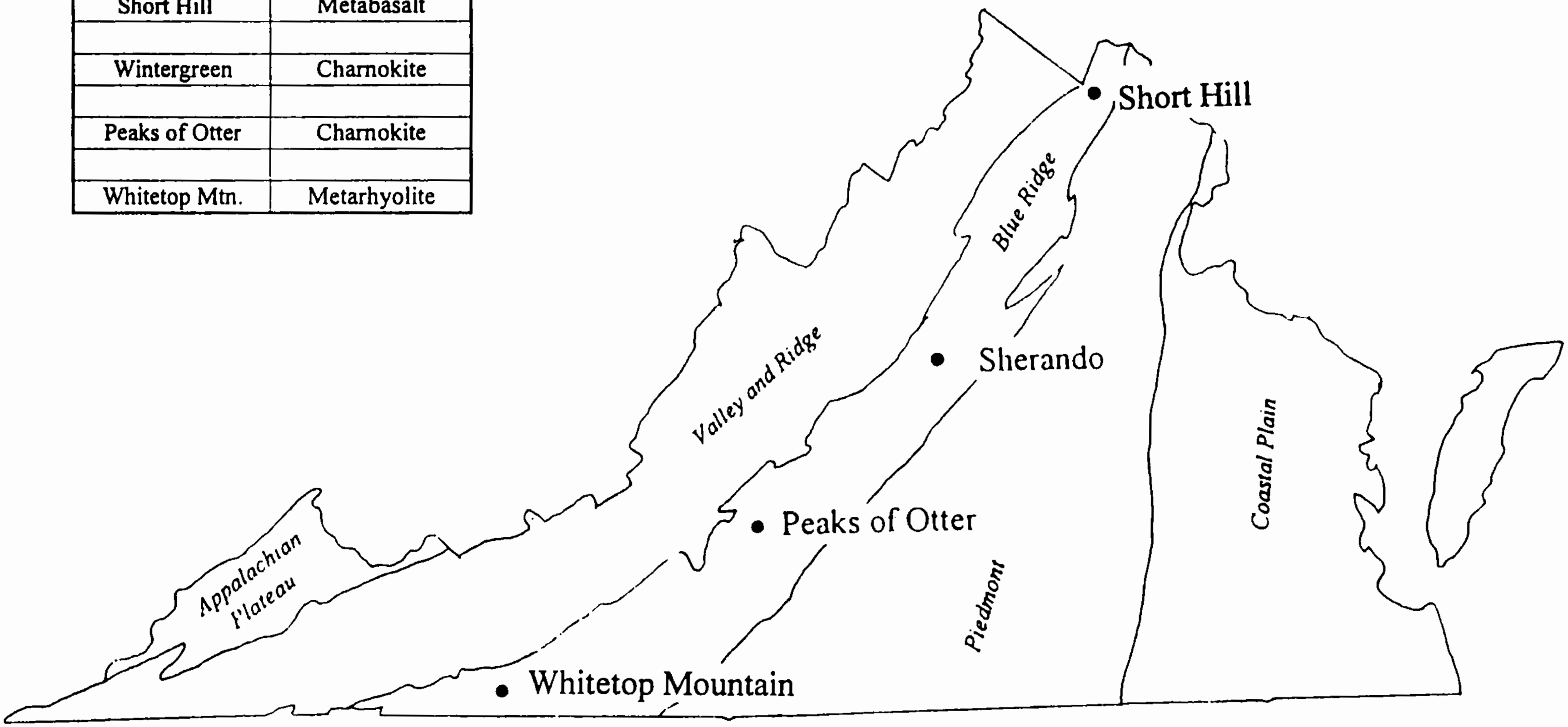


Figure 11 Location of study areas and physiographic provinces in Virginia.

chosen sites not only meet the established criteria but they also were spatially compact with clearly definable margins and acceptable accessibility.

Site selection was also guided by the results of previous workers. Michalek (1968) reported numerous boulder streams in the area around Whitetop Mountain, but provided no detailed maps. Whittecar and Ryter (1992) reported several boulder streams found beneath metabasaltic cliffs in the Wintergreen area, although their field area does not meet the selection criteria for this study. The surficial geology maps made by Jacobson and others (1990) indicated boulder streams were present in Loudon County, Virginia, although the landforms were lumped together in map units with other hillslope features. No previous reports of boulder streams were known for the Peaks of Otter area.

Each valley within the designated field areas was inspected for the presence or absence of boulder streams. The margins and lengths of all boulder streams found were mapped on a 7 1/2 minute quadrangle. For the Short Hill study area, surficial deposit maps constructed by Jacobson and others (1990) were used in order to find valleys that were designated as having coarse, bouldery clasts within them. These valleys were field checked for evidence of boulder streams of periglacial origin.

Once all the valleys in the area had been examined, the elevation at which the lowest valley containing boulder streams and the highest valley not containing boulder streams was documented. This elevation is designated as the "critical elevation" for each study area (Fig. 12). Determination of elevations and latitude/longitude data were made through the use of topographic maps and a hand - held Trimble GPS-9000 Global Positioning System receiver.

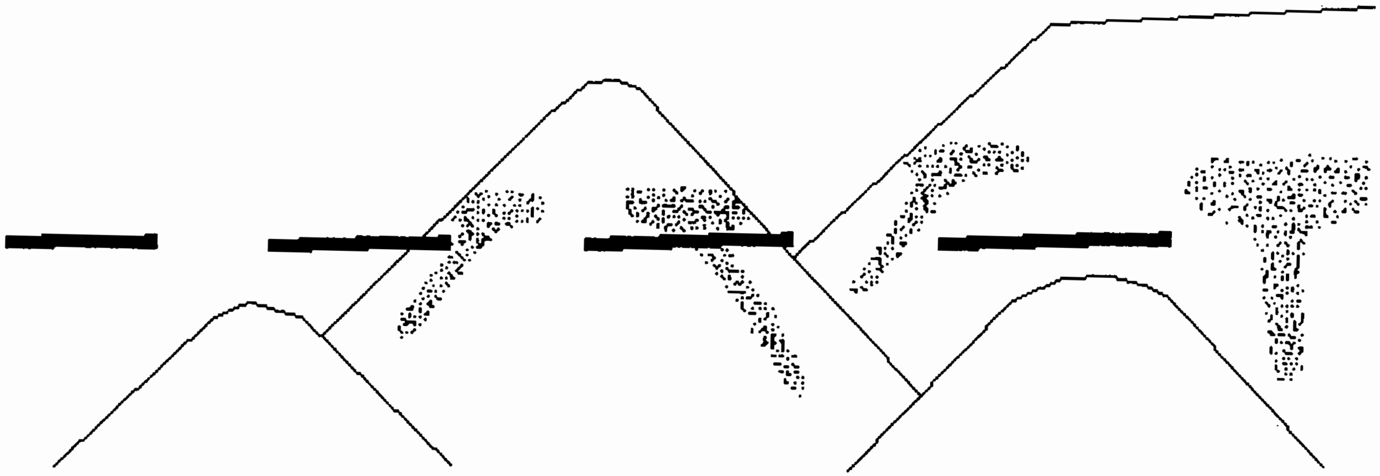


Figure 12 Illustration showing the concept of a critical elevation for periglacial boulder streams.

In order to meet the third research objective, one boulder stream from each site was systematically searched for near vertical clasts. Each selected boulder stream was mapped for a 30+ meter length chosen from a uniform - appearing reach. Cross - stream transects were spaced at 3 m intervals; transects were oriented by compass and measured by tape. Along each measured transect, the location and strike orientation was noted for each near vertical clast (e.g., 70°-90° dip) within 5 meters of either side of the transect. Locations and orientations were recorded on gridded maps of the surveyed areas.

In order to determine numerically whether the placement of near vertical clasts within a boulder stream is random, uniform, or clustered, a quadrat analysis was completed on the data. This analysis can be done by a chi - square test for uniformity. The equation for this test is :

$$\chi^2 = \Sigma(O - E)^2 / E$$

where O is the observed number of vertical clasts in each subarea and E is the expected number of vertical clasts in each subarea. The test has v = (m - 2) degrees of freedom (where m is the number of subareas) (Davis, 1973).

The quadrat analysis uses the number of vertical clasts found in each section (or quadrat) and compares this number to the expected value. The expected number of vertical clasts is derived from the total number of vertical clasts within the entire boulder stream divided by the number of quadrats (Davis, 1973).

In order to graphically show any preferred orientation of the vertical clasts within each boulder stream, rose diagrams were made for sections of each boulder stream. Sections were drawn arbitrarily to illustrate the visibility of clast orientation across each boulder stream. and to have as many clasts as possible in each section.

RESULTS

Boulder Stream Distribution

Short Hill - The Short Hill site contains a large ridge oriented in a northeast-southwest direction (Fig. 13). The main focus of the investigation concentrated on the north end of the ridge immediately south of the Potomac River. The elevation of this ridge ranges from almost 60 m near the Potomac River up to 300 m at the top of the ridge. The predominant rock type at this site is metabasalt (State Geology Map, 1987). Although some quartzite was mapped by Jacobson and others (1990) along some sections of this ridge, none was noted here. Foliation on the north end of the ridge is N 16° E, 24° SE. The slope on the east face is approximately 30% and the slope on the north face is 48%. Access in this area was generally good.

This site was chosen because of the prominent ridge which decreases in elevation to the north and because bouldery deposits had previously been mapped in this area (Jacobson and others, 1990) (Fig. 14). On their maps of Loudoun County, Jacobson and others (1990) designated bouldery "coarse debris" (Qcd) which they described as having clay-to-boulder sized clasts with little or no interstitial matrix. Thus, their map unit included deposits that varied between well-sorted block streams to poorly-sorted diamictons. Immediately uphill of many of these bouldery accumulations were slope deposits mapped as large collections of "rock debris" (Qcc) which could be either talus deposits, block fields, or poorly sorted diamictons.

