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»PIPING« IN RELATION TO PERIGLACIAL BOULDER CONCENTRATIONS

In many areas once affected by periglacial conditions, local concentrations of bare blocks or boulders in an otherwise unsorted and soil-covered mantle of rubble are conspicuous features. These range from small boulder clusters through elongate strips to larger expanses referred to as block or boulder fields, stone rivers, etc., all on low to moderate slopes. Form is irregular and distinctive pattern generally lacking. The boulders are completely „bald", and interstitial open spaces continue to depth, in contrast to the earthy matrix and surface soil of adjoining ground. This contrast impressed various observers, and the boulder concentrations in some of the more striking localities came to be explained as a secondary feature, produced by the action of running water in washing away the interstitial finer material initially present. Specifics of the process, however, received little consideration, and various questions about it have been left unanswered. It now appears that the concept of *piping*, a term borrowed by geologists from engineering usage to designate mechanical removal of clastic materials by underground waters, may contribute to a better understanding of the phenomena concerned. W. M. Davis has remarked that,

> „There can be no question that the adoption of a suitable term as the name for a fact is a great aid to the general recognition of the fact itself." (Davis, 1909, p. 409).

In this paper, it is purposed thus to offer a specific name for the general phenomena in question, with the hope of thereby stimulating further observation and thought concerning the matter.

Background for the present discussion may be provided by a review of ideas on representative examples of the boulder concentrations under consideration, with particular reference to those occurrences which represent a local facies or variant of a more general accumulation of unsorted rubble. This excludes the typical felsenmeere of upland regions, pre-

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sumably formed by frost shattering in place, and containing minimal fine material. It excludes also those accumulations of fragmental material formed on steep slopes by rolling or sliding, or by the action of associated ice, as in the case of rock glaciers. Of the types of occurrences remaining, the „stone rivers" of the Falkland Islands may be regarded as a classic example. As described by Thomson (1877),

> „... the valleys are occupied by pale grey glistening masses, from a few hundred yards to a mile or two in width, which look at a distance much like glaciers descending apparently from the adjacent ridges, and gradually increasing in volume, fed by tributary streams, until they reach the sea ... these are found to be vast accumulations of blocks of quartzite, irregular in form ... from two to eight or ten or twenty feet long and half as much in width ... the blocks are angular like the fragments of a breccia, and they rest irregularly one upon the other, supported in all positions by the angles and edges of those beneath."

These features were interpreted by Andersson (1906) as a product of solifluction under conditions which now would be termed periglacial, followed by secondary removal of interstitial fines; he writes:

> „The open areas and strips consisting only of a chaotic accumulation of large blocks of quartzite evidently have been formed by a secondary washing away of the finer material that once filled all the interspaces between the big blocks or carried parts of them on its surface ... the contours of these vegetationless block-fields, with all their embranchments, give the rude outlines of a small river system, and, as has been mentioned already by Darwin and Thompson, in many places the purling of running water is heard far down below under the blocks, indicating the recent course of a stream in the depth of the stone river.
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> „But the areal extent of the ancient flowing slopes is much larger than that indicated by the open vegetationless block-fields. In all places where running water has not washed away the fine material the old detritus flows remain in their original composition and offer a soil which is able to carry a covering of vegetation. Where there is a small cut of any kind in such an unaltered part of the slope, it is easy to recognize that the mass underneath the mantle of vegetation is the same as in the [recent] waste-streams on Stephens Peak, large blocks imbedded in fine rock detritus".

In my own studies of the Hickory Run boulder field, comparable in many respects to the stone rivers described above, though on a smaller scale, I reached similar conclusions, hypothesizing periglacial solifluction, with subsequent modification of its results to produce the present condition:

> „The bareness of the boulder field is best explained as a secondary feature due to the gradual flushing of fine material by running water... Is seems unlikely that the boulders could have moved to their present position without an interstitial filling of soil material to retain moisture, reduce friction, and promote frost heaving. Although some flushing may have taken place *pari passu* with accumulation, it is belived that this process did the major part of its work after accumulation of the boulders was completed. In marginal parts of the boulder field it appears still to be in progress" (Smith, 1953).