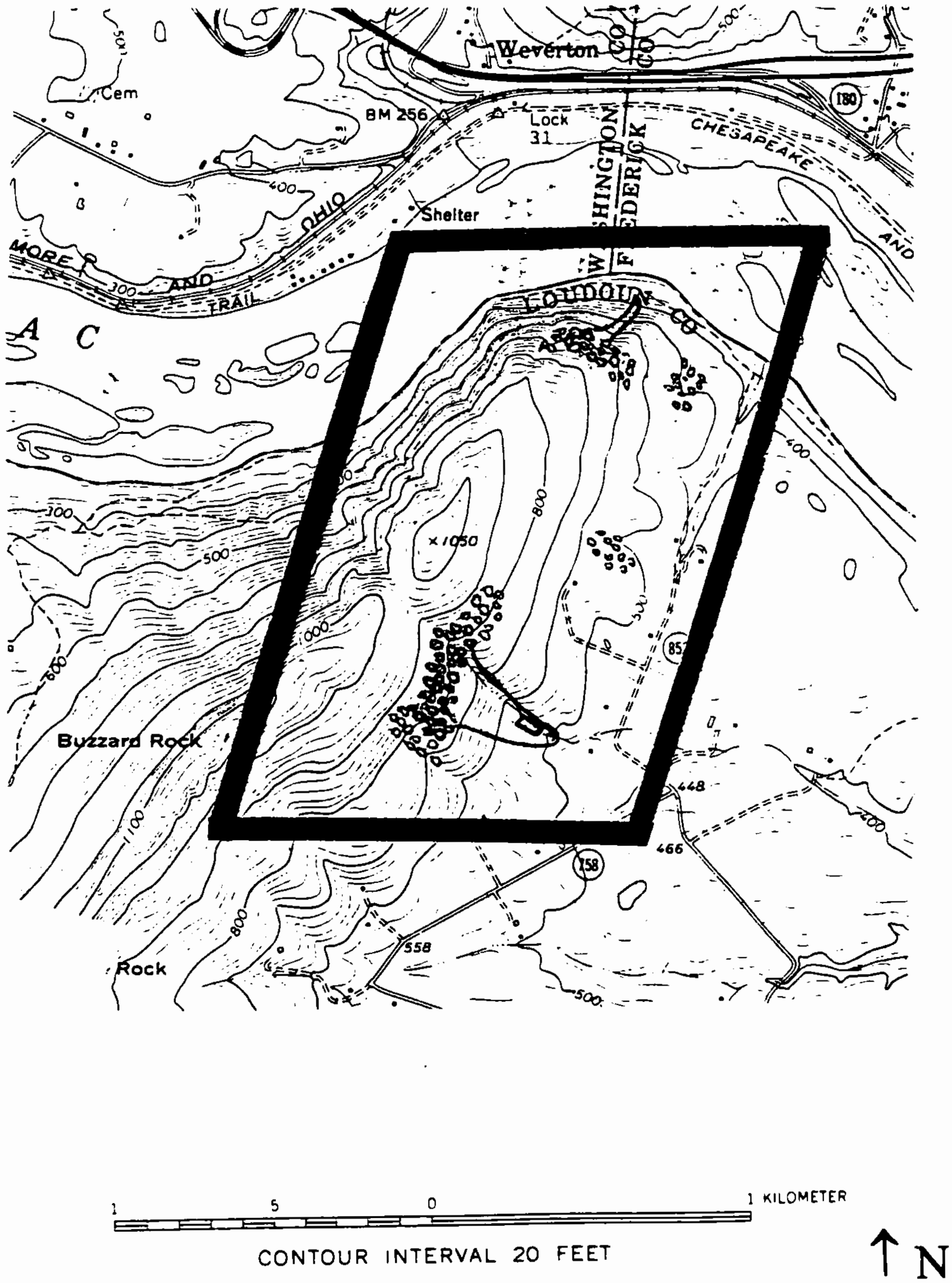
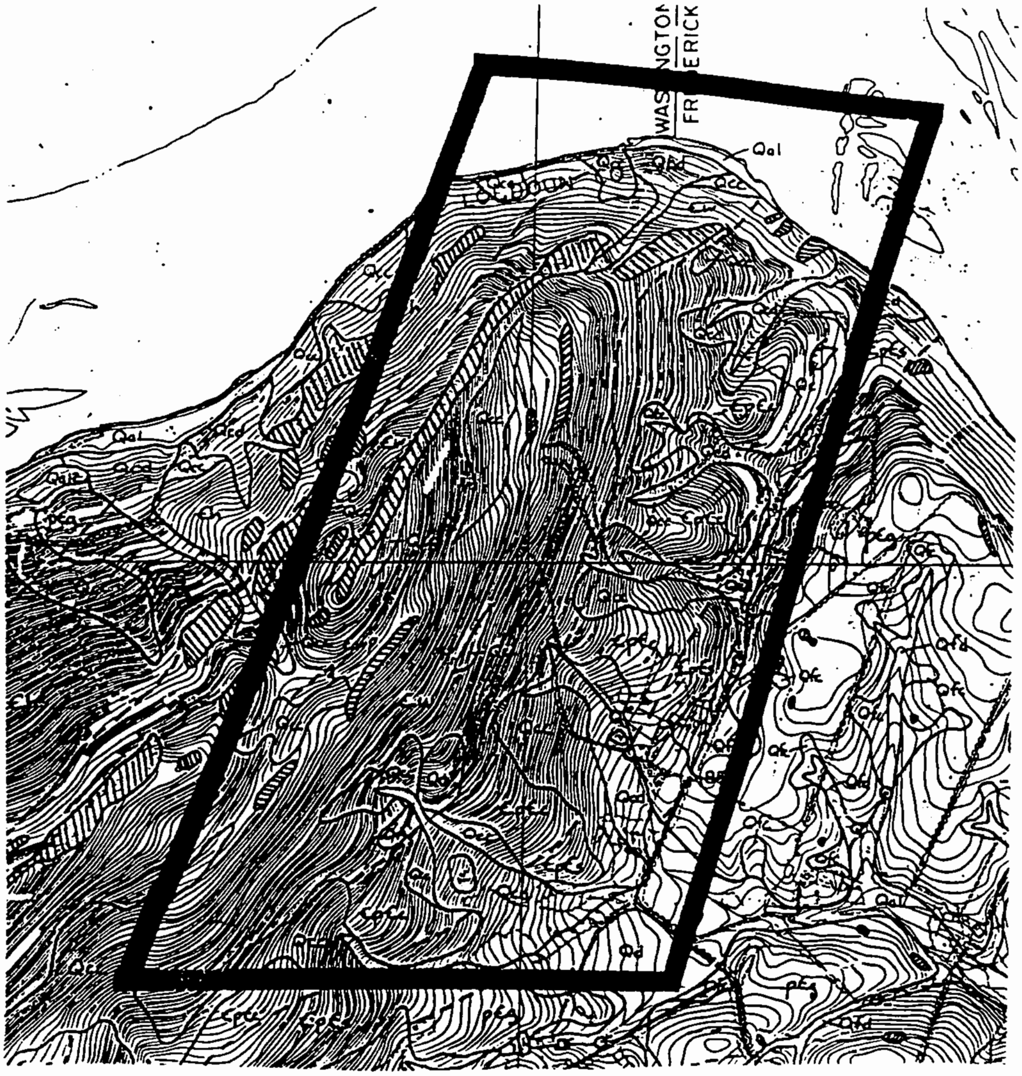


Figure 13 Map of the Short Hill study area, adjacent to the Potomac River in Loudoun County, Virginia. The site is located at 39° 19' north latitude and 77° 41' west longitude. The small circles represent talus deposits and the lines extending down the slopes represent the edges of the boulder stream. The rectangle shows where the vertical clast study was conducted.



Qcd = coarse debris, clay to boulder size particles dominated by boulders. Varies from well-sorted block streams to poorly-sorted diamictons.
Qcc = coarse colluvium, clay to boulder size particles dominated by boulders. Varies from well-sorted block streams (talus) to poorly-sorted diamictons.
Qd = undifferentiated debris, diamictons with intermediate size particles
Qrb = probable landslides
Qal = alluvium
Qc = undifferentiated colluvium

↑ N

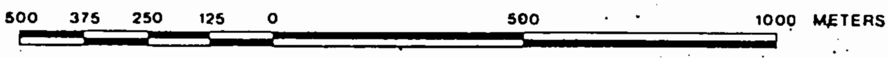


Figure 14 Jacobson and others (1990) surficial map of the Short Hill study area. The location is at 39 17' north latitude and 77 41' west longitude.

Each valley designated with a bouldery accumulation (Qcd) that might contain a boulder stream was examined for the "periglacial" criteria consistent with a boulder stream as determined for this study. That is, each bouldery deposit was checked for continuity, containment within the valley, the presence of near vertical clasts, and a hump-shaped cross-sectional profile. Some of the accumulations mapped as Qcd by Jacobson and others (1990) were often discontinuous, lacked vertical clasts, and had no hump-like profile and thus were not mapped for this study.

The largest boulder stream found in this area lies on the southern edge of the map area. Approximately 400 m long, it is as much as 187 m at its greatest width. The clast size averaged approximately 30-60 cm in diameter and there was little vegetation (i.e., lichens, moss, etc.) on the clasts. Fines (mostly sand) can be seen just beneath the boulders of the boulder stream. This boulder stream is contained mostly in a valley and is quite continuous. Vertical clasts are also very abundant.

The boulder stream on the northern face is identified based on the observation of a few vertical clasts and the apparent continuity of the deposit. Although identified as a periglacial boulder stream, this particular feature is not an ideal example of one. The upper ends of both boulder streams mapped here graded upslope into talus deposits.

Several valleys on the eastern and northern sides of this ridge examined for this study do not have boulder streams. Both of the boulder streams mapped developed at approximately 150 m in elevation. Valleys with heads below 150 m do not have boulder streams. Thus, I determined the critical elevation for the Short Hill area to be 150 m.

Wintergreen - The Wintergreen site was selected for this study because Ryter (1989) noted numerous boulder streams on a neighboring ridge. Also, this site has a reasonable variation of elevations at which the critical elevation for this latitude may be found. The study area consists of a ridge extending southward off Piney Mountain and Bryant Mountain which has an eastward-extending ridge (Fig. 15). The elevation ranges in this area from approximately 360 m towards the east end of the ridge off Bryant Mountain up to over 830 m at the top of Piney Mountain. The primary rock type at this location is a massive charnokite (Bartholomew, 1977). The slope on the west face of the ridge extending to the south of Piney Mountain is approximately 30%.

The accessibility in the Piney Mountain area was quite good. The area which includes the ridge extending south from Bryant Mountain, however, was inaccessible and was not mapped. The boulder streams identified in this study were found on the west face of the ridge extending south of Piney Mountain. These streams are from 60 to 120 m in length and 15 to 30 m wide. These boulder streams also extended upslope into abundant talus deposits which littered the face. Several source areas (i.e., rock outcrops) are also present across the ridge slopes. A small boulder stream was identified in a valley on the southern face. The boulder stream at this location is approximately 60 m in length and about 6 m wide. This boulder stream extended upslope where it graded into talus, which, although scarce across much of the upper ridge, occurred in this local area. A few outcroppings of source rock were observed just east of the small boulder stream on the south face. These outcroppings appeared to feed small talus deposits immediately

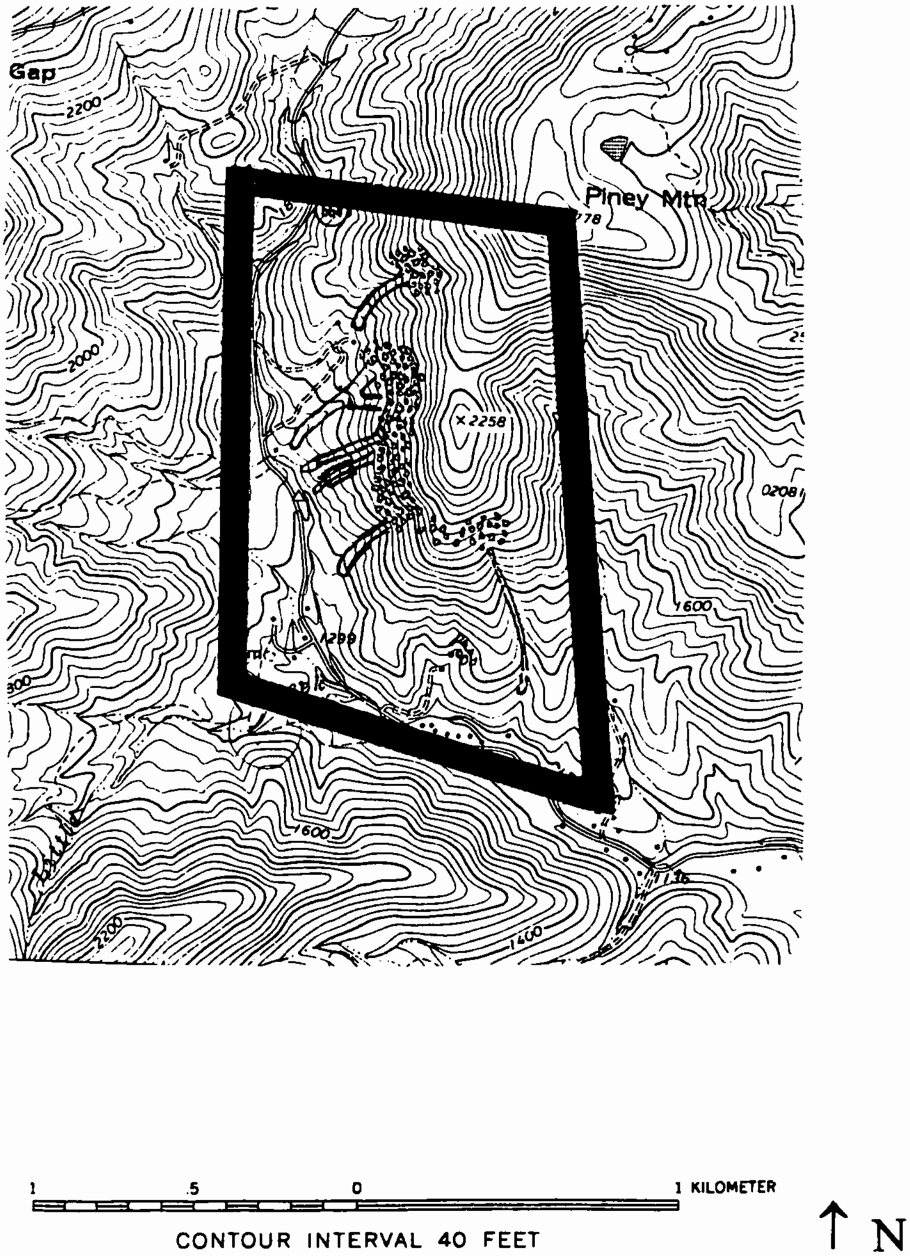


Figure 15 Map of the Wintergreen study area. The site is located at 37° 53' north latitude and 78° 58' west longitude. The small circles represent talus deposits and the lines extending down the slopes represent the edges of the boulder streams. The rectangle shows where the vertical clast study was conducted.

downhill of the outcrops; east of Bryant Mountain was also examined for boulder streams, however, none were found.

The approximate altitude for the critical elevation at this site was determined by the distribution of the several boulder streams mapped on the west side of Piney Mountain. The head of the boulder stream that formed lowest on the hillslope was at an elevation of 480 m. The lack of boulder streams below this altitude suggests that an elevation of 480 m is a reasonable estimation for the critical elevation for this latitude.

Peaks of Otter - The Peaks of Otter area contains several boulder streams. Most of the streams found here lie on the northwest slopes of Flat Top Mountain and Sharp Top Mountain, the two Peaks of Otter. Large amounts of talus derived from exposed bedrock at the top of the peaks are believed to provide the debris necessary for the formation of these boulder streams. Although talus and boulder streams exist on both Peaks of Otter, they were not mapped there because of a lack of low elevation valleys in the immediate area. Chestnut Mountain (Fig. 16), which is approximately 2 km north and west of the Peaks of Otter, was chosen as a more suitable location because of its ridge crest which decreases to a sufficiently low elevation to the south. The bedrock at this location is massive charnokite (State Geology map, 1987).