In the Driftless Area of Wisconsin also, I have studied minor boulder[1] fields and boulder streams or stripes on slopes, together with strips and clusters of boulders on boulder-strewn valley floors, the latter suggesting an incipient stage in the development of larger boulder expanses. In all cases, the boulder concentrations were interpreted to represent local modification of a more general periglacial rubble sheet (Smith, 1949). In some of the localities which I studied, the proportion of larger boulders appeared to be higher at the surface than below, suggesting some segregation by active translocation of the boulders through frost action. However, the dominant process, affecting zones of larger and of smaller boulders alike, and climaxing the sequence of events, was simply one of subtraction, removing fines while leaving the larger fragments undisturbed except possibly for slight settling; the boulders had a purely passive role.

In the above situations, removal of fines was attributed rather casually and in general terms to the work of running water. Since the sound of running water was audible beneath the surface, it seems to have been tacitly assumed that a surface stream gradually worked its way downward, removing fines on the way, and ending as a subterranean stream. This, however, would hardly be applicable to those occurrences where the boulder concentration is surrounded on all sides by unmodified rubble having its soil cover intact, and in any case would present serious mechanical problems. Removal of the fines from the sides of the topmost boulders would be feasible, but removing the fines from beneath the boulders is a very different matter. Analogous features in active stream beds have not been reported. The drag of flowing water is restricted to the stream bed, and is not transmissible below the channel bottom. Only if hydraulic pressure were applied from below it is likely that interstitial fines could

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[1] In the discussion below, for convenience in presentation, the term, *boulder,* is used to include both rounded and angular rock fragments.

be carried upward to a level where velocity of stream flow was sufficient to permit pickup, and this would require a rather special set of conditions entirely independent of those ordinarly operating in the stream channel.

In view of the above difficulties, it might be asked whether the action of subsurface water might make for a better explanation for the observed effects. One indication was given by my observations at a locality in the Driftless Area, although its full significance was not appreciated at the time. I noted that on the valley bottom,

> ,,some blocks are scattered at random, others are clustered, and still others occur in elongated strips. At some places no surface stream is recognizable as such. The sound of running water can be heard locally, however, under the blocks in the elongated strips (pl. 4, A). Where these strips end, the course of the underground streamlet may be traced, in part, along a series of holes in the sod, through which the sound of running water comes. The drainage, at least during times of ordinary flow, is entirely under the surface at these places and appears to be in process of undermining the sod, exposing more blocks and extending the blocky strips by washing away the interstitial fine material from a coarse, rubbly deposit". (Smith, 1949, p. 206—207).

Subsequent studies by other workers in other types of terrain have provided much additional information on the mechanical work of underground water, and the term, *piping*, has been applied to it. An excellent review has been contributed by Parker (1964), who states that:

> ,,Piping, the natural development of subsurface drainage in relatively insoluble clastic rocks of the drylands (arid and semiarid regions) gives rise not only to badlands forms but to a system of geomorphic forms simulating those produced by solution of calcareous rocks. Where solution is quite advanced, a karst topography results, and where piping is well developed a karst-like topography is developed, for which the term 'pseudokarst' is proposed".

The pseudokarst features include small-scale sink holes, natural bridges, blind valleys, caves, tunnels, and related forms, which may be particularly conspicuous in loess (*cf.* Fuller, 1922). In the development of these, water seeping from some outlet removes fine material in suspension and initiates an opening, which then progresses back beneath the surface by headward sapping, adding to flow on the way, and enlarging itself in the process through continued, grain-by-grain removal of fine material picked up from the sides of the conduit or supplied by caving of the roof. Breakthrough to the surface occurs at points of weakness, and the openings thus produced undergo subsequent enlargement. Although most common in unconsolidated surficial deposits, piping has been invoked also in poorly-consolidated sandstone to account for collapse depressions forming lake basins in the Chuska Mountains of New Mexico (Wright, 1964). Sandstone caves attributable to piping have been observed also by me at various places in the Colorado Plateau region.

According to Parker, the process of piping may occur where four essential conditions are fulfilled;

> „(1) Water enough to saturate some part of the soil or bedrock above base level; (2) hydraulic head to move the water through a subterranean route; (3) presence of a permeable, erodible soil or bedrock above base level, and (4) an outlet for flow."

In many of the localities studied by Parker, piping was believed to have been facilitated also by a fifth condition, the presence of swelling clays, which undergo marked expansion and contraction as a result of wetting and drying, thus to form cracks available for movement of water.

The periglacial rubble deposits which this paper is concerned represent a coarser and more heterogeneous type of material than that in which previously-described examples of piping occur, and the results of the process therefore might be expected to have a somewhat different appearence. Removal of fines, however thorough, would always leave a residual accumulation of boulders, and the amount of actual surface lowering would be limited to that involved in the settling and repacking of boulders originally held apart by the finer constituents; pseudokarst depressions would be boulder-filled from the beginning, and their nature obscured. The first effects at the surface, once subterranean flow was initiated, may be visualized as the development of holes between boulders by undermining of soil at the more vulnerable points, diverting surface flow to subsurface routes, augmenting the ground water already at work. Continued undermining, together with the washing effect of descending water, then would tend to extend the openings around and beyond the first boulders affected, carrying away the soil from an area of increasing radius, leaving a bare, bouldery surface, with an open network of voids below. This presumably would take place at many places aligned with the direction of subsurface flow, strating downvalley and progressing upvalley. Outward growth from adjacent centers then would lead to gradual coalescence of the denuded tracts, producing more continuous expanses of larger size. This might be expected to continue, given sufficient time, until limits were reached in trems of susceptible material or of requisite subsurface flow, or other factors intervened. In the developmental sequence pictured above, the various occurrences in the Driftless Area might be regarded as representing the earlier stages, the Hickory Run boulder field a more advanced stage, and the stone rivers of the Falkland Islands as approaching the end product.

Factors localizing subsurface flow for the piping process as outlined above are somewhat conjectural. If the rubble accumulation originally contained zones with relatively higher permeability, resulting from some differential activity of the accumulation process, these undoubtedly would have played a part. Furthermore, if segregations of ground ice were present, as would be expectable in a periglacial environment, with probable permafrost, the melting of this ice might create voids which, if protected from immediate infilling by detritus, could become interconnected to form channelways for movement of meltwater. Cryostatic or hydrostatic pressures during seasonal refreezing might assist by forcing water in directions of least resistance to exploit incipient openings; the fluid pressures involved in the formation of frost blisters, icings, etc. (*cf.* Muller, 1947), are suggestive. The role of subsurface ice thus might be rudely analogous to that of the swelling clay in dry regions. However, observational data are lacking, and additional study is needed to evaluate this possibility.

Is appears from the above discussion that the concept of secondary denudation from the bottom up, by piping, provides a rational working hypothesis for surface characteristics of the various boulder concentrations referred to, and throws new light on a hitherto obscure phase of their development. More general application of the concept may be appraised by considering its suitability for other areas where conditions are different and variant features occur. One such area is found in the Beartooth Mountains of Wyoming—Montana (southeastern Alpine and southwestern Mt. Maurice topographic sheets). The features of interest occur on a rolling upland underlaid by igneous and metamorphic rocks, at elevations between 3000 and 3300 meters. The area is above tree line, and surface features have excellent visibility. The upland is deeply trenched by glaciated canyons, and periglacial conditions are believed to have prevailed when the canyons were ice-filled. Patterned ground is found at many places, but is largely a „fossil" phenomenon (Smith, 1950). The features of particular interest for the present discussion are largely non-patterned, and represent a local bare, bouldery facies of a more general rubble accumulation mantling all but the steeper parts of the upland; this material is believed to have been derived partly from frost weathering and mass movement of local bedrock material, and partly from an ancient glacial till.