One stream can be found extending from the southeastern slope (Fig. 16). This boulder stream is about 50 m wide and approximately 66 m long. This stream grades into talus shortly up the hillside which is found throughout much of the upper ridge. The

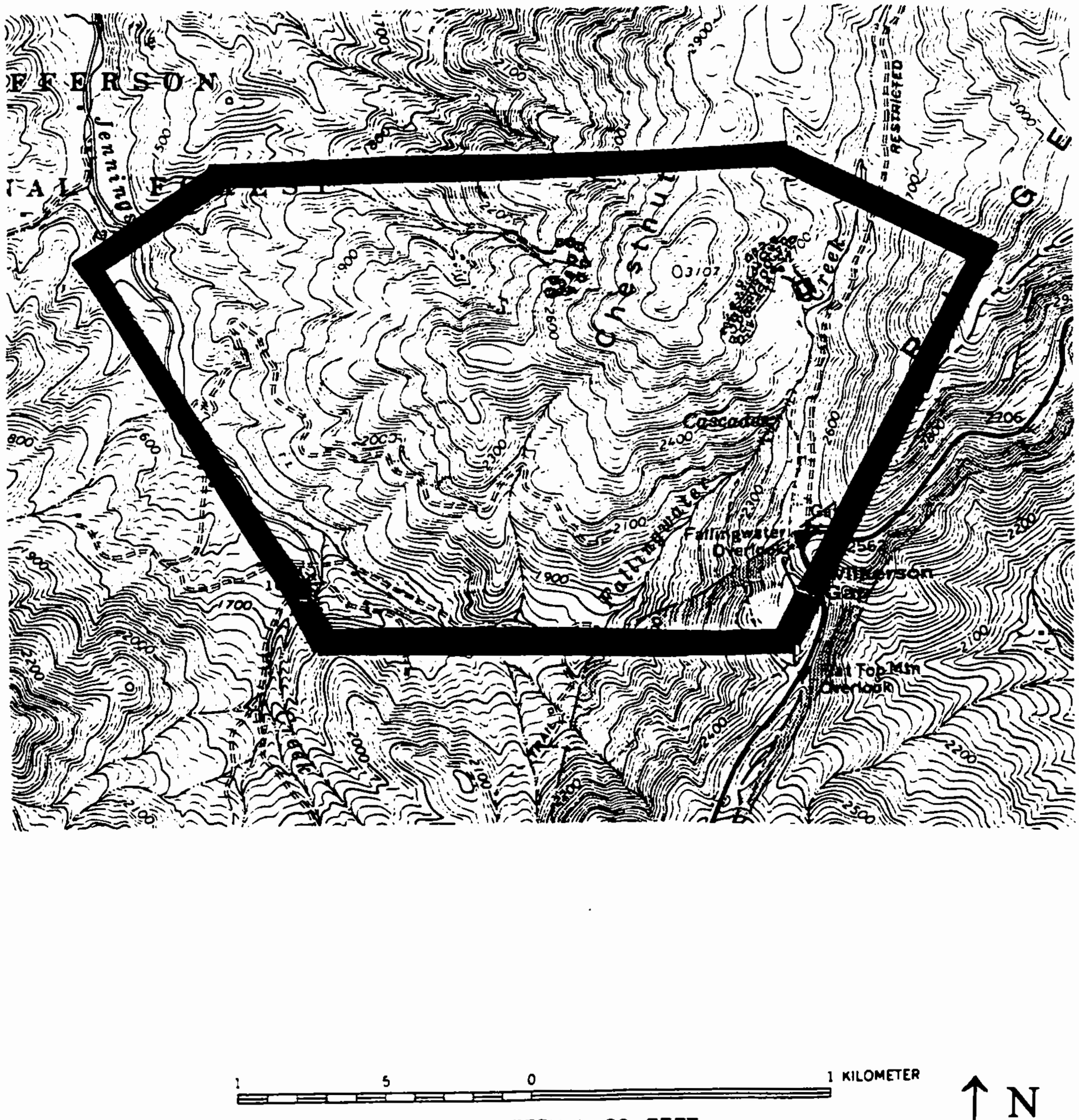


Figure 16 Map of the Peaks of Otter study area. The site is located at 37° 28' north latitude and 79° 36' west longitude. The small circles represent talus deposits and the lines extending down the hillslopes represent the edges of the boulder streams. The recatngle shows where the vertical clast study was conducted.

boulder streams found here are in valleys from the lowest limit of talus to Fallingwater Creek below. The slope at this location is approximately 36%.

The ridge extending off of Chestnut Ridge to the south and west apparently has no boulder streams. Abundant talus was mapped just uphill of the dirt road that crosses the southern part of the ridge, but no boulder streams were observed. Downhill of the dirt road on the southern face of the ridge, no talus or boulder streams were found.

On the west side of Chestnut Ridge, only one boulder stream was found. This boulder stream is about 300 m long and approximately 15 m wide. Valleys along this side of the ridge lack boulder streams, despite the increase in elevation for the ridge crest. Aside from the small amount of rock debris found toward the top of the boulder stream, the western face of this ridge has very little talus and few large outcrops.

The critical elevation at this site was determined to be 750 m. This value was derived from the elevation of the boulder stream on the west face of Chestnut Ridge. The upper ends of boulder streams were not observed below this elevation although many were found above this eleavtion. Because no boulder streams were observed in this area at an elevation of less than 750 m, this value is determined to be a reasonable approximation for the critical elevation at this latitude.

Whitetop Mountain - The focus of the present investigation was predominately around the east and north faces of Whitetop Mountain (Fig. 17). The primary rock type at this location is metarhyolite (State Geology Map, 1987). The strike and dip measurement taken on the north face of Whitetop Mountain was N 80° E, 30° S. This site varies in

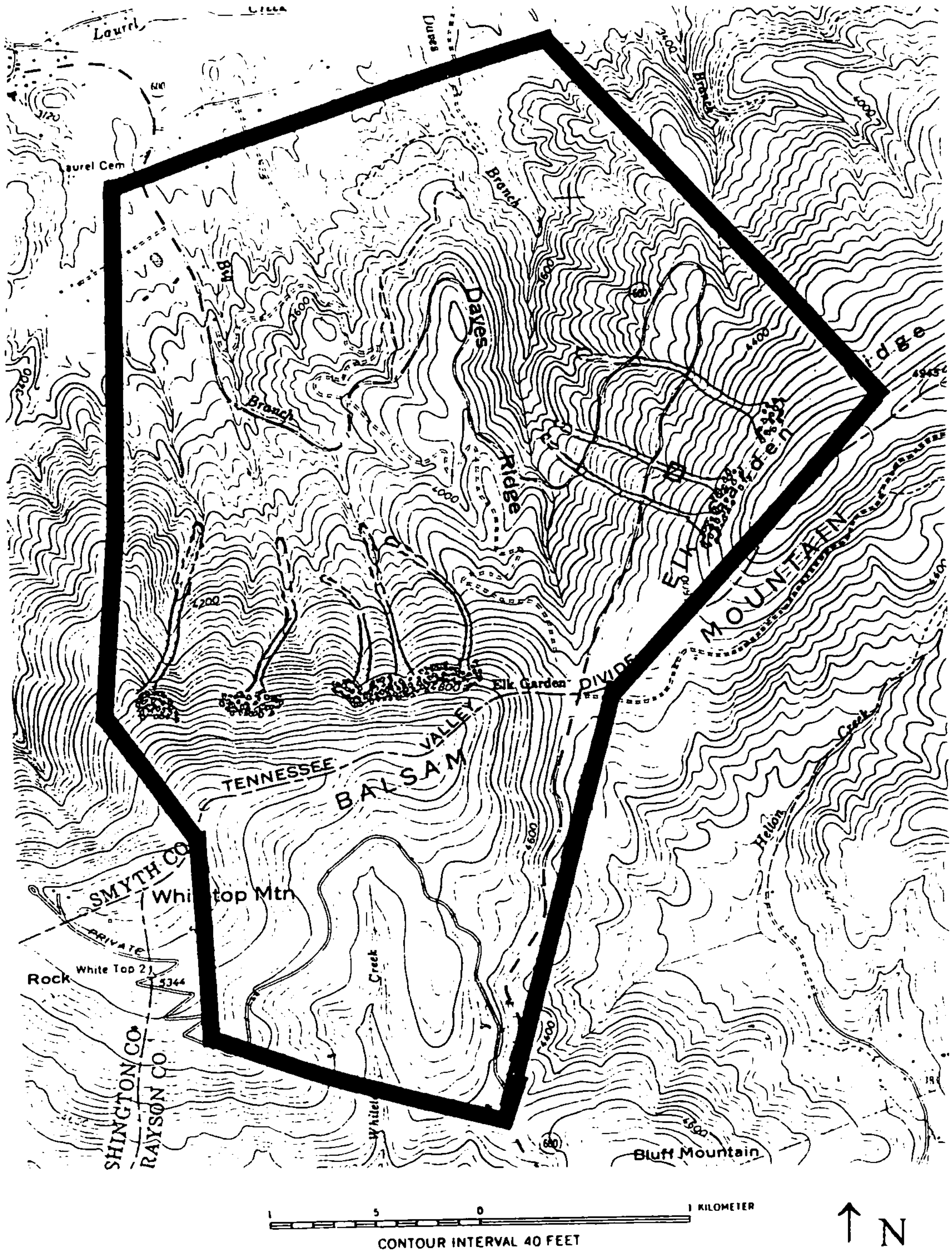


Figure 17 Map of the Whitetop Mountain study area. The site is located at 36° 38' north latitude and 81° 36' west longitude. The small circles represent talus deposits and the lines extending down the slopes represent the edges of the boulder streams. The rectangle shows where the vertical clast study was conducted.

elevation from about 1200 m at the crest of Daves Ridge to approximately 1830 m at the top of Whitetop Mountain. Mount Rogers, which is just to the east of the map area, peaks at an elevation of about 1700 m. Other major ridges in this area include Elk Garden Ridge at an elevation of approximately 1480 m, a ridge descending in elevation to about 1440 m which extends off the east end of Whitetop Mountain, and another smaller ridge extending off the southern end of Whitetop Mountain to an elevation of 1380 m. The slope on the north face of Whitetop Mountain was calculated to be 44% and the slope on the north face of Elk Garden Ridge is about 30%. Access in these areas is generally fair.

This site was chosen for this project because there are favorable altitude variations and boulder streams have been previously identified here. Michalek (1968) reported boulder streams on and around Mount Rogers and Whitetop Mountain. However, he did not disclose any specific locations of the boulder streams nor did he present any maps of this particular location.

Boulder streams are found in the valleys just west of the dirt road extending north from Elk Garden Ridge. The boulder streams range from about 20 to 45 m in width and roughly 400 to 500 m in length. A few of the boulder streams observed contained abundant organic matter and other fines filling the holes between the clasts. These boulder streams also exhibited near vertical clasts, continuity, and other criteria to suggest a periglacial origin. Therefore, these streams are counted as periglacial boulder streams as opposed to those formed by debris flows or some other mechanism.

The boulder streams grade into talus at their upper ends at an elevation of approximately 1533 m. Talus exists throughout the upper portion of Elk Garden Ridge, but it is predominately found in the valleys. Talus also is found along the eastern face of Whitetop Mountain. No boulder streams were found downslope of these talus deposits.

Boulder streams were also found along route 600 on the north side of Elk Garden Ridge. These boulder streams were approximately 30 to 45 m in width and approximately 600 to 800 m in length. Many of the clasts within the boulder stream were covered by moss and lichens. These boulder streams also grade into talus at the upper ends although in places, the talus appears thin. Investigations into the presence of boulder streams along Daves Ridge was also conducted. No boulder streams were found extending off of the ridge and an obvious lack of talus was present.

The fact that Daves Ridge is made of metarhyolite but did not have any boulder streams provides a minimum limit for the critical elevation at this location. The boulder stream found at the lowest elevation above Daves Ridge was approximately 1533 m. The highest valley in this area without a boulder stream is at an elevation of approximately 1467 m. Therefore, a conservative estimate for the critical elevation at this site is determined to be 1500 m.

RESULTS

Analysis of Vertical Clast Data

The distributions of near vertical clasts within one boulder stream at each site was analyzed. The results of this analysis for a boulder stream at Short Hill, Wintergreen, Peaks of Otter, and Whitetop Mountain are shown in Figures 18-21. These maps clearly indicate that near vertical clasts are not unusual in the study areas. Using the average size of the clasts at each site to infer the total number of clasts in each boulder stream studied, I estimate that up to 5% of the clasts in a given section might rest at high-angle dips. In most randomly chosen sites selected for standard fabric analysis (e.g., Mills, 1988; Whittecar and Ryter, 1992), these clasts would not strongly influence fabric trends. The importance of the near vertical clasts lies in their interpretation as being oriented by frost heave.

The data of the near vertical clast analyses were subjected to a Chi-square test for randomness. The map areas were divided into five sub-areas and the number of vertical clasts for each sub-area was then compared with the expected number of vertical clasts in each sub-area. The expected number of vertical clasts is the total number of vertical clasts in the map area divided by the number of sub-areas. The results of these calculations are shown in Figures 22-23.