Of the various boulder concentrations, the largest and most distinctive is a well-developed boulder stream (Pl. 1), unique for the area, and unusual for any alpine region. Length is some 500 meters, width is irregular, with an average of about 30 meters, and axial gradient is between 2° and 3°. The surface is a jumbled mass of bare, weathered, lichen-covered boulders up to several meters in length; it is very rough and irregular from a closeup view, but appears flattish from a more distant view. Openings between boulders are clean, and extend down out of sight, two meters or more. The sound of running water is audible from beneath the boulders at various places, and is visible at a few low spots, where flow is seen to be vigorous. Surface characteristics are very similar to those of the Hickory Run boulder field, referred to above, although the setting, the rock, and the dimensions are quite different. The margins of the boulder stream are ragged, with barren areas and sod-covered areas dovetailed together. In the headward section, irregularity increases, and ,,islands" of sod-covered ground occur interspersed with barren stretches, interrupting the continuity of the latter (Pl. 2).

On the flat to gently-sloping surface bordering the boulder stream, minor, irregular pits and hollows, a fraction of a meter in depth, are common. Some are dry, some moist, and some have standing water. Sides and bottoms range from grassy through muddy to bouldery. At some places, incoming streamlets are seen to disappear under the sod cover, headed for the main open bouldery expanse.

The lower end of the boulder stream is marked by a V-shaped boulder ,,cascade" descending steeply some 10 meters to a lower bouldery tract (Pl. 3). The coarse and well-washed material of the accumulation is fully exposed in the steep-sided reentrant. Water is heard flowing below the bottom of the notch and passes under a snowbank.

As in the case of the other boulder concentrations referred to earlier in this paper, the surface bareness here is best explained as a secondary characteristic, and for similar reasons. No satisfactory precedent exists, and no logical argument has been advanced for attributing the contrast between the boulder stream and the unsorted rubble in topographic continuity and in internal contiguity with it, to any original processes of emplacement. Known processes of accumulation on low gradients all involve the presence of an earthy matrix. Some vertical segregation of different-sized materials within the coarser fraction, by frost action or related processes, during or immediately following accumulation, is not excluded, but this also would have required the earthy matrix; thorough separation of coarse and fine materials en masse is an entirely different matter. Removal of the fines thus must have been a secondary phenomenon, initiated after the primary process of emplacement had done its work. Flowing water ist he one available agent to produce this effect. For the reasons set forth earlier in this paper, surface flow appears incompetent to remove fines to depth, and in this locality the area of the drainage basin is too small even to have produced any very large volume of surface flow. Analogies with the other areas thus leave piping as the only credible process that could have been effective. The four conditions listed by Parker as requisite for the process appear to be fulfilled. The presence of the islands of unsorted rubble in the boulder stream are explicable on this basis as remnants of a once-continuous, pre-piping surface, fortituously bypassed by that process. The various pits and hollows near the boulder field, and the islands of sorted boulders interspersed with sod-covered ground, may be considered as forerunners of the stripping effect, with piping in an early or incipient stage. Where the hollows have standing water, it is suggested that subsurface openings initiated by piping were later plugged by accumulation of organic material and soil material now found in them, perhaps after changing conditions caused the relative effectiveness of piping to decline. At the present time, piping does not appear to be progressing at a significant rate.

If the concept of piping is applicable to the boulder field and its immediate surroundings, does it apply also to the smaller and less conspicuous boulder concentrations widely though irregularly distributed on the upland? Of the latter, features that may be referred to as boulder clusters, „nests", or „sinks", are of particular interest. These occur mainly on the flatter slopes, and appear to be randomly described. The individual clusters differ considerably in appearance. Some involve only a few boulders of relatively larger size, while others comprise more numerous boulders of smaller size. The former commonly project above general ground level, while the latter do not. Where larger boulders dominate (Pl. 4) they characteristically are stripped of soil below ground level on one or more sides, leaving moat-like depressions, completely inclosed. Where smaller and more numerous boulders prevail (Pls. 5 and 6), they are loosely packed, present a jumbled appearance, and show open interstitial spaces, free of fines. The effect is that of an open pit filled by tossing in boulders. The boulder-studded aspect of surrounding ground suggests that it differs only in having interstitial spaces filled with soil material, and that removal of the latter enlarge the area of the original cluster without appreciably changing its characteristics. Nearly all of the boulders involved in the above, both large and small, are more or less weathered and lichen-covered, and appear to have been motionless for a relatively long time. And in all occurrences observed, despite other variations, the common characteristic is the presence of open space to depth between bare boulders; differences are mainly in the size and shape of the openings. The surface characteristics are essentially those of any tract of the same size on the boulder stream. Soil material apparently has been removed from around, between, and under the boulders. There is no indication of any way in which the fine material could have been carried upwards or sidewise, and it seems rather that it must have been removed from below, and that piping was the effective process. Similarity to the bouldery embayments and sod-bordered ,,islands'' associated with the boulder stream itself suggests formation in the same way as the latter, although the outlet for subsurface flow is less in evidence.

On steeper slopes, boulder concentrations tend to be elongated across the contour, and there are various gradations between clusters, elongate clusters, aligned clusters, and irregular stripes (Pl. 7). The materials involved and the surface characteristics, however, are esentially the same, and there are no indications that the mode of origin was basically different. In some cases, however, it seems possible that frost sorting, of the type involved in producing the more regular and symmetrical sorted stripes, may have had a preparatory role, localizing the piping process.

One other type of boulder concentration possibly related genetically to the features discussed above is found in the rude stone nets occurring where the larger rock fragments are either absent or less numerous. These are between one and two meters in diameter, and the stony rims are between a quarter and a half meter in width. Central areas contain coarse fragments similar to that in the rims, but embedded in finer material. On a reduced scale, the stony, soil-free material of the rims has some similarity to the larger boulder concentrations described above. The possibility that piping played some part in forming them, or in developing their present condition, is speculative, but warrants consideration. Possibly the melting of ground-ice wedges in polygonal form localized the effects.

From the foregoing, it may be concluded that observations in the Beartooth area are in accord with the interpretations made for other areas, and lend additional support to the piping hypothesis. Further conclusions of a more general nature are suggested also:

(1) In studying the various types of relict periglacial boulder concentrations, it is important to distinguish between the effects of primary segregation or rearrangement of materials by frost-induced sorting, and of secondary denudation by removal of the fines. Although the two processes may occur in sequence, the latter is not necessarily dependent on the former, although it may be localized thereby and accentuate the effects thereof.

(2) The concept of piping provides an explanation for removal of fines in situations and to depths otherwise difficult to account for, and

analogies from other types of terrain in which piping is demonstrable seem applicable to periglacial features.

(3) Piping contributes to the understanding of some hitherto obscure aspects of periglacial phenomena, and may enter into the explanation of features previously attributed entirely to other processes.

(4) The effects of piping appear sufficiently prominent in periglacial deposits as to suggest that its initiation was related to some phase of the periglacial sequence of events, perhaps the melting of ground-ice segregations and integration of the resulting openings. There is some indication also that later changes in conditions may have tended to check or retard the process.

(5) Much additional observation, supplemented perhaps by experimentation, is needed to further test the applicability of the piping hypothesis to periglacial phenomena — to delimit the controlling factors, ascertain the mode of initiation, trace the sequential effects, clarify the hydrology of the process, and determine the range of features to which it is relevant.