The results of the Chi-square test reveal that the distribution of vertical clasts within each boulder stream is not unevenly populated. Each boulder stream used in this

Short Hill
250 feet x 175 feet
1 inch = 40 feet

upstream

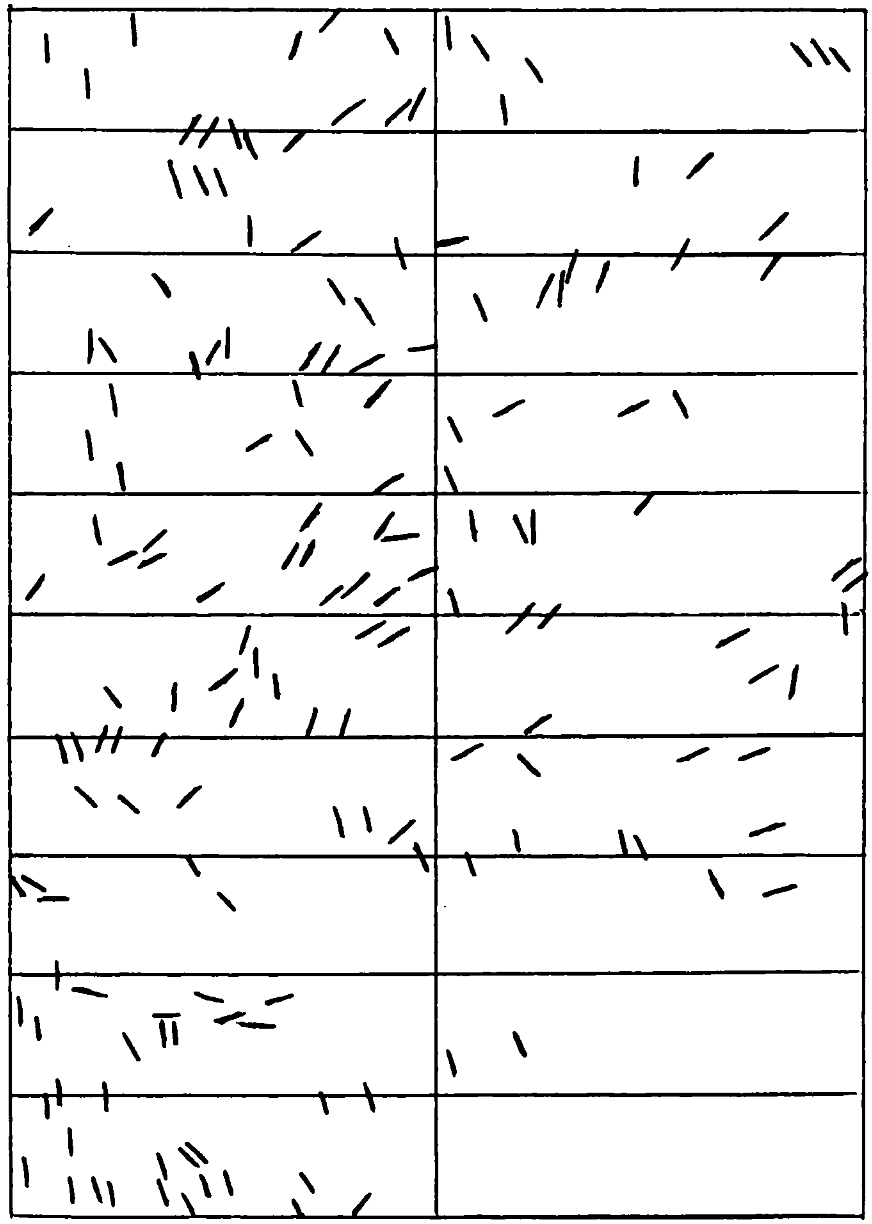


Figure 18 Grid map showing the distribution of near vertical clasts at the Short Hill study area.

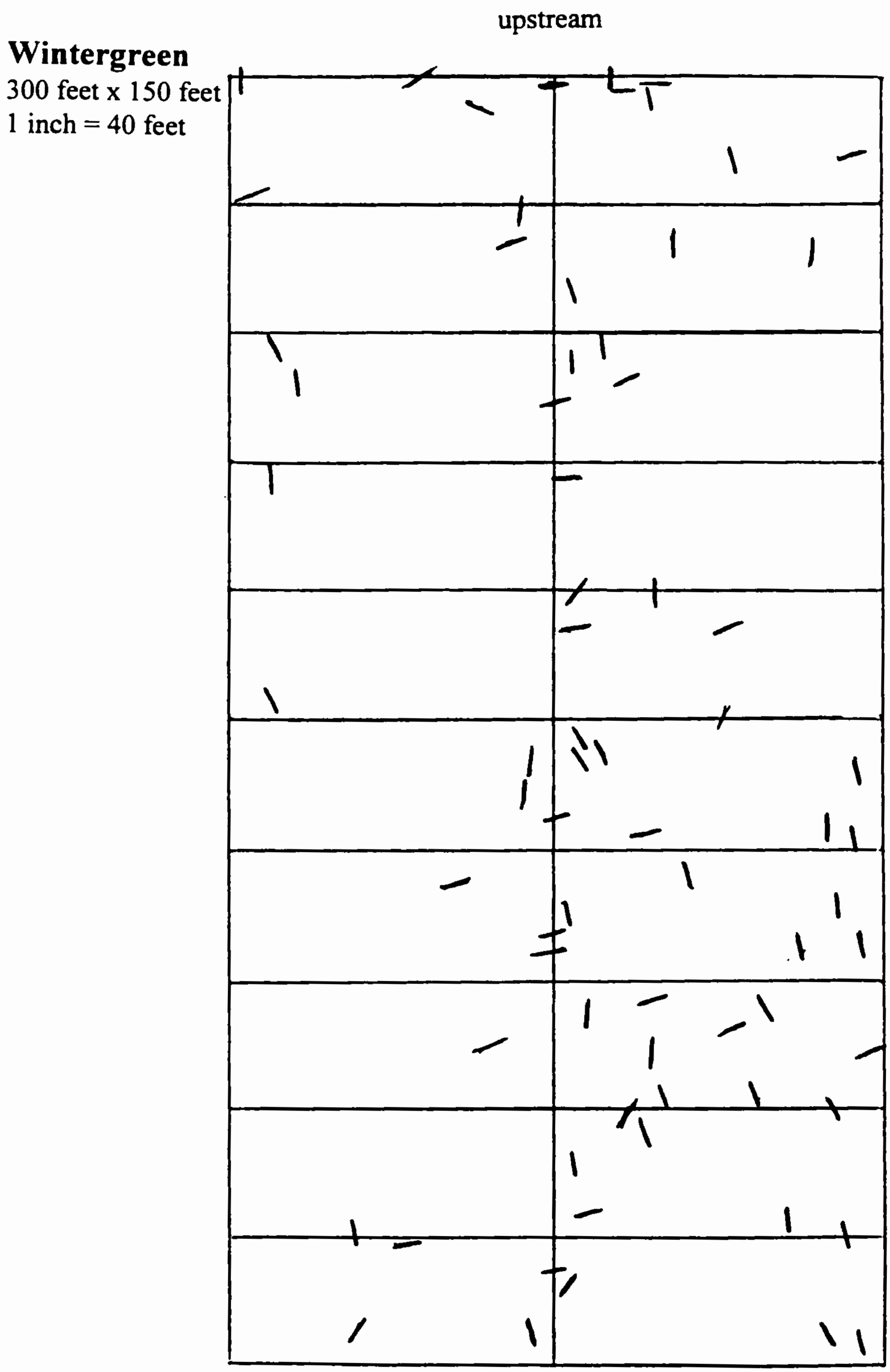


Figure 19 Grid map showing the distribution of near vertical clasts at the Wintergreen study area.

Peaks of Otter
100 feet x 85 feet
1 inch = 20 feet

upstream

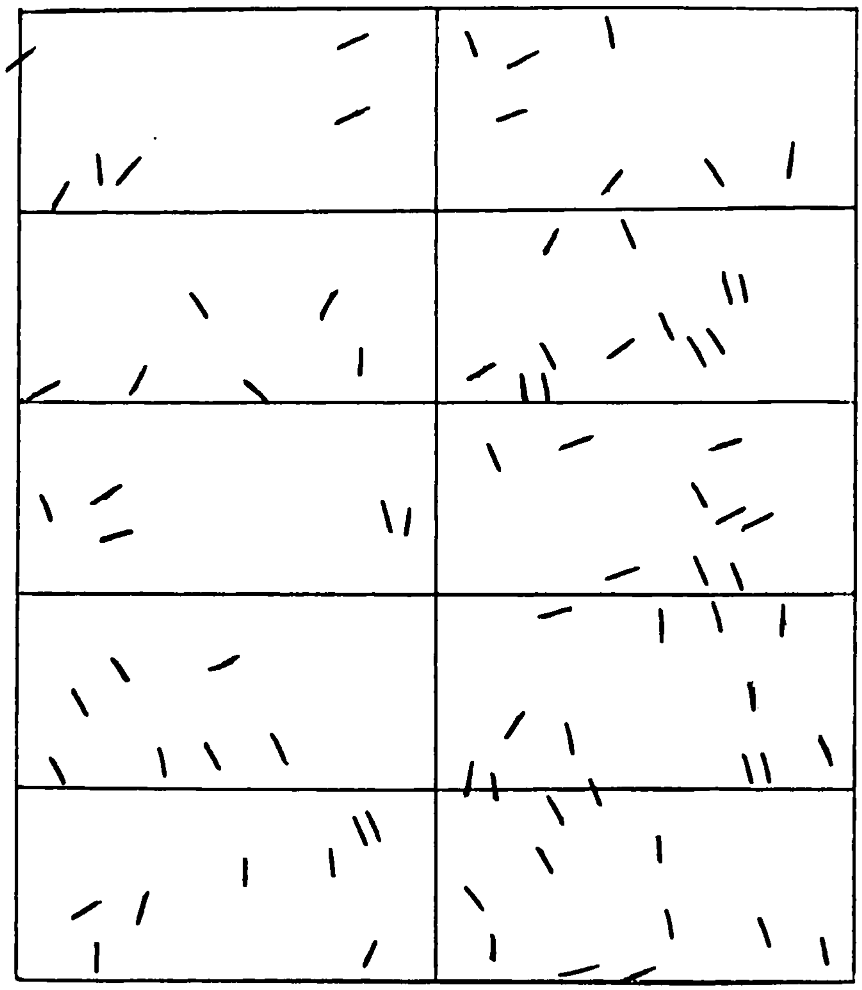


Figure 20 Grid map showing the distribution of near vertical clasts at the Peaks of Otter study area.

Whitetop Mountain
250 feet x 100 feet
1 inch = 40 feet

upstream

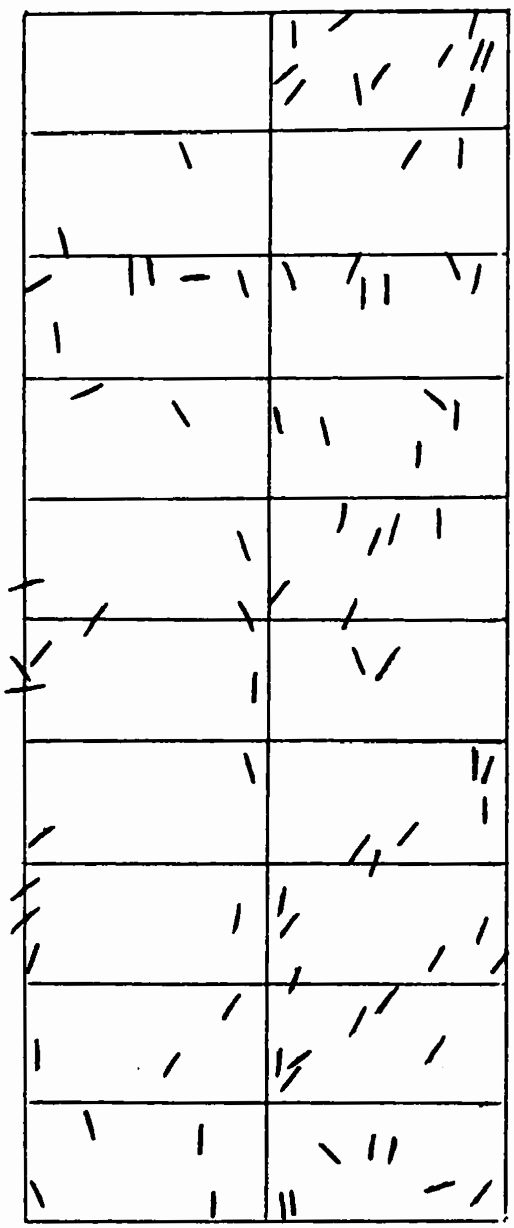


Figure 21 Grid map showing the distribution of near vertical clasts at the Whitetop Mountain study area.

Short Hill

α= .05
Degrees of Freedom = 3
Critical Value = 7.81

O = Observed
E = Expected = 33.6

	Observed	$(O-E)^2/E$
	35	0.058
	28	0.933
	40	1.220
	32	0.076
	33	0.011
Total	168	2.300

The Chi - square value of 2.30 is not greater than the critical value, therefore, there is no evidence to suggest that the quads are unevenly populated i.e., non-clustered distribution

Wintergreen

α = .05
Degrees of Freedom = 3
Critical Value = 7.81

O = Observed
E = Expected = 14.4

	Observed	$(O-E)^2/E$
	14	0.011
	14	0.011
	20	2.180
	8	2.840
	16	0.178
Total	72	5.220

The Chi - square value of 5.22 is not greater than the critical value, therefore, there is no evidence to suggest that the quads are unevenly populated i.e., non-clustered distribution

Figure 22 Results of the quadrat analysis for the distribution of near vertical clasts at the Short Hill site and the Wintergreen site.

Peaks of Otter

$\alpha = .05$
Degrees of Freedom = 3
Critical Value = 7.81

O = Observed
E = Expected = 16.8

	Observed	$(O-E)^2/E$
	21	1.050
	17	0.002
	15	0.193
	18	0.086
	13	0.860
Total	84	2.200

The Chi - square value of 2.20 is not greater than the critical value, therefore, there is no evidence to suggest that the quads are unevenly populated
i.e., non-clustered distribution

Whitetop Mountain

$\alpha = .05$
Degrees of Freedom = 3
Critical Value = 7.81

O = Observed
E = Expected = 17.6

	Observed	$(O-E)^2/E$
	21	0.657
	17	0.020
	16	0.145
	19	0.111
	15	0.384
Total	88	1.320

The Chi - square value of 1.32 is not greater than the critical value, therefore, there is no evidence to suggest that the quads are unevenly populated
i.e., non-clustered distribution

Figure 23 Results of the quadrat analysis for the distribution of near vertical clasts at the Peaks of Otter site and the Whitetop Mountain site.

analysis shows a random distribution of vertical clasts. Observation of the grid-maps constructed for each site would agree with this conclusion; the near vertical clasts appear to be distributed randomly throughout the map area.