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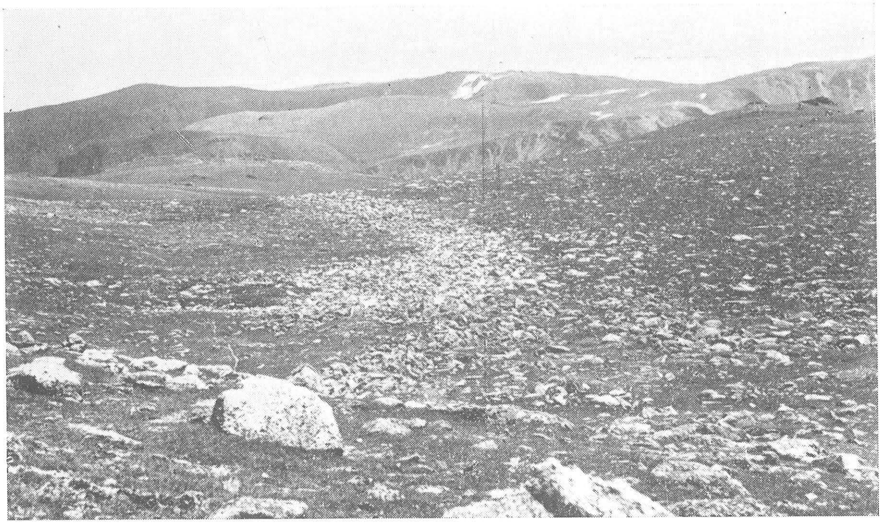
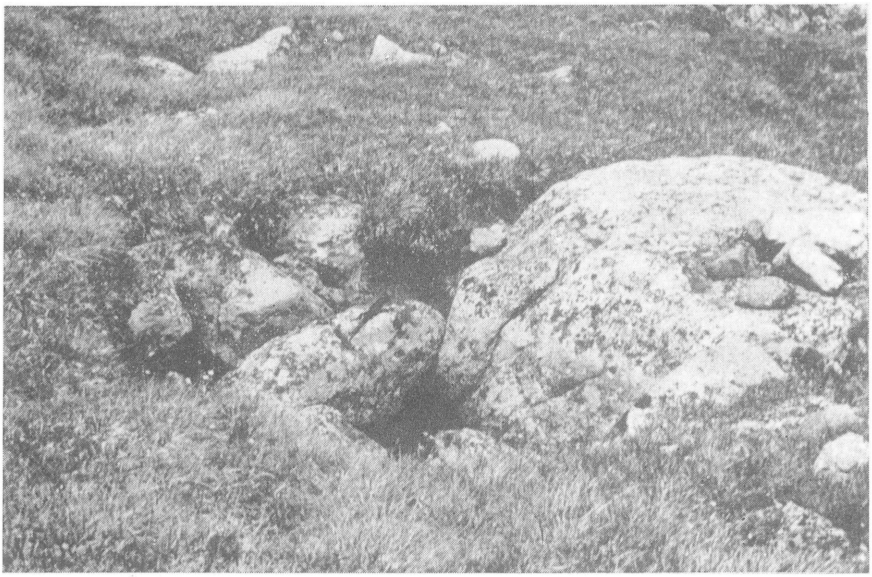


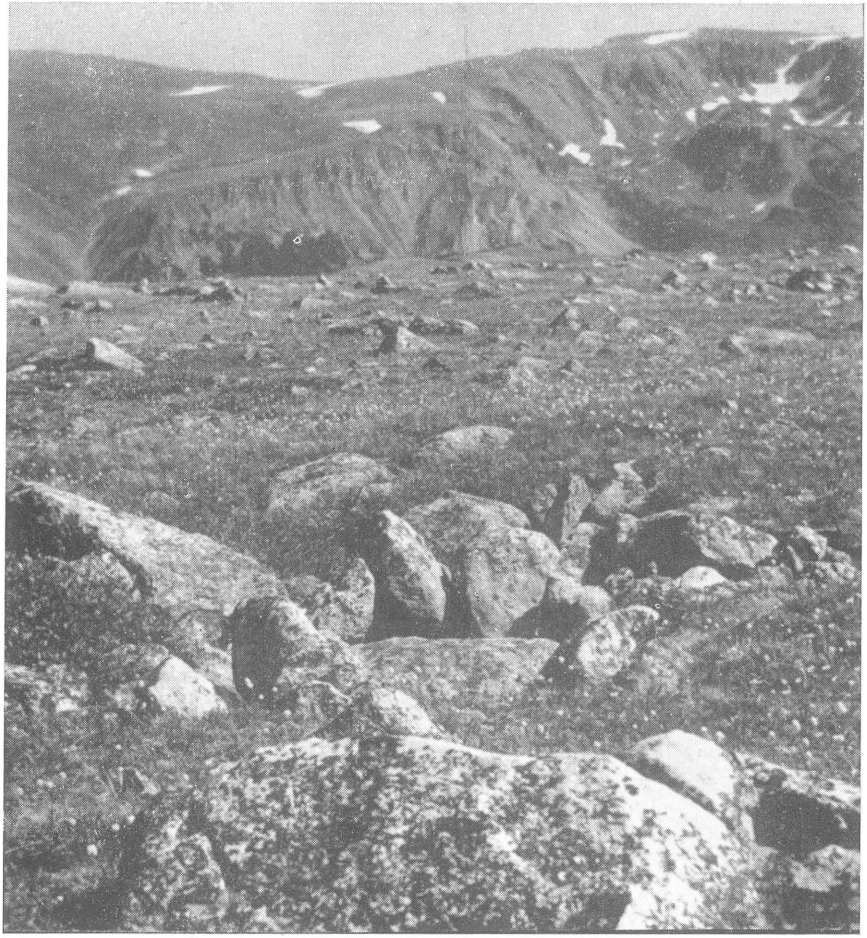
Pl. 1. View of boulder stream in Beartooth Mountains (just east of Shelf Lake, in southeastern corner of Alpine, Mont.-Wyo., topographic sheet), looking eastward

Pl. 2. View near upper end of boulder stream, showing interspersed bouldery and sod-covered tracts

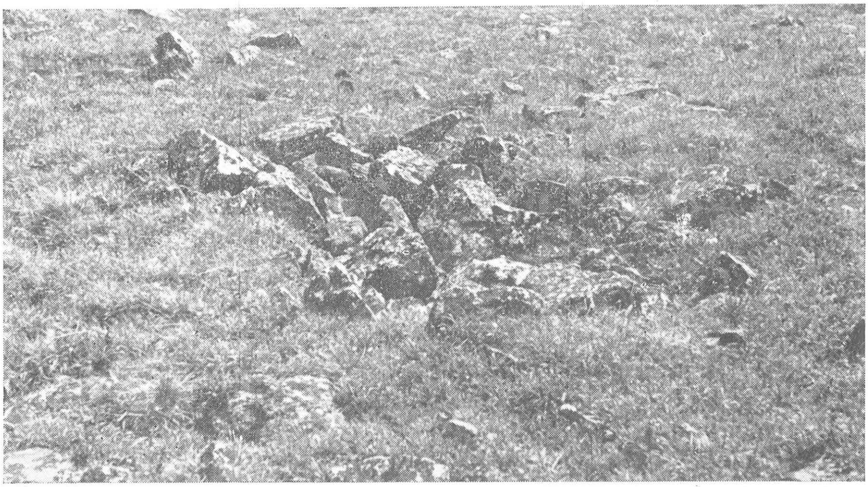
Pl. 3. Dropoff at lower end of boulder field



Pl. 4. Boulder cluster with depressed area partway around one large boulder



Pl. 5. Cluster of loosely-packed smaller boulders on gentle slope, with boulder-studded turf in background



Pl. 6. Another variation of the boulder cluster

Pl. 7. Elongate boulder clusters and strips on steeper slope, with cross section of the materials exposed in highway cut