Further analysis on the near vertical clasts within boulder streams was conducted by creating rose diagrams for the alignment of near vertical clasts in one boulder stream at each site (Figs. 24-27). The rose diagrams illustrate the general orientation of the A-B plane of the near vertical clasts and thus allow for easy interpretation of any predominant arrangement. The rose diagrams were constructed by analyzing the general orientation for each clast within the map area; however, the length of the bars in the rose diagrams are not proportional to the total number of vertical clasts for each respective orientation.

A-B planes for many of the clasts lie parallel or sub-parallel to the central axis of the boulder stream itself. However, at several sites, many near vertical clasts lie nearly perpendicular to the predominant clast orientation. This arrangement, as well as those nearly parallel with the central axis of the boulder streams, can be seen in Figures 24-27. By observing the grid maps (Figs. 18-21) constructed for each area, one can also see this trend.

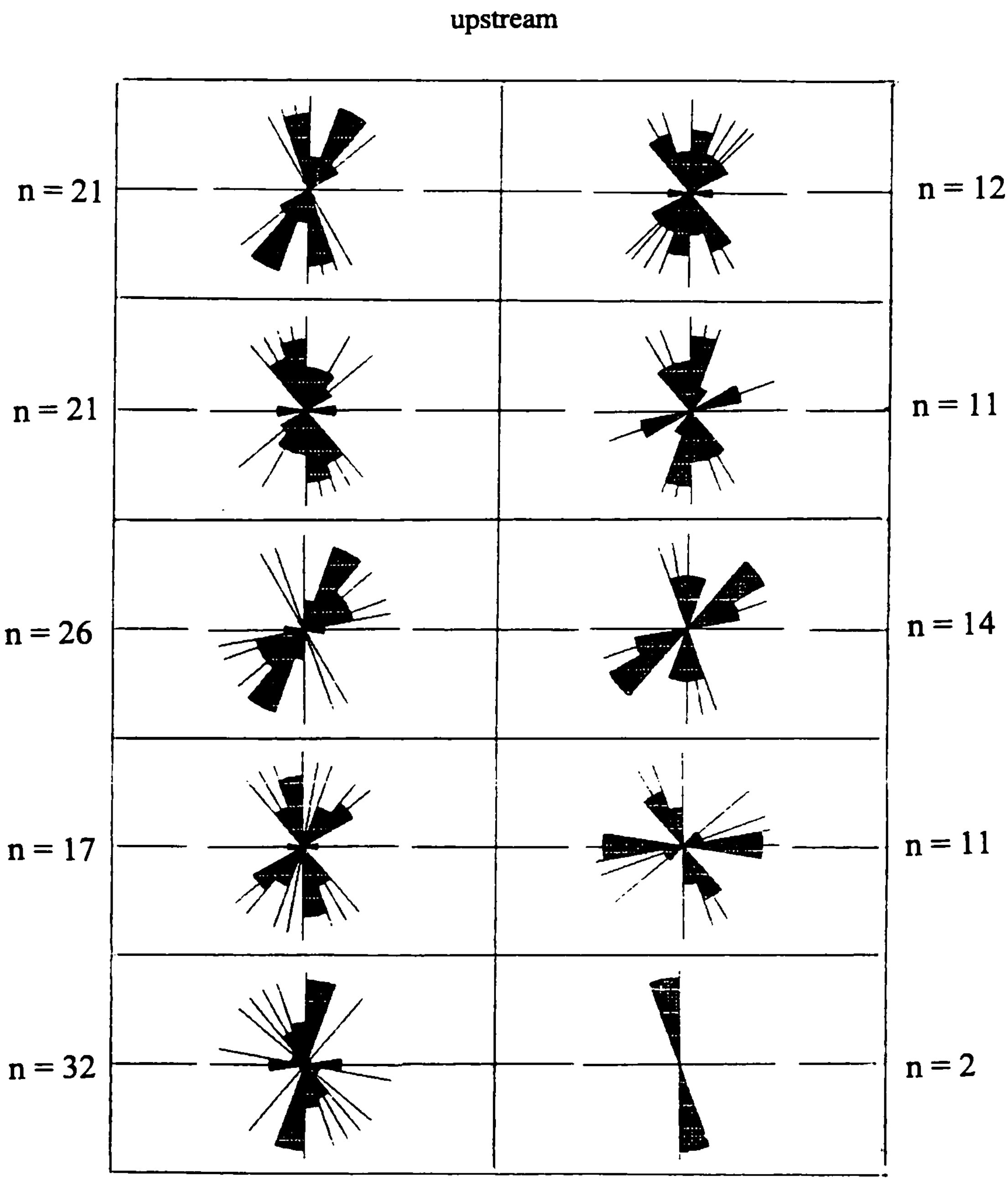


Figure 24 Rose diagrams for each section of a boulder stream at the Short Hill site. The length of the bars in the rose diagrams are not proportional to the total number of vertical clasts for each respective orientation. Each cell with a rose diagram is 50 feet in length and 87.5 feet in width.

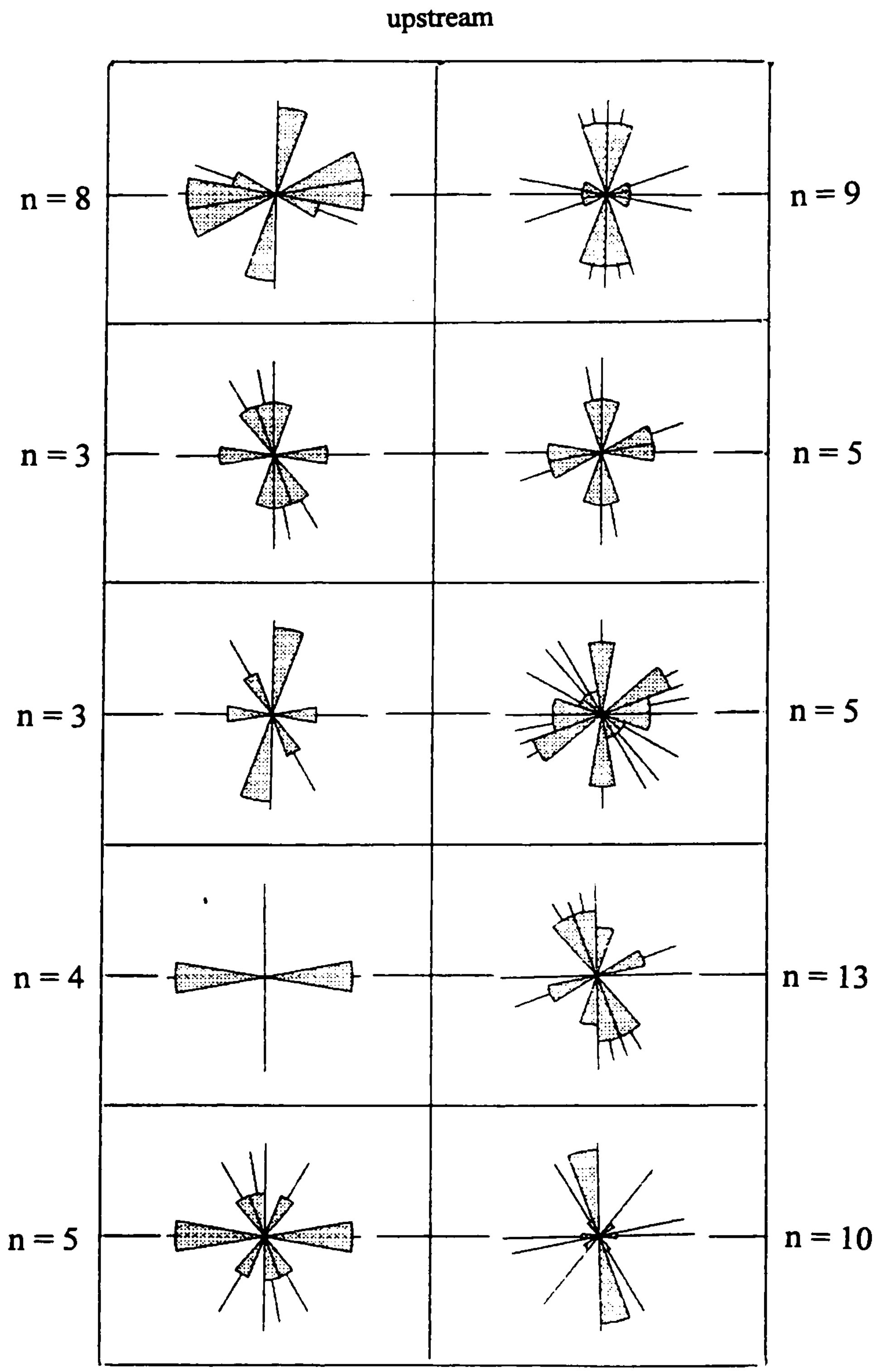


Figure 25 Rose diagrams for each section of a boulder stream at the Wintergreen site. The length of the bars in the rose diagrams are not proportional to the total number of vertical clasts for each respective orientation. Each cell with a rose diagram is 60 feet in length and 75 feet in width.

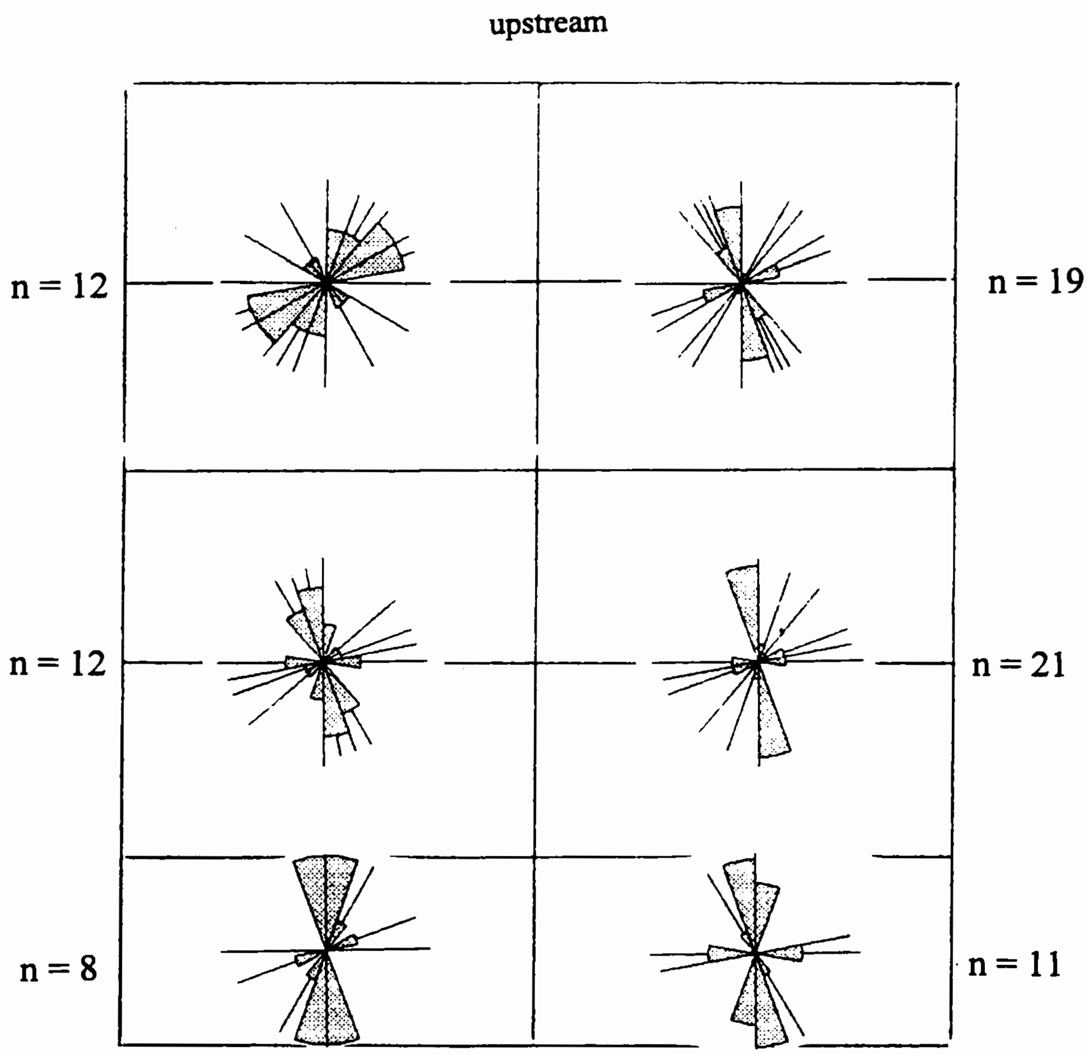


Figure 26 Rose diagrams for each section of a boulder stream at the Peaks of Otter site. The length of the bars in the rose diagrams are not proportional to the total number of vertical clasts for each respective orientation. The upper four cells are 40 feet in length and 42.5 feet in width. The lower two cells are 20 feet in length and 42.5 feet in width.

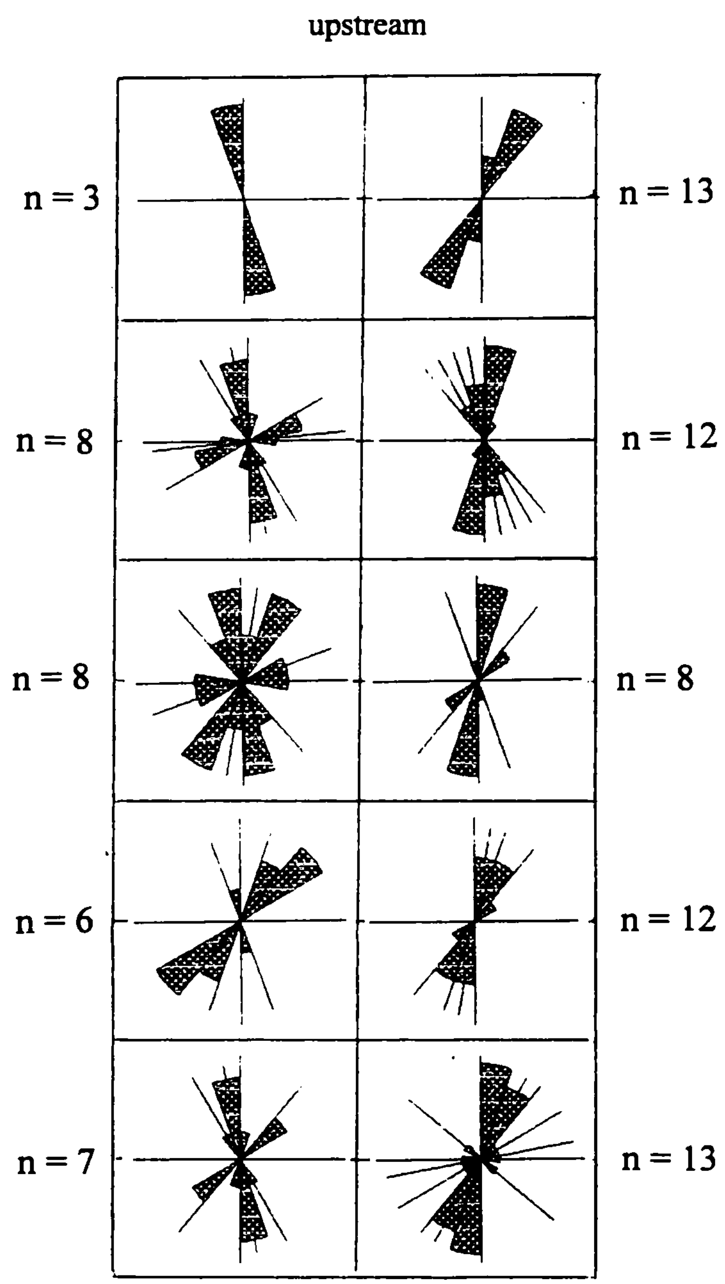


Figure 27 Rose diagrams for each section of a boulder stream at the Whitetop Mountain site. The length of the bars in the rose diagrams are not proportional to the total number of vertical clasts for each respective orientation. Each cell with a rose diagram is 50 feet in length and 50 feet in width.

DISCUSSION

Map Analysis

The minimum critical elevation for boulder stream formation, as determined for the four sites in this study (Table 1), clearly increases to the south.

TABLE 1. LATITUDE AND CRITICAL ELEVATION FOR STUDY SITES

Location	Latitude	Critical Elevation
Short Hill	39° 19' N	150 m
Wintergreen	37° 53' N	480 m
Peaks of Otter	37° 28' N	750 m
Whitetop Mountain	36° 38' N	1500 m

Figure 28 clearly shows that as latitude decreases, the minimum elevation at which the tops of boulder streams can form increases. This information suggests that a paleotemperature trend existed during Pleistocene periglacial periods. Because severe climates were more frequent in northern regions, temperatures would be cold enough to produce boulder streams even at low elevations. In more southerly regions where episodes of freezing would have been less frequent and less intense, temperatures were probably not low enough to warrant the formation of boulder streams except at increasingly higher elevations. This type of paleotemperature

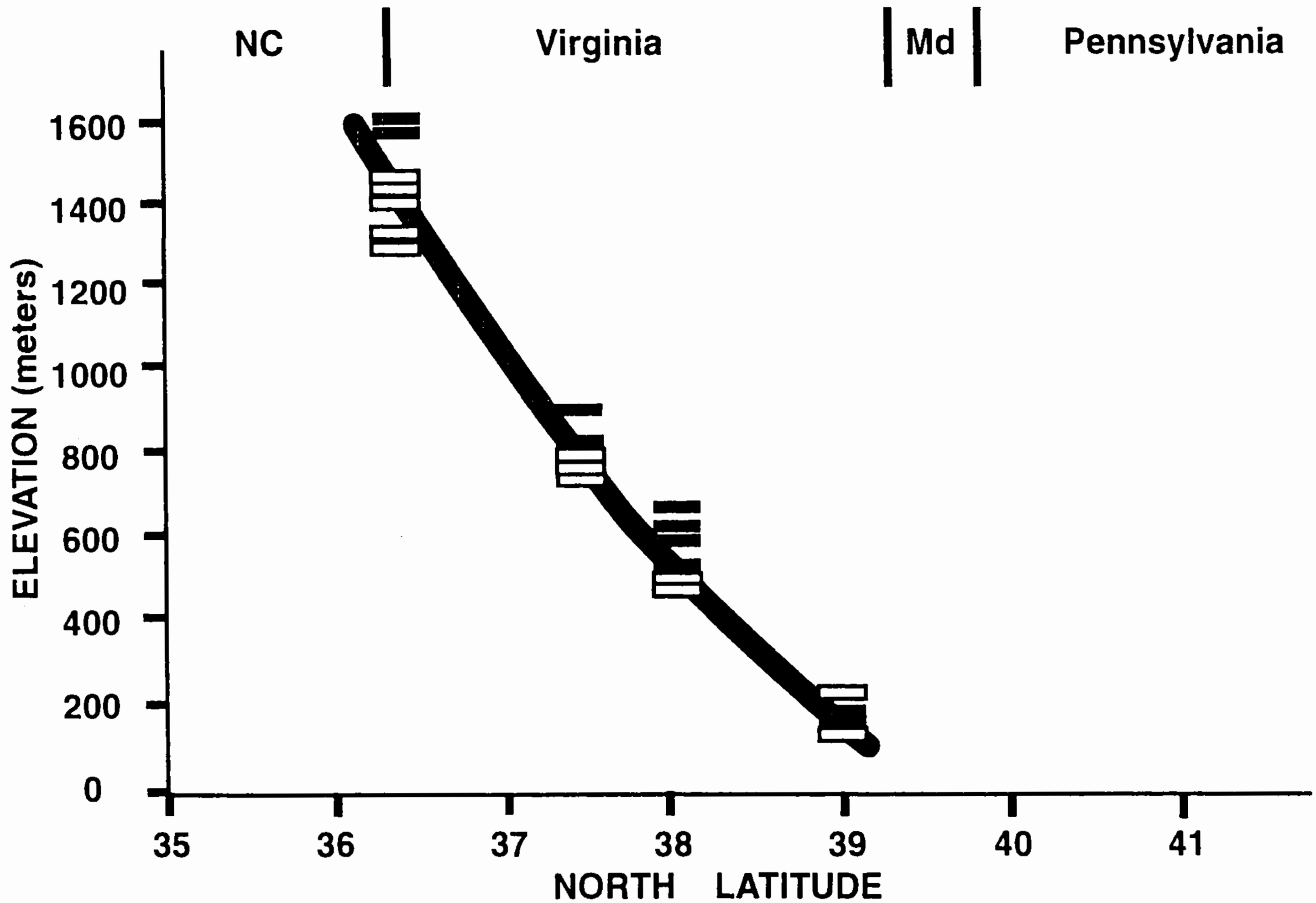


Figure 28 Critical elevation graph constructed from the data found at each study site. Empty squares represent valleys with no boulder streams and black squares represent valleys with boulder streams. The lines represent the suggested critical elevation zone for boulder stream formation across Virginia.

relationship is similar to that reported in a study conducted by Delcourt and Delcourt (1985) (Fig. 10) which involved the formation of patterned ground. With this graph they inferred that the severity of periglacial conditions decreases to the south. Using just the Virginia boulder stream data, I reach the same conclusion.

However, after combining the Virginia observations with those of boulder streams throughout the Appalachians (Fig. 29), the interpretations become more complex. From these data, it appears that a regional paleoclimatic trend existed for periglacial conditions from the Virginia area northward into Pennsylvania. However, from Virginia southward, the gradient of the trend is much less distinct, if a trend exists at all. If the "northern" paleoclimatic trend is projected southward, one might infer that the critical elevation for boulder stream formation in the Great Smoky Mountains of North Carolina and Tennessee is higher than the tallest peaks, clearly an untenable hypothesis (Fig. 29). Also, the trend based on boulder stream data in Virginia is much steeper than the trend drawn by Delcourt and Delcourt (1985) through patterned ground in the same area.

These differences between the apparent trends to the north and to the south of Virginia and between boulder streams and patterned ground values dictate a critical re-examination of the data in Figure 28. Considering the trend of decreasing critical elevations for boulder streams noted to the north from Virginia to Pennsylvania, it is conceivable that the gradient is a coincidence, despite the development of objective selection procedures. However, several sets of independent field observations support the concept of the "northern trend" reported in the present study. Several geologists who have recognized boulder streams in various parts of the Virginia highlands confirm the general

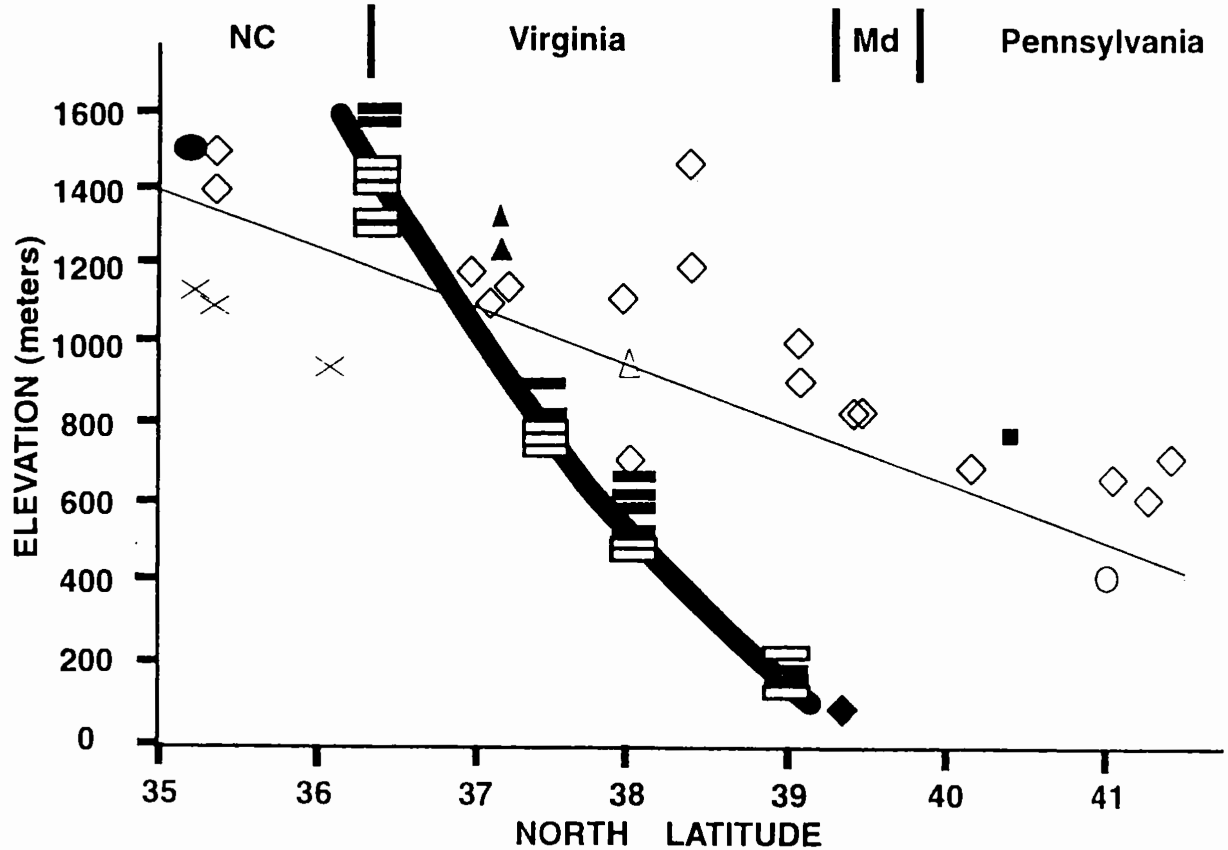


Figure 29 Graph showing the elevation and latitude of boulder streams and patterned ground in the Appalachian region. Open diamonds=Delcourt & Delcourt(1985); closed rectangles represent valley heads with boulder streams and open rectangles represent valley heads without boulder streams=Zamkotowicz(1997); open circle=Sevon(1987); closed square=Potter & Moss(1968); closed diamond=Clark and others(1992); open triangle=Ryter(1989); closed triangle=Mills(1988); closed circle=Shafer(1988); X=Michalek(1968). ~~Wide~~ line represents paleoclimatic trend for patterned ground. Wide line represents paleoclimatic trend for boulder streams.

levels of critical elevations suggested by this trend (personal communications with D. Harbor, C. Watts, C. Sherwood, and R. Whittecar). Also, colluvial and frost-shattered soils are very common in the Piedmont of northern Virginia (elevation approximately 100 m) but much thinner or non-existent at similar elevations in southern Virginia (Clark and Ciolkosz., 1988). Finally, similar paleoclimatic trends exist in other areas (e.g., the cirque limits in the Cordillera (Meier, 1960)). From a more theoretical aspect, paleoclimatic reconstructions based on pollen data suggest that the average summer position of the polar front crossed the Appalachian highlands somewhat south of Virginia during times of maximum glacial expansions (periglaciation) (Bryson and Wendland, 1967; (Fig. 30); Connors, 1986). A steep temperature gradient would have existed south of this front. This interpretation suggests that areas from Virginia north to the glacial margin would have been dominated by polar air masses even during the summer, while North Carolina and Tennessee probably experienced considerably more time under more temperate air masses. Thus, if boulder streams are relics of periglacial conditions, the boulder stream trend to the north of Virginia is considered both empirically and theoretically sensible, although repeated testing of the trend by future field workers will be necessary to verify this conclusion.

If the paleoclimatic trend to the north of Virginia is realistic, we must deal with both the differences in slopes of the boulder stream and patterned ground gradients in Virginia and the apparent lack of a paleoclimatic gradient across the southern Appalachians (as seen in Fig. 29). As described in an earlier section, past morphogenetic studies (e.g., Washburn, 1980; Willliams and Smith, 1989) indicate that a variety of

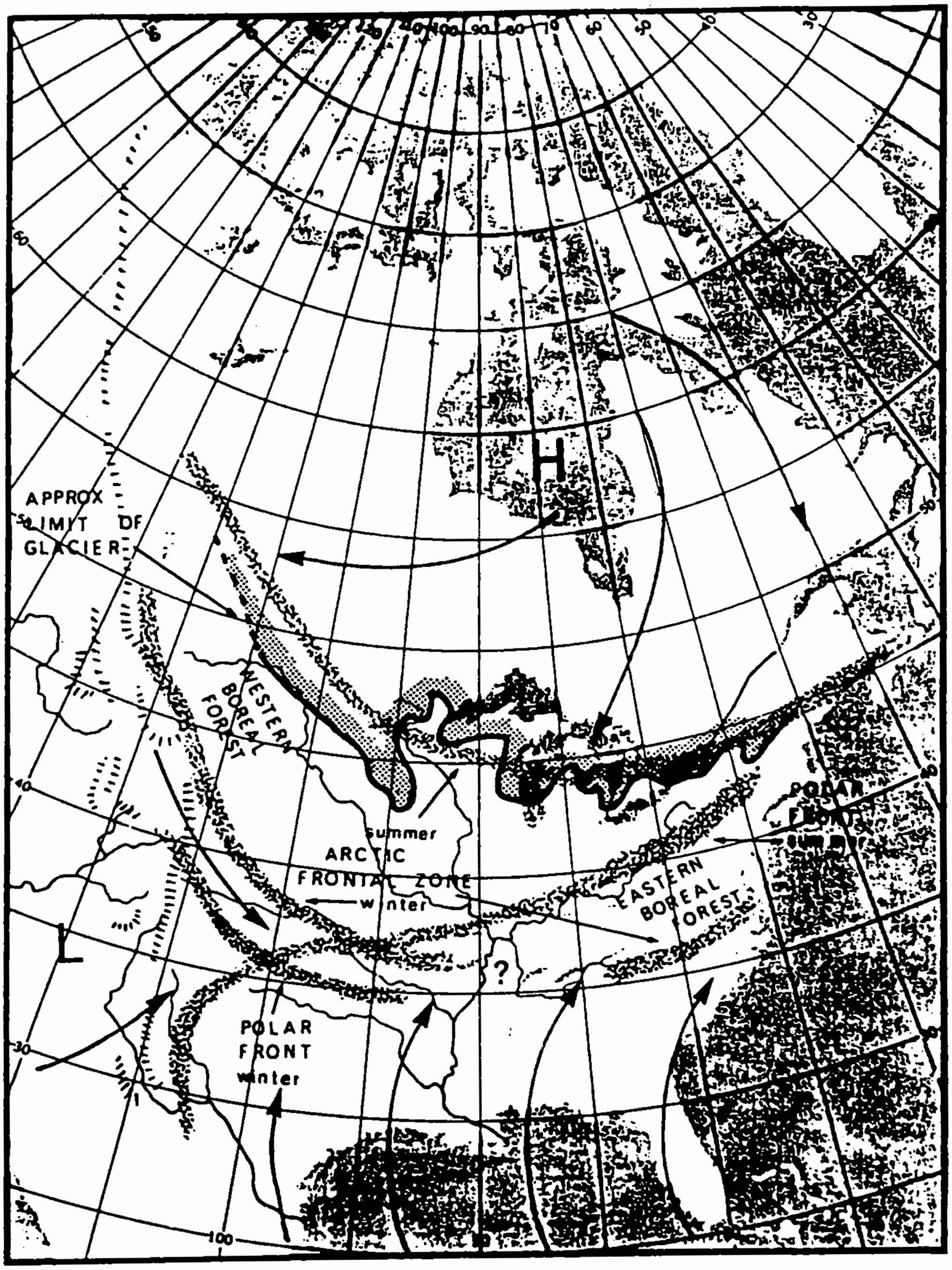


Figure 30 Map showing the mean airstream boundaries in late-glacial time. Note the positions of the arctic frontal zones during the winter and the summer (after Bryson and Wendland, 1967).

geologic, topographic, and microclimatologic factors may control the distribution of these features in many areas. At present, we can use these studies to speculate about the causes for the differences revealed between the results of the present and past studies and to suggest lines of research for the future.

Differing paleoclimatic gradients - patterned ground vs boulder streams : The data used in the present study and those in Delcourt and Delcourt (1985) were gathered for different purposes, and so we can not rule out the possibility that the differences between the two graphs reflect important variations in temperature regimes, moisture, or other microenvironmental conditions. Most of the patterned ground studies used by Delcourt and Delcourt (1985) lie along the rim of the Appalachian Plateau, 50-100 km west of the Blue Ridge chain. Perhaps variations in climate between the two mountain ranges might explain the discrepancy.

Another environmental factor might be the temperature range at which each of the periglacial features form. If boulder streams form in a wider range of temperatures than patterned ground then it seems reasonable to suggest that this periglacial feature may be found with a greater distribution. The influence of water is also important in the formation of both features. For patterned ground, the freezing and melting of water plays a critical role in its formation and for boulder streams, the freezing of water physically weathers the source rock to provide the debris that feed the boulder streams. If water was more or less abundant during periglacial episodes along either mountain chain, then this variability might account for the distribution of the periglacial features at these locations.

Differences in geology also may explain why the two paleoclimatic trends intersect. Boulder streams require a source outcrop toward a ridge crest and a rock type susceptible to breaking off large pieces of rock. Patterned ground, however, does not require a supply of bedrock debris, but a reasonable amount of regolith instead. The nature of the soil in which the features form (particularly patterned ground) is also an important factor in development. The properties of the soil in any location generally determine the frequency of thermal cracking and thus influence the formation of patterned ground (Williams and Smith, 1989).

A third factor that may influence the distribution of boulder streams and patterned ground may be the unique formational mechanics for either feature. The development of patterned ground relies on the freezing and thawing of ground ice in a low relief area with abundant regolith (Embleton and King, 1975). The formation of boulder streams in the southern Appalachians relies on the frost shattering of rock and the subsequent movement of the debris on steep slopes. Thus, each feature has its own restrictions on where and how it may form. Also, as illustrated in Figure 29, patterned ground in the southern and central Appalachians formed at much higher elevations than boulder streams. This pattern suggests that patterned ground requires more severe polar climatic conditions to develop than do boulder streams.

The presence of a latitudinal gradient in the formation of boulder streams further verifies that these features formed by periglacial processes. The latitudinal trend of boulder streams, documented here for the first time, was predicted by the "periglacial hypothesis" of boulder stream formation. If these bouldery colluvial masses formed by winnowing of the fines from the tops of debris flows, as suggested by several workers, boulder streams would be quite common at all elevations along steep terrains. Instead, at these four sites, they occur at elevations less than 170 m in northern Virginia and Maryland but not below 1300 m in southwest Virginia. The boulder streams mapped in this study were presumed to be periglacial based on criteria developed by previous workers (i.e., continuity of deposits, gradational upper end with talus deposits, stability of interlocked boulders, etc.); however, these studies used indirect evidence to deduce a periglacial origin for these boulder streams. Thus, the paleoclimatic gradient (e.g., Fig. 28) may be used as direct evidence for the periglacial origin of boulder streams with these features.

Boulder stream distributions south of Virginia :

Boulder streams have been documented at elevations of 1000 to 1300 m in North Carolina (Michalek, 1968; Shafer, 1988), far lower than would be expected given the paleoclimatic trend in Virgina and Pennsylvania. The presence of these boulder streams at these locations may be attributed to a couple of factors. The authors of these papers were not specifically looking for a critical elevation at these locations. Therefore, the bouldery accumulations they studied may or may not conform to the criteria designated for periglacial boulder streams in this study. Although Michalek (1968) determined a periglacial origin for the colluvium he observed, he did not use all of the characteristics of boulder streams denoted in the present study.

Another plausible explanation for this discrepancy is the possibility that the critical elevation boundary for the formation of boulder streams (or any other periglacial feature) may not increase uniformly to the south. There may be undulations or plateaus in the minimum elevation at which boulder streams can form (e.g., Fig. 9). As the critical elevation increases in altitude to the south, it may increase or decrease due to some unknown reason. It may also be possible that, between some areas, the environmental conditions are similar such that the critical elevation neither increases or decreases. Although this probably would not occur over a large area (for example, the entire north half of Virginia), it may happen over much smaller distances (maybe two adjacent counties in North Carolina).

As noted in Fig. 28, many valleys lie above the critical elevation line that do not have boulder streams. Field observations suggest several formational factors that change over short distances may be important in governing the placement of boulder streams. One such local factor may be the thickness of the overlying regolith or the depth of the bedrock from the surface. If the source rock is considerably buried beneath the soil and regolith, frost action may be less effective in breaking apart the rock into boulders. Another factor could be the rock type itself. Different rock types are likely to have different strengths so that certain rocks would produce debris (i.e., talus) easier than others. The presence of cliffs also affects the placement of boulder streams. Cliffs are more likely to form if the bedding or foliation dips into the hillside. On dipslopes, cliffs may form only if the dip is far less than the hillside angle. For example, at the Whitetop Mountain site, the bedrock dips to the south. Cliffs and boulder streams at this location have been found more regularly on the steeper northern side. At many of the sites I studied, the dip of the bedding or foliation of the bedrock influenced the distribution of cliffs, talus, and boulder streams.

Other environmental factors may also affect the distribution of boulder streams on hillslopes. These may include amounts of water within the regolith, soil texture, and structures within the source rock (Whittecar and Ryter, 1992; Williams and Smith, 1989). Thus, local controls on boulder stream formation, such as specific rock type and structure and dip angle of the rock, could become the controlling mechanisms for boulder stream development, particularly in the absence of a strong paleoclimatic gradient. Perhaps to the south of the average position of the summer polar front during periglacial periods, local factors were more important. Consider slope orientation for example. Although, in this study, aspect did not seem to control the placement of boulder streams on hillslopes, it may be possible that as distance from the glacial margin increases, aspect may have been more important. It may be that north of Virginia, where polar air masses dominated year - round, aspect was not critical to boulder stream development. However, as distance from the glacial margin increases, so may have the influence of local controls on the production of rock debris, talus, and eventually, boulder streams. It could be suggested that, although slope orientation does not seem significant in boulder stream formation north of Virginia, it could be significant south of Virginia. Thus, the direction of the slope upon which boulder streams may form, in addition to other environmental factors listed here, may be a local control which determines the formation of boulder streams at distances far from the glacial margin.

Vertical clast analysis

The direction of the A - B plane on the grid maps and the orientation of the rose diagrams (Figs. 24-27) reveals that a majority of the vertical clasts are oriented parallel with the central axis of the boulder stream. Based on studies regarding flow patterns within the boulder stream matrix (Potter and Moss, 1968), it is likely that this orientation for the near vertical clasts is caused by the downhill movement of the clasts. One mechanism that could produce such a result might be shearing produced between longitudinal zones with different rates of movement (Fig. 31a). Differential movement of the clasts on the surface would cause the application of pressure unequally on the A-B plane of any given tabular block. This in turn would cause the rotation of the clast from any original orientation to a direction almost parallel with the central axis of the boulder stream.

The other common orientation for the near vertical clasts within the boulder streams is that in which the clasts are aligned almost perpendicular with the central axis. One explanation for this may be longitudinal compressive (decelerating) flow within a portion of the boulder stream (Fig. 31b). If differential compressive pressures exist in the boulder stream, the clasts which are positioned between these pressures might be squeezed and reoriented to almost perpendicular to the axis of the boulder stream (Fig. 31b).

The near vertical clast data for each of the sites show no general organization in the distribution of these boulders. The quadrat analyses of these data (Figs. 22-23) indicate the near vertical clasts are not clustered. If the near vertical clasts were strongly

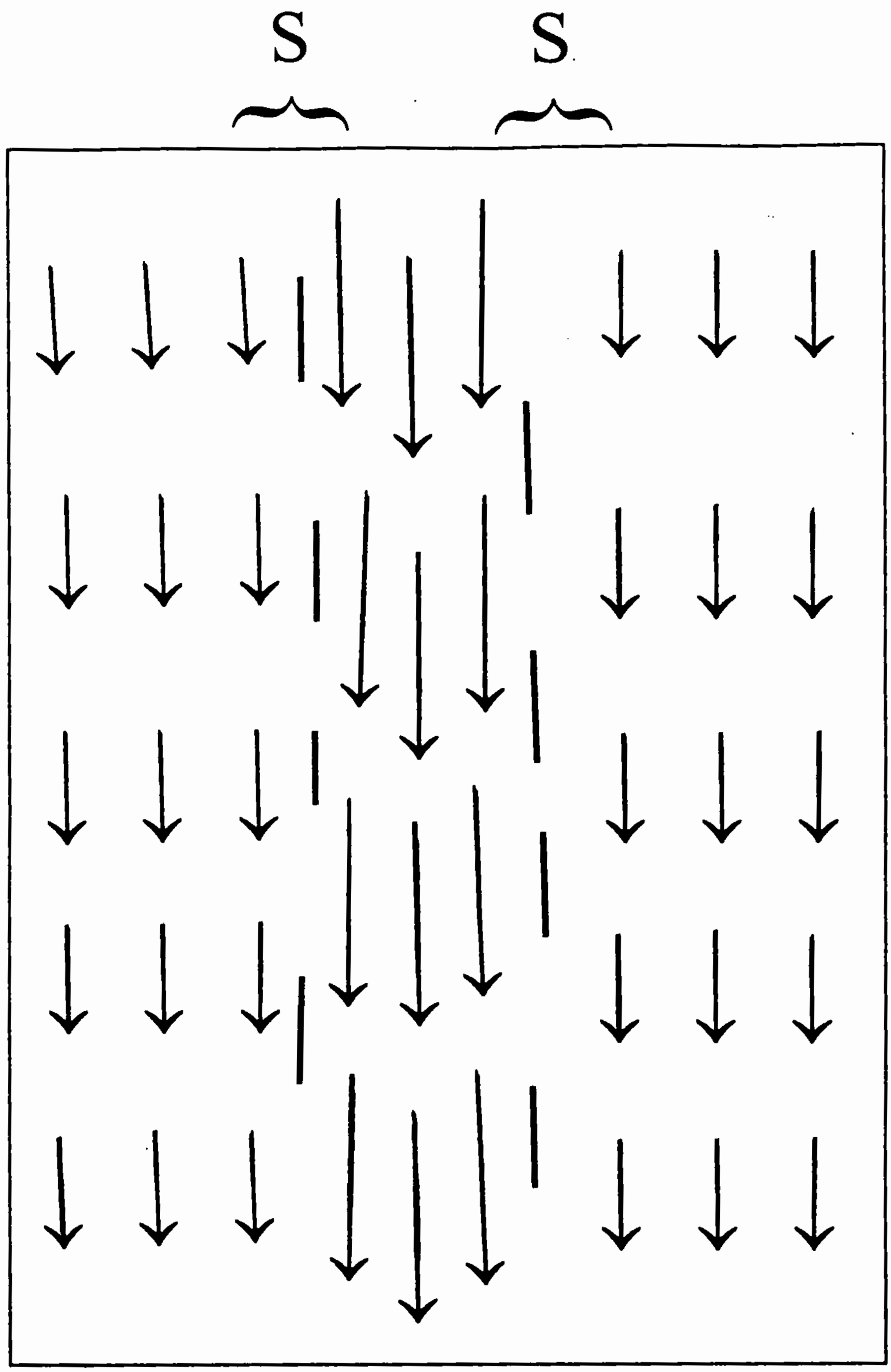


Figure 31a Longitudinal shear formed between zones with different velocities along a hypothetical boulder stream. Arrow lengths represent flow velocities; short lines represent near vertical clasts. S marks zones of shear where clasts may be oriented parallel to the boulder stream axis.

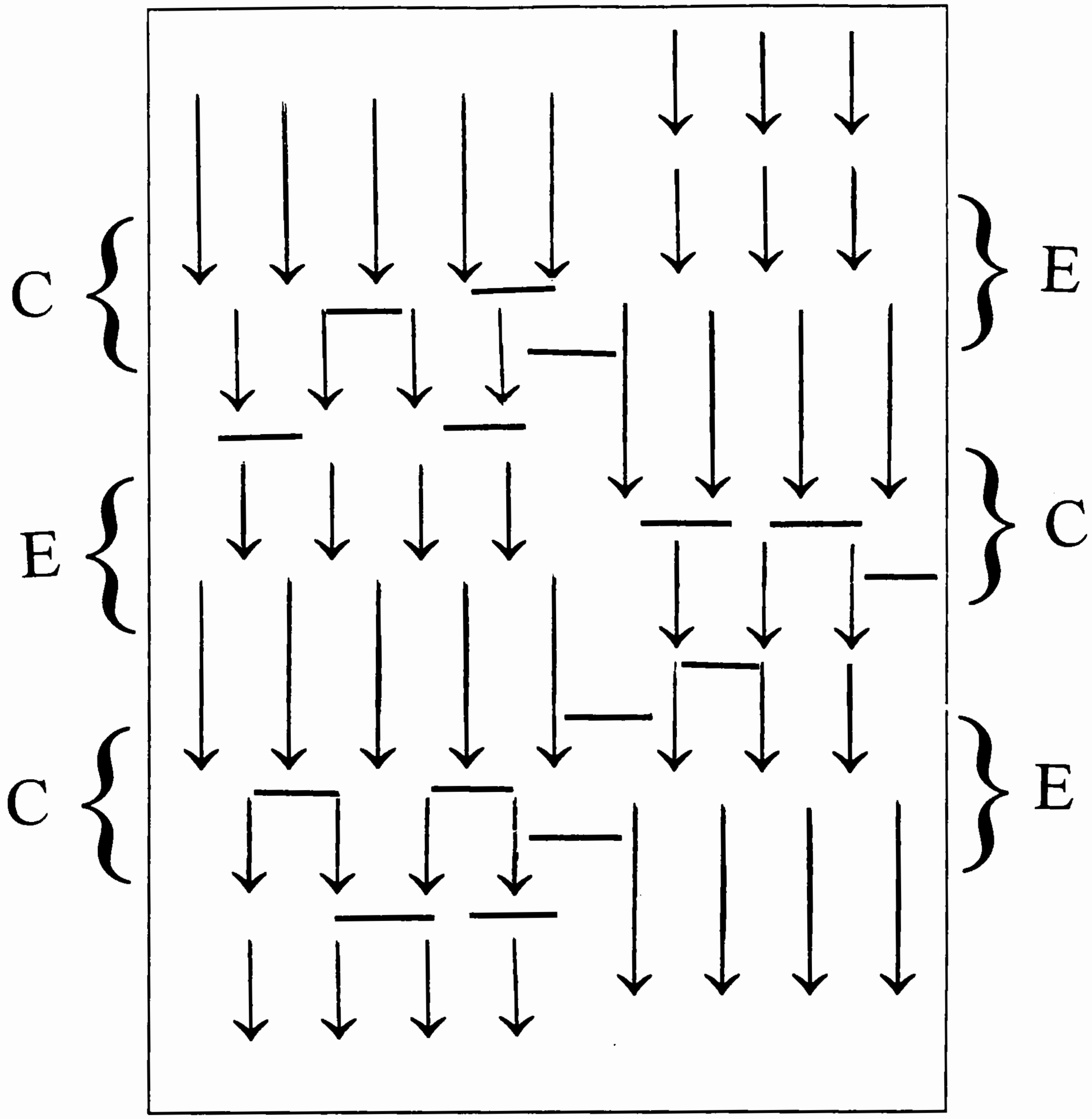


Figure 31b Compressive flow zones formed along a hypothetical boulder stream where portions of boulder streams decelerate. Arrows represent flow velocities; short lines represent near vertical clasts. C marks zones of compressive flow where near vertical clasts may become oriented perpendicular to flow. E marks zones of extending flow.

clustered we might conclude 1) that the vertical orientation process occurred repeatedly at certain isolated sites and 2) that downslope movements cause the near vertical clasts to topple within a short distance of where they were oriented. However, because their spatial patterns are non-clustered, it may be that the formation of the near vertical clasts occurs at many times and at many places. For example, if the center of the boulder stream moved most often and farthest compared to the margins, then the width and position of shear zones could vary during a periglacial period and thus near vertical clasts may be widely scattered throughout the boulder stream. We might also see a dispersed pattern of the near vertical clasts if several zones of various flow rates existed within the boulder stream at different times. Another factor which must be considered is the possibility that small irregularities in the slope of the underlying bedrock would cause zones of compressive or extending flow in addition to the natural movement of the boulder stream. The magnitude and spacing of these irregularities, might control whether the near vertical clasts appear to be clustered.

It is also possible the near vertical clasts within the boulder stream may have been previously clustered but are presently scattered because of movement of the clasts downhill. However, given that most lateral movements of the boulder streams would probably topple high-angle clasts in a short distance, it seems more reasonable to conclude that the processes which oriented the clasts occurred close to where they are now seen.

Thus, based on the flow models described previously, one might expect to see a relatively clustered pattern in the distribution of the near vertical clasts. However, the more dispersed pattern mapped suggests the possibility that several factors influence the movement of the boulder stream including multiple areas of differential flow within the boulder stream, a range of flow rates, or undulations of the underlying valley slope.

CONCLUSIONS

The data examined in this study provides insight into some of the factors affecting boulder stream distribution and morphology. This study supports the following inferences regarding boulder streams :

1) The distribution of boulder streams in the Blue Ridge province of Virginia reveals that a critical elevation needed for formation exists and that it is related to latitude. The critical elevation determined for each site increases in altitude toward the south. The presence of boulder streams in valleys may or may not occur above this critical elevation because boulder stream formation is also dependent on certain formational mechanisms. These mechanisms may include moisture content, depth to bedrock, and dip angle of the source rock. It is unlikely boulder streams will be found in valleys below this elevation due to less frequent freeze-thaw conditions.The graph of boulder stream elevation versus latitude (Fig. 29) reveals that the general trend of the critical elevation for boulder streams and patterned ground intersect. This suggests that the formation of patterned ground and boulder streams differ with respect to latitude.

Another observation is the variability of elevations of boulder streams noted in this study versus those discussed by previous researchers. One reason for this variability may lie in the possibility that the boulder streams documented by previous workers may not fit the criteria designated in this study for boulder streams of periglacial origin. It may also be that the critical elevation for boulder stream formation does not increase uniformly with latitude. There may be undulations in the minimum elevation throughout the Appalachian mountains.

The discrepancy of other workers' results with those found in this study seem to be more apparent south of Virginia. In addition to the possible reasons for this break in trend listed above, another cause may be the distance from the glacial margin. Hypothetically, regional climatic controls on boulder stream formation may be dominant from the Virginia area northward, but south of Virginia, local formational controls may prevail. That is, environmental conditions may exist from the Virginia area north that allow for the formation of boulder streams more readily. However, south of Virginia, climatic conditions may vary more from region to region due to increased distance from the glacial margin (i.e., milder temperatures, water content of the atmosphere and soil, etc.). Thus, local controls on boulder stream formation, such as specific rock type and structure, dip angle of the rock, and aspect, could be the controlling mechanisms for boulder stream development south of Virginia.

Earlier studies on boulder streams in the central and southern Appalachians suggested that these boulder streams formed by periglacial processes by using indirect evidence which include continuity of the deposits, a gradational upper end with talus deposits, and stability of the interlocked boulders. However, based on the information in this study, the increase in the critical elevation for boulder stream formation with a decrease in latitude provides direct evidence for the periglacial hypothesis for the formation of boulder streams in the Appalachians.

In order to better understand past climatic variations with latitude, much more work is necessary. A better understanding of the processes and conditions under which modern boulder streams develop is necessary in interpreting more clearly the paleoclimatic conditions across the Appalachians of Virginia and how these conditions varied from region to region.

2) The presence of near vertical clasts within boulder streams seems to be common. The distribution of the near vertical clasts appears to be random with a large number of them oriented parallel with the central axis. The quadrat analysis performed on the data reveals a non-clustered distribution of near vertical clasts throughout the boulder stream. This result is either an indication of the original placement of the near vertical clasts or it may be due to the movement of the clasts throughout the stream (primarily downslope) through time. In order to determine whether the random distribution occurs originally or if it happens through time, more research is needed on active boulder streams.

The distribution of near vertical clasts within the framework of the boulder stream does not appear to yield insight into the movement of the boulder stream itself. However, the large number of the near vertical clasts which are oriented with the long axis parallel to sub-parallel with the central axis of the boulder stream indicates shearing of the clasts as they travel downslope. This type of vertical clast pattern has also been documented in active boulder streams (Washburn, 1980).

The presence of vertical clasts that are oriented almost perpendicular to the main axis of the boulder stream is likely due to compressive flow within the boulder stream. Differential pressures occurring in the boulder stream as gravity pulls it downhill may cause certain portions of the boulder stream to be squeezed. This would rotate the clast from a parallel position to a more perpendicular orientation. Despite the presence of near vertical clasts oriented in such a fashion, a majority of them lie almost parallel to the central axis of the boulder stream.

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